The Integration of Fluctuating Renewable Energy Using Energy Storage

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Publication date:
2010

Document Version
Accepted author manuscript, peer reviewed version

The Integration of Fluctuating Renewable Energy Using Energy Storage

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The Integration of Fluctuating Renewable Energy Using Energy Storage

by

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A thesis submitted to the University of Limerick
in fulfilment of the requirements for the degree of

Doctor of Philosophy

in the
Charles Parsons Initiative at the Department of Physics and Energy
University of Limerick
Ireland

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EAGNA·CHUN·GNÍMH·
UNIVERSITY of LIMERICK

Submitted to the Univeristy of Limerick, December 2010

Abstract

Energy storage is often portrayed as an ideal solution for the integration of fluctuating renewable energy (RE) due to the flexibility it creates. However, there is uncertainty surrounding energy storage in terms of the technologies that currently exist, the additional RE it enables, and its role in modern electricity markets. These uncertainties have hampered the deployment of large-scale energy storage and hence, this research examined these concerns.

This research began by identifying the most feasible energy storage technology available for the integration of fluctuating RE, specifically for Ireland. Due to its technical maturity and large-scale capacities, pumped hydroelectric energy storage (PHES) was deemed the most viable technology, but the literature outlined a lack of suitable sites for its construction. Therefore, a new software tool was developed in this study to search for suitable PHES sites, which was then applied to two counties in Ireland. The results indicate that these two counties alone have over 15 sites suitable for freshwater PHES, which in some cases could be twice as large as Ireland's only existing PHES facility. Hence, the next stage of this research assessed the benefits of constructing large-scale energy storage in Ireland. To do this, a model of the Irish energy system was needed and so a review of 68 existing energy tools was completed. From this review, EnergyPLAN was chosen and subsequently it was used to simulate various capacities of wind power and PHES on the 2020 Irish energy system. The results reveal that PHES could technically enable RE to provide 100% of Ireland's electricity if very large capacities were used under certain operating strategies. However, under conventional economic assumptions this would cost more than the reference 2020 scenario. In addition, alternatives were identified which could offer similar savings as PHES, while also being more robust to changes in fuel prices, interest rates, and annual wind generation, but they did consume more fossil fuels. Finally, a new practical operating strategy was created for energy storage while operating in a wholesale electricity market. Results indicate that approximately 97% of the maximum feasible profits are achievable. However, the annual profit could vary by more than 50% and hence, energy storage will need more profit stability to become feasible for investors.

To summarise, this work concludes that PHES is the most promising energy storage technology for integrating fluctuating RE. More sites do exist than previously expected and constructing them will enable higher penetrations of fluctuating RE. However, based on predicted 2020 costs, using PHES is more expensive than the reference scenario and alternatives could be more cost-effective, but this requires further analysis. Finally, if energy storage is required, electricity markets will need to create more certainty surrounding their potential profits.

Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree or diploma of the University or other institute of higher learning, except where due acknowledgment has been made in the text.

David Connolly 10/DEC/2010

This is to certify that the thesis entitled "The Integration of Fluctuating Renewable Energy Using Energy Storage" submitted by David Connolly to the University of Limerick for the award of the degree of Doctor of Philosophy is a bona fide record of the research work carried out by him under our supervision and guidance. The contents of the thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any other degree or diploma.

Martin Leahy, University of Limerick, Ireland 20/01/11

Henrik Lund, Aalborg University, Denmark 19/JAN/2011

Brian Vad Mathiesen, Aalborg University, Denmark 20/1/2011

Dedication

To Kieran

For your unwavering support

...

Til Danmark

For alt

Preface

My first interaction with energy storage came during a module I completed as part of my undergraduate degree in Mechanical Engineering in the winter semester of 2006 called "Energy Management". I can still remember the day when our lecturer, Tony Kay, explained the concept of energy storage. We discussed Ireland's enormous and freely available wind resource, which could, if harnessed, transform Ireland into a renewable energy goldmine. However, not long after this thought had sparked a few big ideas in my head, I was brought back to reality by the sound of that frightful word: intermittency. Unfortunately, we cannot rely on wind power to meet our energy demands because there are times when it doesn't blow. We subsequently discussed a range of potential energy storage devices that could solve this problem, focusing primarily on Ireland's only existing pumped hydroelectric energy storage facility, Turlough Hill. As a naive student, the concept seemed so simple. When there is too much wind, store it; when there isn't enough, use the stored energy. However, as we proceeded through the details of the problem, the complexity of the challenge became all too apparent. Energy storage is difficult to construct, expensive, and limited. Even so, it was from that day onwards that my fascination with energy storage began, and so I investigated how I might gain a greater understanding of this area.

After completing my undergraduate degree, I began my PhD in October 2007 under the Charles Parsons Initiative at the Department of Physics & Energy, University of Limerick. This thesis documents over three years of investigation into the role of energy storage, focusing specifically on the integration of renewable energy. The thesis structure reflects my learning process throughout the PhD, thus taking the reader along the same path I have also followed. I hope that it informs the debate surrounding energy storage and renewable energy, particularly in Ireland.

This work would never have been possible without the help and inspiration of many people along the way. I wouldn't have the space to thank them all, but there are a few people I would like to mention in particular. Firstly, I would like to thank my father, Kieran, for being a constant source of encouragement throughout my time as a PhD student. Also, thanks to Anna, for all your help and support over the last three years. To Martin Leahy, the staff in CPI/Department of Physics & Energy, and my PhD colleagues for all your help during my time at the University of Limerick. A special thanks to Henrik Lund and Brian Vad Mathiesen for your hospitality, patience, guidance, and inspiration, and also to the staff at Aalborg University, particularly in the Department of Development and Planning, for my wonderful stay during this work. I would also like to thank Shane MacLaughlin from Atlas Computers Ltd, Amanda Barriscale from the Sustainable Energy Authority of Ireland, and Margaret McCarthy from EirGrid. Thanks to the Irish Research Council of Science, Engineering, and Technology (IRCSET) for funding my PhD over the last three years. Last, but not least, thanks to all my friends, especially the lads in number 1 The Birches and those from AAU!

Finally, thank you to anyone I may have omitted and I hope you enjoy reading my thesis.

David

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Nomenclature

Symbol, description, and unit

A_L	Polygon area for lower reservoir, m^2
A_U	Polygon area for upper reservoir, m^2
CEEP	Critical excess electricity production, TWh/year
C_{Pump}	Capacity of the PHES pump, MW
$C_{Storage}$	Capacity of the PHES storage, GWh
$C_{Turbine}$	Capacity of PHES turbine, MW
E_L	Max excavation volume for lower reservoir, m^3
E_U	Max excavation volume for upper reservoir, m^3
FFD	Fossil fuel demand, TWh/year
FR	Grid search interval for lower reservoir, m
PES	Primary energy supply, TWh/year
$P_{Capacity}$	Power capacity of a PHES facility, W
Q	Discharge through the turbines, m^3/s
H	Head of PHES facility, m
I_{Annual}	Annual repayment costs, €M
I_P	Investment cost of PHES pump, €M/MW
I_T	Investment cost of PHES turbine, €M/MW
I_S	Investment cost of PHES storage, €M/GWh
$O\&M_{Fixed}$	Fixed O&M costs, % of total investment
s_{PHES}	Hourly energy stored in the PHES facility, GWh
SR	Radial search interval for upper reservoir, m
SV	Vertical search tolerance for flatness, m
V	Volume of water between PHES reservoirs, m^3
d	Maximum acceptable horizontal separation, m
e_{CEEP}	Hourly critical electricity production, MWh
e_{PP}	Hourly power plant electricity production, MWh
e_{Pump}	Hourly PHES pump electricity consumption, MWh
$e_{Turbine}$	Hourly PHES turbine electricity production, MWh
g	Acceleration due to gravity in m/s^2
i	Interest rate, %
n	Lifetime, years
η_{PHES}	Round-trip efficiency of PHES, %
η_{Pump}	PHES pumping efficiency, %
$\eta_{Generation}$	PHES generating efficiency, %
ρ	Mass density of water, kg/m^3

Energy, economic, and other units

W	Watt
kW	Kilowatt (1000 W)
MW	Megawatt (1000 kW)
GW	Gigawatt (1000 MW)
TW	Terawatt (1000 GW)
kWh	Kilowatt hour
MWh	Megawatt hour (1000 kWh)
GWh	Gigawatt hour (1000 MWh)
TWh	Terawatt hour (1000 GWh)
ktoe	Kilo ton of oil equivalent
Mtoe	Million ton of oil equivalent
GJ	Gigajoule
PJ	Petajoule
kg	Kilogram
Mt	Megaton
Gt	Gigaton
m	Metre
km	Kilometre
s	Second
h	Hour
€(M)	(Million) Euro
$	US Dollar

Abbreviations

ACTES	Air-conditioning thermal energy storage
Bbl	Barrel (of oil)
BES	Battery energy storage
BES	Biomass energy system (chapter 11 only)
BEV	Battery electric vehicle
BP	British Petroleum
CAES	Compressed air energy storage
CCGT	Combined cycle gas turbine
CHP	Combined heat and power
COMBO	Combination energy system
DSM	Demand side management
DTM	Digital terrain model
EES	Electricity energy system
EU	European Union
EV	Electric vehicles
EA	Ex-ante (electricity market prices)
EP	Ex-post (electricity market prices)
FBES	Flow battery energy storage
FES	Flywheel energy storage
GDP	Gross domestic product
GHG	Greenhouse gases
GIS	Geographic information system
HES	Hydrogen energy system
HESS	Hydrogen energy storage system
HP	Heat pump
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land-use, land-use change, and forestry
MFWP	Maximum feasible wind penetration
O&M	Operation and maintenance costs
OECD	Organisation for Economic Co-Operation and Development
OCGT	Open cycle gas turbine
OSI	Ordinance Survey Ireland
PHES	Pumped hydroelectric energy storage
pop.	Population
PP	Power plant
Ref.	Reference (citation)
RE	Renewable energy
REF	Reference energy system
REF2020	Reference energy system for the year 2020
RES	Renewable energy system
RD&D	Research, demonstration and development
SCC	Survey control centre
SCES	Supercapacitor energy storage
SEAI	Sustainable Energy Authority of Ireland
SEM	Single Electricity Market
SEV	Smart electric vehicle
SMES	Superconducting magnetic energy storage
SMP	System marginal price
TES	Thermal energy storage
TESS	Thermal energy storage system
TFC	Total final consumption
TIN	Triangulated irregular network
TSO	Transmission system operator
UPHES	Underground PHES
US(A)	United States (of America)
V2G	Vehicle to grid

Chapter 1

1. Introduction

"So this is a wish, it's a very concrete wish, that we invent this technology. If you gave me only one wish for the next 50 years, I can pick who's president, I can pick a vaccine, which is something I love, or I could pick that this thing that's half the cost with no CO_2 gets invented, this is the wish I would pick, this is the one with the greatest impact."

Bill Gates, Chairman of Microsoft, February 2010 [1].

This research will contribute towards this wish by identifying if and how large-scale energy storage can unlock the potential within fluctuating renewable energy resources. Such a broad and global issue incorporates a very wide range of technologies, resources, issues, and assumptions. As a result, each chapter in this dissertation covers a unique challenge encountered during this research and hence, they contain an independent background, literature review, discussion, and range of conclusions. Therefore, this introduction is a signpost towards the chapters of most relevance to the reader.

In chapter 2, a broad background relating to the major concerns of global energy supply and demand is provided, while also outlining the consequences of burning fossil fuels. During this process, chapter 2 illustrates why fluctuating renewable energy is a resource which must be utilised for a sustainable energy supply and reveals how energy storage can unlock its potential. To some, these issues may be common knowledge and if so, then chapter 3 may be a more suitable starting point where the objectives of this study are discussed in detail, including the motivation behind this research and its primary focus points.

In chapter 4, Ireland[1]'s energy system is discussed in detail to outline why it is a suitable case study for analysing the role of large-scale energy storage when integrating fluctuating renewable energy. To illustrate this, chapter 4 discusses the structure of the Irish energy system, its renewable energy potential, and the targets included within current energy policies. It is evident from this breakdown that wind energy, which is Ireland's most economical fluctuating renewable energy technology, will play a pivotal role in a sustainable energy future for Ireland. Therefore, to complete this chapter, a thorough review of the current wind energy research being carried out in Ireland is provided, to illustrate how this thesis will complement existing work.

[1] Ireland refers to the Republic of Ireland only, unless otherwise specified.

After establishing Ireland as a suitable case study, chapter 5 discusses the type, capacity, cost, and potential of all large-scale energy storage facilities identified during this work. The aim here is to identify what energy storage technology would be most suitable for integrating wind energy in Ireland and based on the evidence presented, it was concluded that pumped hydroelectric energy storage (PHES) is the most attractive large-scale energy storage option for Ireland at present.

Thus, chapter 6 provides a detailed overview of how PHES operates, the mathematical equations governing is capacities, its current role within energy systems around the world, the typical costs to construct it, as well as a detailed review of existing literature relating to PHES and the integration of wind energy. Based on this investigation, the most concerning issues facing the development of PHES are identified and hence, these become the primary focus within the remaining chapters.

In chapter 7 a software tool is developed which can identify suitable locations for the construction of PHES, along with a complimentary spreadsheet tool for estimating the cost and capacity of the sites identified. Subsequently, these tools are applied to a 1 km^2 artificial terrain for testing, an 800 km^2 site for an initial search, and a 3150 km^2 county in Ireland. The results from each of these applications are displayed, analysed, and discussed throughout chapter 7, where it is concluded that Ireland has a significant freshwater PHES resource.

After concluding that numerous PHES sites exist in Ireland, chapter 8 then assesses the technical and economical implications of constructing PHES. To do this, the literature indicated that a detailed model of the Irish energy was required and hence a review of 68 existing energy tools is carried out in chapter 8. The primary purpose of the review is to identify an existing energy tool which can be used to develop an accurate and detailed model of the Irish energy system. After concluding that the energy-systems-analysis tool, EnergyPLAN, is the most suitable for this research, it is subsequently used to create a model of the 2020 Irish energy system. For the technical analysis of PHES, the maximum wind penetration which can be achieved on the 2020 Irish energy system with the introduction of PHES is identified. Initially, a metric is developed to define a maximum feasible wind penetration and then, different PHES operating strategies and capacities are analysed for wind penetrations of 0-100% of electricity demand on the 2020 Irish energy system. Results reveal that PHES can enable wind penetrations of up to 100% on the 2020 Irish energy system, but it requires very large PHES capacities. Hence, an economic assessment was also carried out in chapter 8 to identify if the economic savings from the additional wind power feasible due to PHES, were greater than the initial investment costs required. In addition, the economic savings from PHES are compared to those from alternative technologies in the form of heat pumps and district heating. Here it is concluded that PHES will most likely increase the costs of the Irish energy system, but the additional socio-economic benefits may be worth this additional cost. Also, the results demonstrate the importance of assessing alternatives across any energy system, especially through the integration of the electricity, heat, and transport sectors.

Chapter 9 examines the structure of the existing Irish electricity market and examines how energy storage could make a profit on wholesale electricity markets using electricity price arbitrage. A new practical operating strategy is developed for energy storage and then assessed on 13 different electricity markets. The results illustrate how an energy storage facility could operate to achieve approximately 97% of the profits feasible when taking advantage of electricity price arbitrage, but conclude that the uncertainty in annual profits from one year to the next could be a significant deterrent for investors.

To finish, chapter 10 discusses the key conclusions from this work and chapter 11 outlines the immediate objective of the work to follow this study. Overall, it is evident that this dissertation provides a wide range of various analyses, investigations, methodologies, and conclusions. As a result, this thesis is divided so that each topic is discussed independently, but structured so they can also be read progressively. Therefore, the reader can decide where to introduce, focus, and conclude in this thesis, based on topics which are most relevant to them.

2. Contextual Framework

This chapter explains the background of this research and outlines its context relative to the global energy challenge. After an overview of the problems relating to global energy production, the discussion concentrates on the role of renewable energy as a solution for the future. Subsequently, the function of energy storage in conjunction with renewable energy is illustrated, thus refining the objective of this particular research.

2.1. Global Energy

Overall, the push towards renewable energy in any nation is typically driven by three main concerns: climate change, security of supply, and job creation. Although the significance of these issues changes from one country to the next depending on their natural resources, political stability, and demand for energy, the world as a whole will need to overcome two of these if it will ever achieve a sustainable future: climate change and energy security.

Climate change is caused by a change in the balance between the short-wave solar radiation coming into the earth's atmosphere and the long-wave solar radiation leaving the earth's atmosphere, which is displayed in Figure 2-1. As the proportion of greenhouse gases within the earth's atmosphere increases, the 'absorbed by atmosphere' and 'back radiation' depicted in Figure 2-1 also increases. This subsequently alters the earth's solar radiation balance: there is now more solar radiation entering the earth's atmosphere than there is leaving it, which is called radiative forcing.

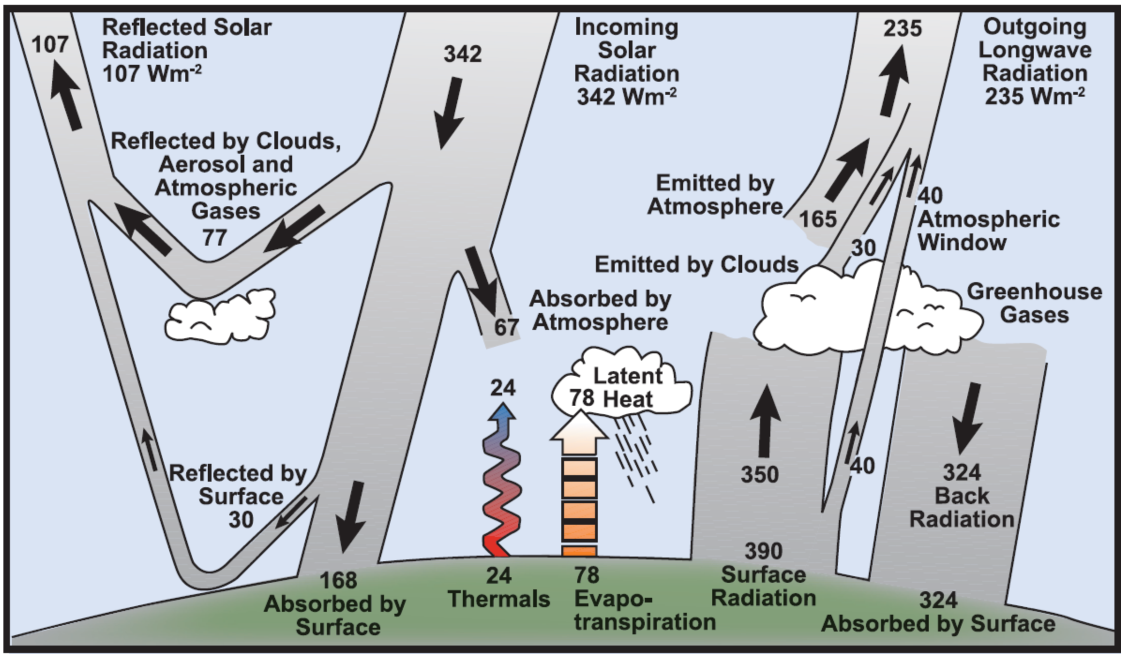
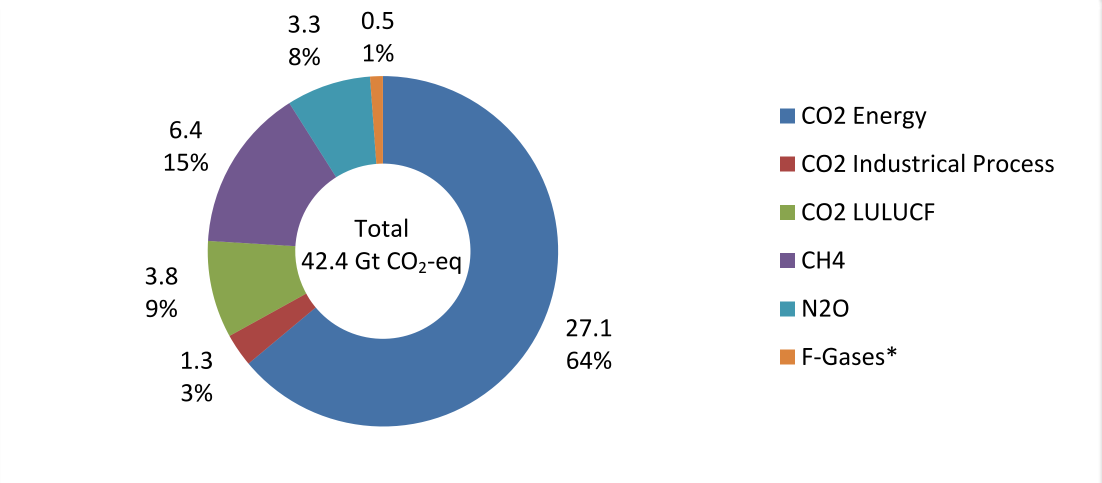


Figure 2-1: Estimate of the earth's annual and global mean solar radiation balance [2].

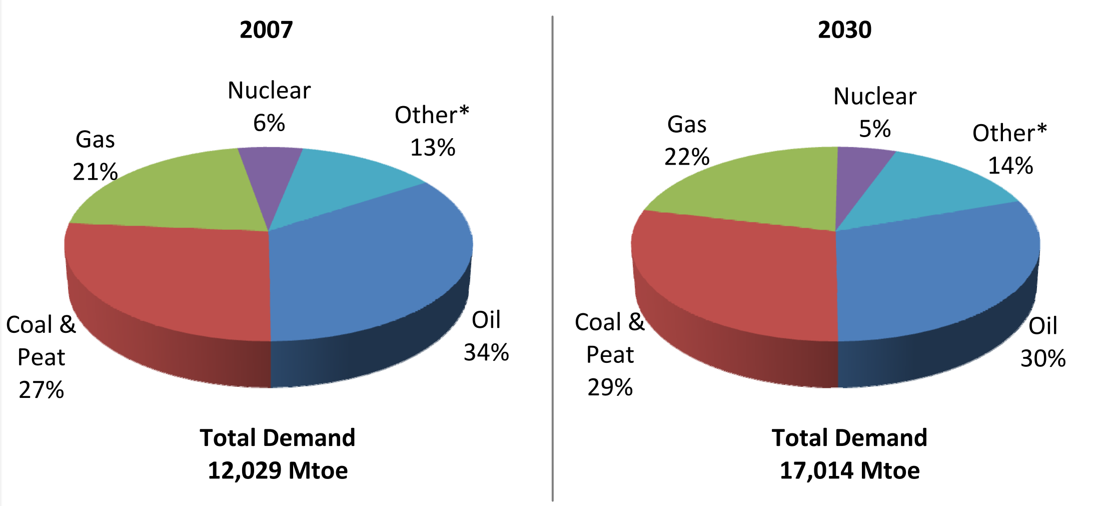
The recorded consequences of radiative forcing over the past two centuries include an increase in global average surface temperatures, an increase in global average sea level, and a decrease in northern hemisphere snow cover [2]. If these trends continue, predictions indicate that it will lead to dramatic changes in the world's climate which will alter water supplies, ecosystems, food supplies, coastlines, and even health. The potential implications are so devastating that the Intergovernmental Panel on Climate Change (IPCC) believes that "unmitigated climate change would, in the long term, be likely to exceed the capacity of natural, managed and human systems to adapt" [3]. However, the severity of these changes will depend on the level of greenhouse gases (GHG) which are emitted into the atmosphere in the future. As illustrated in Figure 2-2, CO_2 from energy production creates 64% of the world's GHG emissions alone and hence the IPCC have concluded that "all assessed stabilisation scenarios concur that 60 to 80% of the reductions over the course of the century would come from energy supply and use and industrial processes" [3]. Consequently, to avoid devastating and irreversible changes to the world's climate over the next century, energy production will need to be decarbonised by replacing fossil fuel production with renewable energy.



*F-gases include hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride from several sectors, mainly industry. Note: Industry CO_2 includes non-energy uses of fossil fuels, gas flaring, and process emissions. Energy methane includes coal mines, gas leakages, and fugitive emissions. N_2O from industry and waste amounts to 0.12 Gt CO_2-eq.

Figure 2-2: World anthropogenic greenhouse-gas emissions quantified by CO_2 equivalent and divided by source for the year 2005 [4].

At present the world's energy supply is dominated by fossil fuels. Figure 2-3 indicates that in 2007, 81.4% of the world's energy was produced from fossil fuels, which included 20.9% from gas, 26.5% from coal, and 34% from oil, with almost all of the remainder coming from renewables and waste (9.8%), nuclear (5.9%), and hydro (2.2%).



*Other includes combustible renewables, hydro, geothermal, waste, wind, solar, etc.

Figure 2-3: World's energy supply by fuel from historical data in 2007 and projected for 2030 [5].

Even more concerning however are the current projections for the future of global energy consumption [4]. Using current trends, the International Energy Agency (IEA) expects the world's energy demand to grow from 12,029 Mtoe in 2007 to 17,014 Mtoe (142%) in 2030, with fossil fuels then accounting for 80.5% of supply.

Mirroring this increase in energy production towards 2030 will be an increase in world CO_2 emissions. As discussed previously, further increases in CO_2 emissions will have detrimental implications for the world and hence, future energy production is clearly not sustainable. Furthermore, this increase in energy production and increase in fossil fuel consumption will lead to another major global issue, which is energy security of supply.

The most recent assessment of fossil fuel reserves carried out by British Petroleum (BP) estimated that there is only 46 years of oil, 63 years of gas, and 119 years of coal (which could be significantly reduced if carbon capture and storage is widely used due to the 10-40% energy penalty [6]) remaining which is economically accessible based on 2009 consumption levels [7]. Although it could be argued that technological developments will increase production in the future, as they have done in the past, any increase will most likely be offset by the aforementioned increase in future demand (Figure 2-3) and the expected reduction in new reserves. This was quantified by Shafiee and Topal [8] who created a model that included the projected consumption and depletion of fossil fuels into the future. The results indicated that reserve depletion times for oil, gas, and coal could be as soon as 35, 37, and 107 years respectively [8]. Therefore, although there is ambiguity surrounding the exact date of fossil fuel depletion, it is evident both within [7] and outside [8] of the petroleum industry, that reserves are depleting within decades not centuries. The amount of fossil fuel remaining is not the only concern however, so is the fossil-fuel depletion trend expected in the coming years. Historical evidence indicates that productions rates from a fossil fuel reserve increase steadily until eventually reaching a peak, after which production rates decline at a similar rate to the initial increase. Therefore, the decline in fossil fuel production will occur many years before the reserve depletion times already discussed. When this decline will begin is very unclear, but once again it illustrates the risk associated with the global dependence on fossil fuels. Consequently, due to the scale of the world's dependence on fossil fuels and the timescale required to create alternative sources of energy, changes must occur now to ensure a sustainable energy supply in the future.

As well as the inevitable decline of fossil fuel production, there are also significant issues regarding the location of reserves. In particular, oil and gas reserves are centralised in a relatively small number of countries. In fact, 90% of global oil reserves are located within 15 countries and 90% of global gas reserves are located within 20 countries [7]. In contrast, global energy demand is not focused within these areas and therefore, if the world does not reduce its dependence on oil and gas in the future then the distribution of these limited resources could become a very politically sensitive issue. Furthermore, as the historical energy prices displayed in Figure 2-4 indicate, a shortage in energy supply leads to a dramatic increase in energy costs. For example, in 1973 the United States aided the Israeli military in the Yom Kippur war with Syria and Egypt, who were supported by a coalition of oil-producing Arab states. In response, the Arab coalition reduced their oil production and hence created a global shortage. Again in 1979, the Iranian revolution occurred and reduced Iranian oil production, which created another global oil shortage. As displayed in Figure 2-4, in both 1973 and 1979 there was a dramatic increase in global fossil fuel prices when these global oil shortages occurred. Considering the historical political instability in some countries with significant fossil fuel reserves such as Iran, Iraq, Kuwait, Venezuela, Russia, Nigeria, Libya, Angola, Algeria, and Kazakhstan who between them contain over 50% of global oil and gas reserves, it is possible that a dramatic increase in fossil fuel value could also lead to conflict and disruptions in supply.

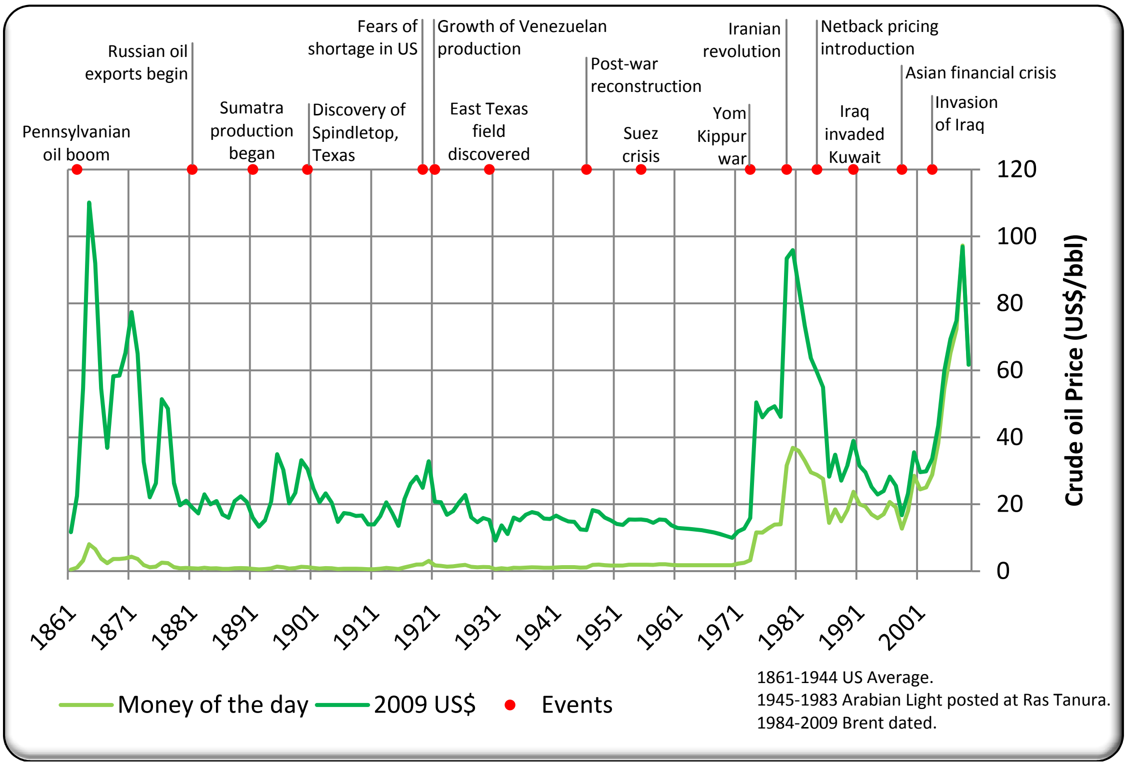


Figure 2-4: Historical price of crude oil corresponding to major global events [7].

In summary, climate change is already being witnessed around the globe through increasing surface temperatures, rising sea levels, and decreasing snow cover. However, these changes are expected to intensify as more GHG emissions are emitted into the atmosphere. It is evident that 64% of total GHG emissions are related to CO_2 from energy production alone, primarily through the burning of fossil fuels and hence the energy sector needs to be decarbonised. However, based on current and projected trends in global energy production, it is clear that the world's dependence on fossil fuels is set to increase and correspondingly GHG emissions will also increase. In addition, due to the scale of the world's fossil fuel dependence it is currently predicted that oil and gas resources will have depleted within the next century. Therefore, from an environmental, sustainability, and even security perspective, it is essential that the world eradicates its addiction to fossil fuels and moves towards a renewable based energy supply.

2.2. Renewable Energy

Renewable resources can produce energy without catastrophic climate issues and in a sustainable manner. However, it exists in many forms, with each type offering some unique advantages and drawbacks. To fully portray these issues, it is important to understand how the modern energy system was established.

Renewable energy was the most widely used energy resource in the 19th century. However, as the steam engine developed, the fossil fuel age began to mature. Coal was an energy dense and abundant fuel which enabled the development of steam engines, while steam engines were a cheap and powerful method of transportation, which brought coal to many people. Together, coal and the steam engine created the world's first source of cheap, abundant, and easily transportable fuel, which powered the industrial revolution. This new power enabled the development of new technologies such as electricity and automobiles, which caused the world's human population to sextuple in less than 200 years[2].

As more technologies evolved, energy production became more and more dependent on fossil fuels. Power plants were centralised and located near fossil fuel supply chains, automobiles were designed to burn oil, while heating systems were developed and optimised for coal, oil, and gas. Under this model, energy resources needed to be controllable, abundant, and cheap, which meant only two renewable technologies could compete with fossil fuel production during the early 20th century: biomass and hydroelectricity. Therefore, by 1974 approximately 86% of world's energy was supplied by fossil fuels, as nations immersed themselves in cheap and abundant power [9]. However, as outlined in Figure 2-4, during the 1970's the first backlash of this dependence was realised when fossil fuel prices rose dramatically. Consequently, the quest for new forms of energy began and this reinvigorated the renewable energy sector, which is evident in Figure 2-5 from the sharp increase in renewable energy RD&D budgets at the time.

[2] The world population in 1800 was approximately 900 million people and in 2000, it was 6.08 billion.

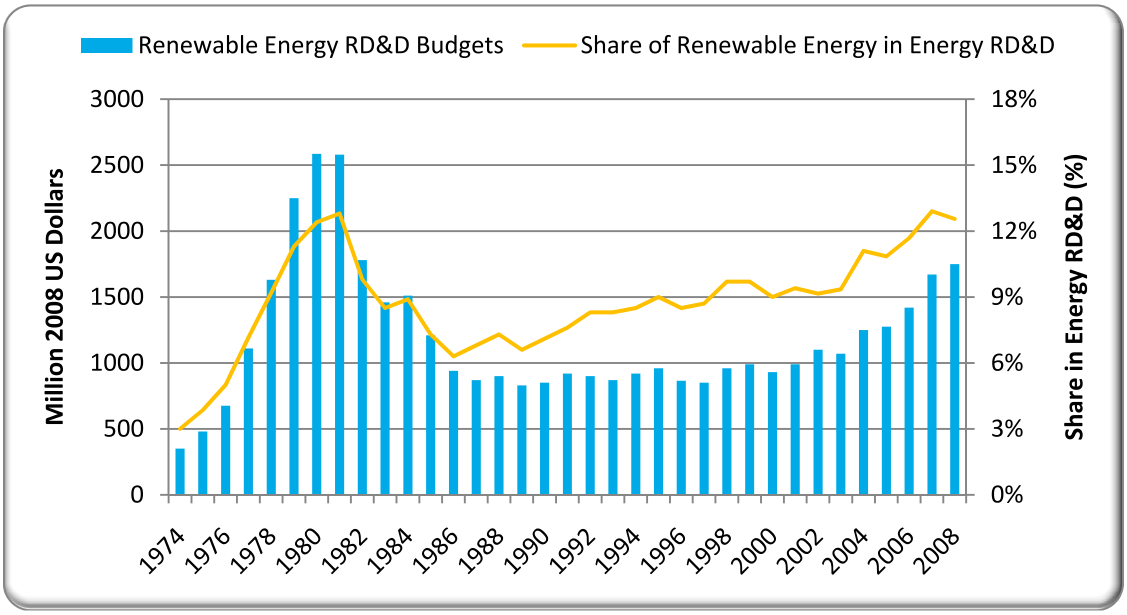


Figure 2-5: Renewable energy RD&D budgets within the IEA from 1974 to 2008 [9].

In total, there are five sources of renewable energy: biomass, wind, water, solar, and geothermal. As mentioned earlier, only biomass and water, in the form of hydroelectricity, were competitive with fossil fuels during the early 20th century. However, after 30 years of significant RD&D, a number of renewable technologies have now become economically competitive with conventional fossil fuels, which is evident from Figure 2-6. As a result, renewable energy has started to play an increasing role in energy production (Figure 2-3). Furthermore, with continued RD&D, the projections in Figure 2-6 indicate that the cost of renewable energy is expected to fall even further, while conventional fossil fuel generation is expected to rise. Consequently, from a costs perspective, renewable energy has and will continue to be a realistic alternative for large-scale energy production. However, there is one key difference between conventional fossil fuels and a number of evolving renewable energy technologies: control.

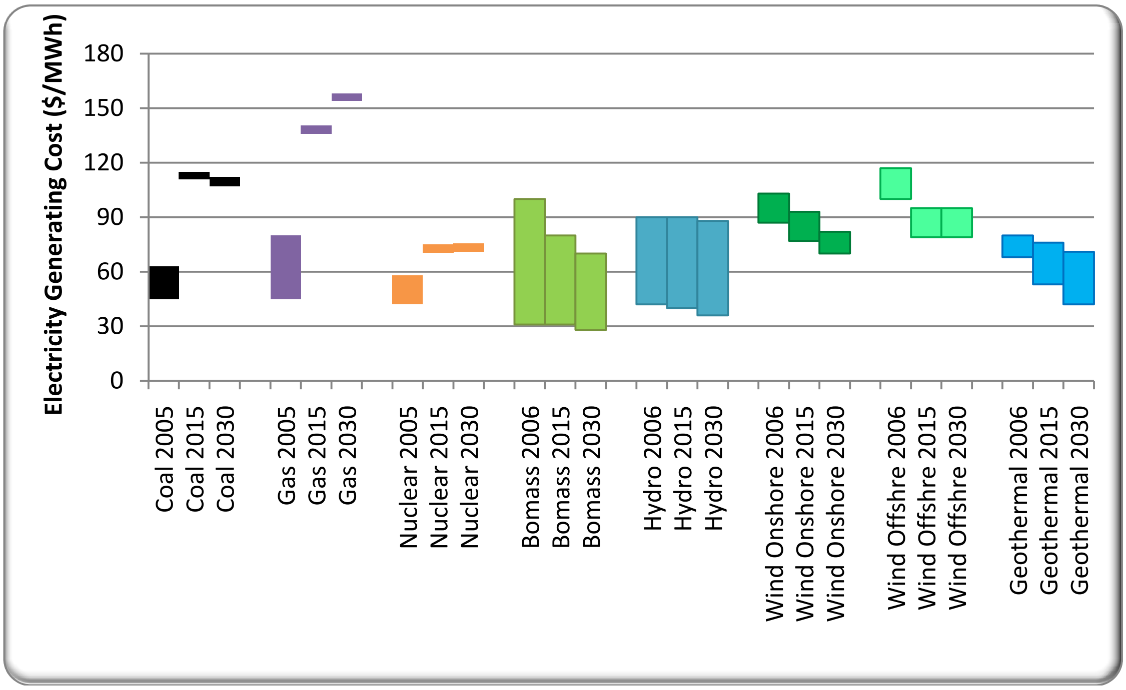


Figure 2-6: Current cost of renewable and fossil fuel based electricity generation along with projected costs for 2015 and 2030 [10-12].

These new renewable energy devices harness resources such as wind, wave, tidal, and solar, with the most suitable device usually dependent on the natural resources within the region being considered. Naturally, these resources cannot be controlled to suit the demands of humans and hence the electricity generated from these renewable devices can vary significantly, which is portrayed in Figure 2-7. Therefore, renewable energy is providing a new form of intermittent power onto a system which has been designed to operate using dispatchable and predictable fossil fuel technologies. To accommodate this, greater flexibility will be necessary within future energy systems as intermittent renewable energy becomes more prominent, especially due to the problems that occur within the electricity sector [13-20]. These issues include grid capacity constraints such as voltage regulation and network congestion, as well as the creation of harmonics, the modification of network impedances, grid stability problems, and a lack of ancillary services. Considering these, Weisser and Garcia indicated that there should be no technical issues for instantaneous penetrations of fluctuating renewable energy, in the form of wind, of up to 20% on an electric grid [15]. In the future though, Lundsager *et al.* estimates that the maximum annual wind penetration feasible is 25-50% within the electricity sector [19]. However, Lundsager *et al.* also stated that based on the annual wind penetrations achieved on existing systems, it is evident that the feasibility of very high annual wind penetrations decreases dramatically when the size of the electricity grid increases from 100 kW to 10 MW: to date, 100 kW grid systems have achieved annual wind penetrations of 80%, but electric grids which are greater than 10 MW have only reached 20% [19]. The authors concluded that primary reason for this dramatic reduction in the annual wind penetration feasible on existing systems was due to the lack of energy storage on the grid [19].

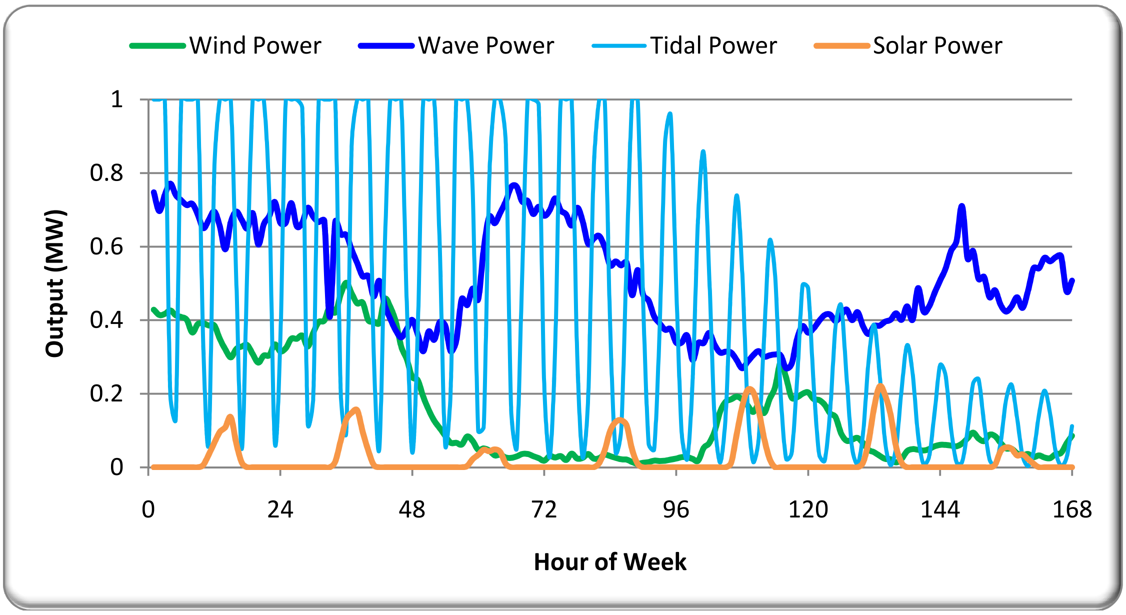


Figure 2-7: Predicted hourly output from a 1 MW wind, wave, tidal, and solar electricity generator in Ireland during week 1 of January 2007.

2.3. Role of Energy Storage

In essence, energy storage is a source of additional flexibility within an energy system. Naturally, the benefits of such flexibility will vary depending on the flexibility that already exists within that energy system and hence, energy storage is not ideal everywhere. However, for many existing energy systems the lack of sufficient flexibility is a key limiting factor for the integration of renewable energy. To illustrate the benefits of energy storage in this case, a hypothetical scenario has been created here based on real world wind data from the Irish energy system. Electricity demand and wind production data from the 17^{th} of April 2008 in Ireland has been graphed in Figure 2-8. On this day, there was approximately 900 MW of wind power installed in Ireland [21], which produced a relatively low electrical output compared to the demand, as displayed in Figure 2-8. Therefore, in line with the findings from Weisser and Garcia [15] mentioned previously, it was possible to integrate 900 MW of wind power in Ireland. However, if this was scaled up to represent an installed wind capacity of 5400 MW, which is expected to be installed in Ireland by 2020 [22], then the wind energy generated would have exceeded the electricity demand from approximately 00:00 to 06:00 in the morning. Later in the day, demand would then have exceeded the wind energy generated and thus created a shortfall between supply and demand. If however, sufficient energy storage was available on the Irish electricity network, then the excess wind energy that was created between 00:00 and 06:00 could have been stored and subsequently discharged onto the grid later in the day when demand exceeded supply. Clearly, there are many other issues that need to be considered under this scenario, but this demonstrates the theory behind energy storage and the integration of fluctuating renewable energy. This principal can be extended over a longer period of time such as days, weeks, and in some rare cases months. Hence, the intermittent and unpredictable nature of wind can be managed by the flexibility of energy storage. This technique could also be used for any other form of fluctuating renewable energy such as wave, tidal, and solar. Therefore, energy storage could enable the large-scale integration of an intermittent resource onto an electrical system designed for predictable and dispatchable fossil fuel based generators. Such a breakthrough would connect many inflexible countries to an ample amount of renewable and sustainable energy while also combating climate change and improving global energy security. Consequently, the primary role of this research is to identify the role of energy storage for integrating fluctuating renewable energy.

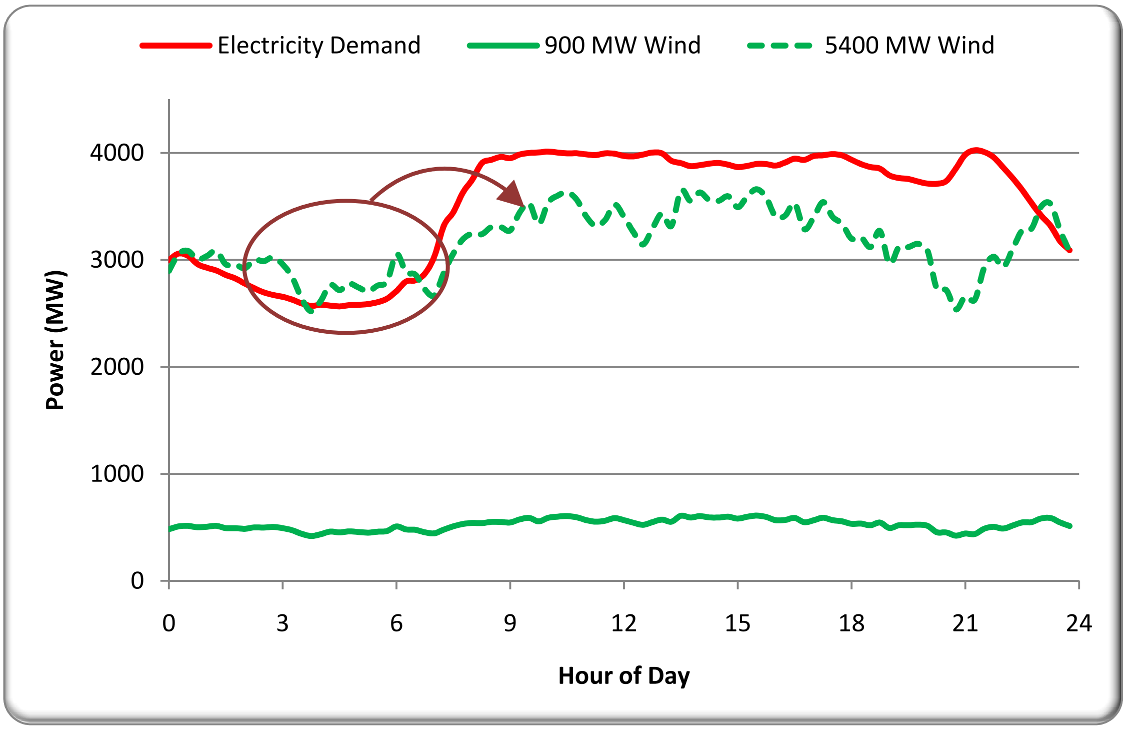


Figure 2-8: Electricity demand, actual wind energy produced (900 MW), and hypothetical scaled (5400 MW) wind energy output in Ireland on the 17th of April 2008 [23].

3. Objective

Energy storage is a very unique type of plant on an energy system. Like generators energy storage can produce power for the electric grid and like consumers it can also consume power. Uniquely though, energy storage has a limit on the total amount of energy which it can generate over any period of time, and this limit is defined by the amount of energy it could consume at an earlier point in time. This specific constraint distinguishes energy storage from other plants and thus has created the uncertainty surrounding the role of energy storage, specifically when integrating fluctuating renewable energy.

Firstly, there is a lot of uncertainty surrounding the range of different energy storage technologies that currently exist. Energy storage is defined by a range of key parameters including its power capacity, storage capacity, efficiency, response time, lifespan, and costs. As each energy storage technology has its own unique value for each of these, not all technologies are suitable for the same application. Consequently, the first primary objective in this study is to identify from the literature, which energy storage technology is the most suitable for the integration of fluctuating renewable energy. Therefore, chapter 5 summarises a review of existing energy storage technologies, which is documented in detail in Appendix A. Based on the findings in this review, PHES was identified as the most suitable energy storage technology for the integration of fluctuating renewable energy and hence it is described in detail in chapter 6. However, it is also evident from the literature review in chapter 6 that PHES is generally not considered a viable alternative due to the lack of suitable sites. Hence, a software tool was then developed in this study that can locate suitable sites for the construction of PHES, which is discussed in chapter 7, Appendix B, and Appendix C.

Secondly, the actual implications of constructing energy storage are also unclear at present. Implications in this study are defined under two specific categories: technical and economical. Technically, it is unclear how much additional fluctuating renewable energy would be feasible on an electric grid with the introduction of energy storage, while economically it is unclear if this is affordable and if it is the optimum alternative. Many studies have been carried out which investigate stand alone wind-storage systems and the benefits of storage for island[3] electricity grids, which are discussed later in section 6.2.1. However, it is unclear how these

[3] Island electricity systems refer to small-scale stand-alone energy systems where the installed generating capacity is usually between 1 and 100 MW.

results translate to a national[4] energy system assessment, especially when considering the electricity, heat, and transport sectors. Therefore, the third key objective in this work is to assess how much additional wind could be integrated onto a national energy system with more energy storage, how much would this cost, and if there are cheaper alternatives? This is discussed in chapter 8 and Appendices D, E, F, and G.

Finally, another uncertainty relating to energy storage is the policy surrounding its dispatch on existing electricity markets. Even if it is proven that energy storage is a key technology for future energy systems, under the policies in some existing electricity markets energy storage would not be able to maximise its profits. This is due to the debate on the purpose of energy storage. Many participants believe that energy storage is an additional grid asset, which enables the Transmission System Operator (TSO) to adequately maintain the electric grid. As such, the TSO should be responsible for its construction and operation. Conversely, other participants believe that energy storage should be treated as just another generator, which profits from the fluctuating prices on the electricity and regulation markets. Therefore, it should be constructed as a merchant unit by private investors who bid on these markets along with the other generators. To create some degree of clarity around this debate, the final key objective in this research was to assess if it there are any policies that could be implemented on an electricity market, which would enable energy storage to make sufficient profit to attract private investment. The results from this assessment are outlined and discussed in chapter 9 and Appendix H.

To recap, the three key objectives in this research are to identify a suitable energy storage technology for the integration of fluctuating renewable energy, to identify how much additional fluctuating renewable energy can be integrated with energy storage on a national energy system, and to investigate if it is possible to profit from an energy storage unit on electricity markets.

[4] National energy systems refer to large-scale interconnected energy systems where the installed generating capacity is usually above 1 GW.

4. Ireland as a Case Study

For this study, Ireland was used as a case study to analyse the integration of fluctuating renewable energy using energy storage. Discussed here is an overview of the current Irish energy system, Ireland's renewable energy consumption and potential, Ireland's energy targets, and a literature review of the work published in relation to wind energy and the Irish energy system. It is clear from this overview that Ireland's ambitious targets for wind energy in 2020, along with the lack of flexibility within its existing energy system, could make energy storage an attractive technology in the near future. Hence, Ireland is an appropriate case study for the analyses proposed in this research. In addition, as the Irish energy system is structured in similar way to many others worldwide [24], the results can be interpreted for other national energy systems also.

4.1. Ireland's Energy System

The island of Ireland is located in the North-West of Europe and is divided into two countries: Northern Ireland and Ireland[5]. Ireland has a population of approximately 4.4 million people and an area of approximately 70,000 km^2. Economic growth in Ireland throughout the 1990s and early 2000s was very strong, with Gross Domestic Product (GDP) in 2007 reaching almost three times that of 1990. As a result, there was a corresponding increase of 74% in total primary energy supply (PES) and a 53% growth in energy-related CO_2 emissions over the same period, as outlined in Figure 4-1 and Figure 4-2 respectively.

[5] Ireland refers to the Republic of Ireland only, unless otherwise specified.

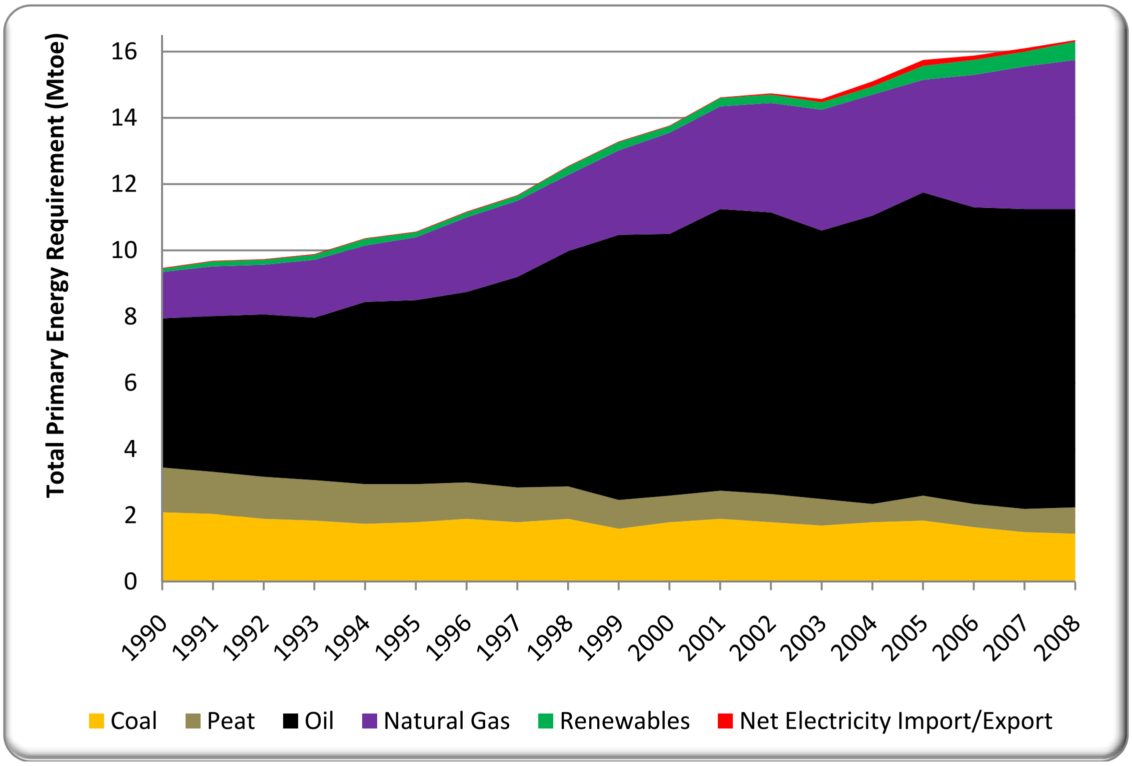


Figure 4-1: Ireland's total primary energy requirement by fuel from 1990 to 2008 [25].

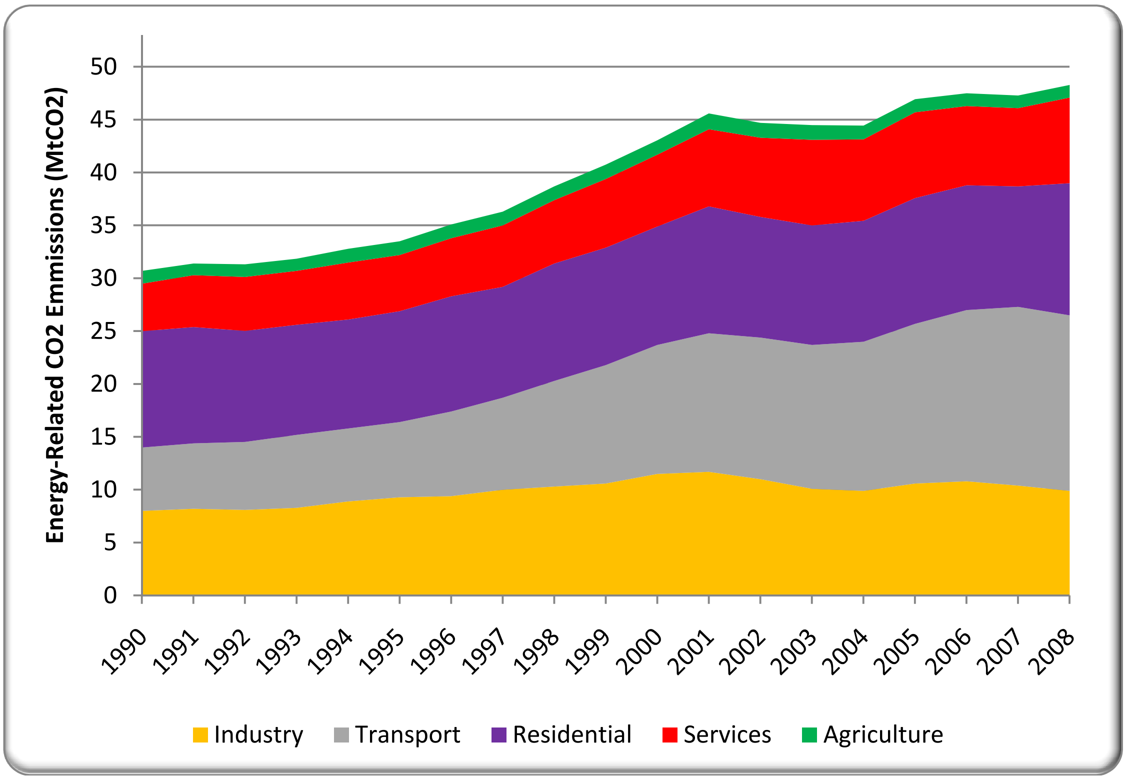


Figure 4-2: Ireland's energy-related CO_2 emissions by sector from 1990 to 2008 [25].

By 2008, transport accounted for approximately 34.5% of total energy consumed in Ireland, followed by heat at 34% and then electricity at 31.5%, as outlined in Figure 4-3. Although both the electricity and heat demands grew by approximately 67% and 30% respectively from 1990 to 2008, transport has now surpassed them both. Over this period, there was a 177% increase in the energy required for transport, which corresponded to a 103% increase in the demand for oil as displayed in Figure 4-1. As Ireland has no indigenous oil resources, Figure 4-4 reveals that Ireland's growing transport demand has dramatically increased its dependence on imported fuels. In addition, due to a declining production of Ireland's indigenous gas resources over the same period, Ireland's overall import dependency has now reached approximately 90% and as displayed in Figure 4-5, Ireland is thus spending over €6 billion each year on imported fuels (compared to an annual revenue of €3.85 billion in 2008 from all overseas visitors [26]). Therefore, Ireland is now very exposed to both the price of energy on global markets as well as the risk of failing to meet its domestic energy demand.

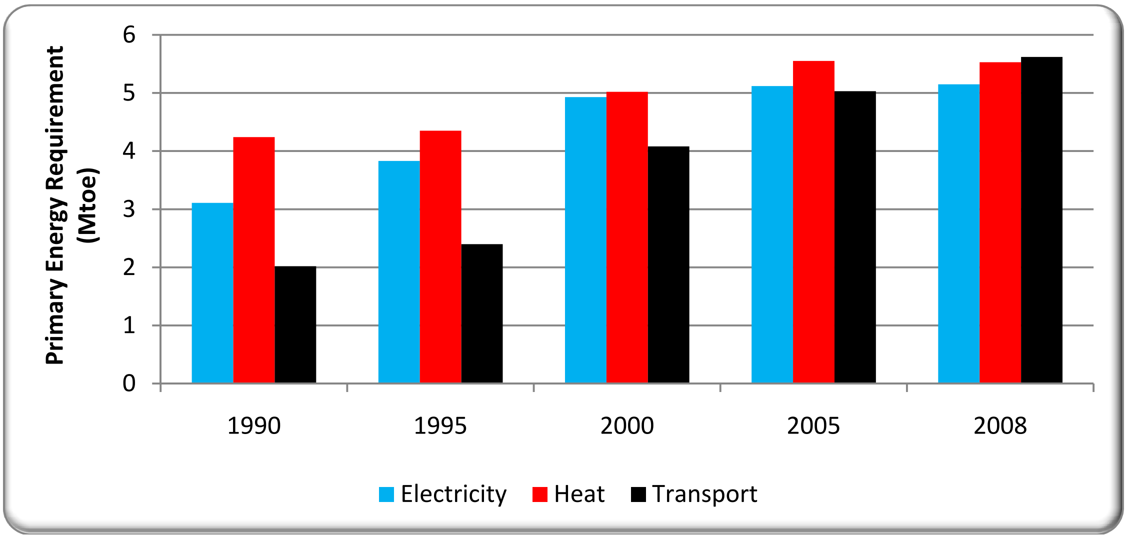


Figure 4-3: Ireland's growth in electricity, heat, and transport from 1990 to 2008 [25].

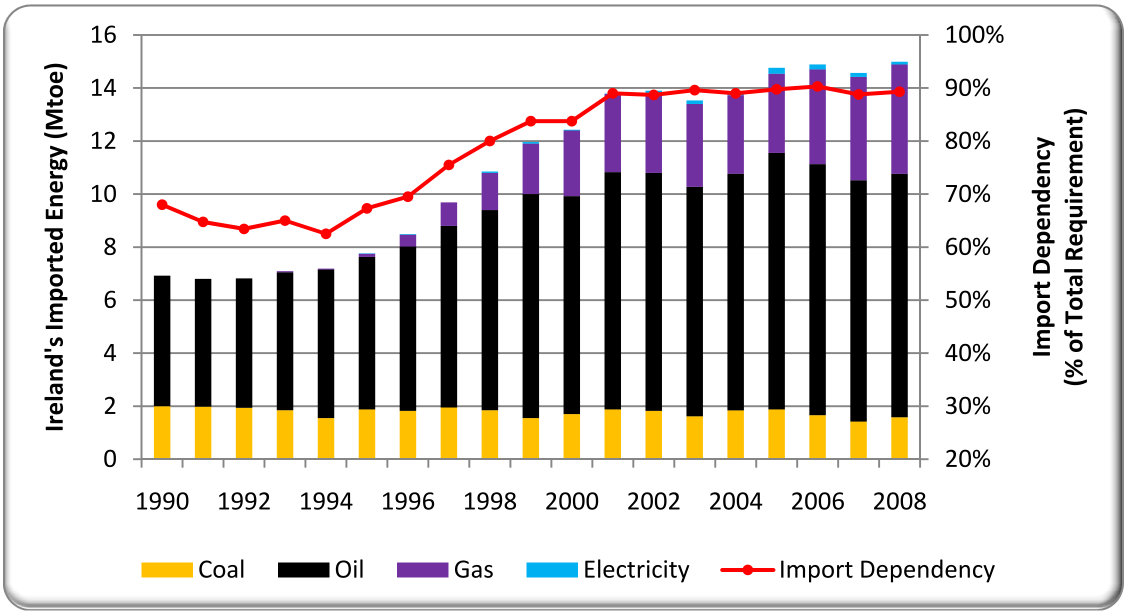


Figure 4-4: Ireland's imported energy by fuel and dependency from 1990 to 2006 [25, 27, 28].

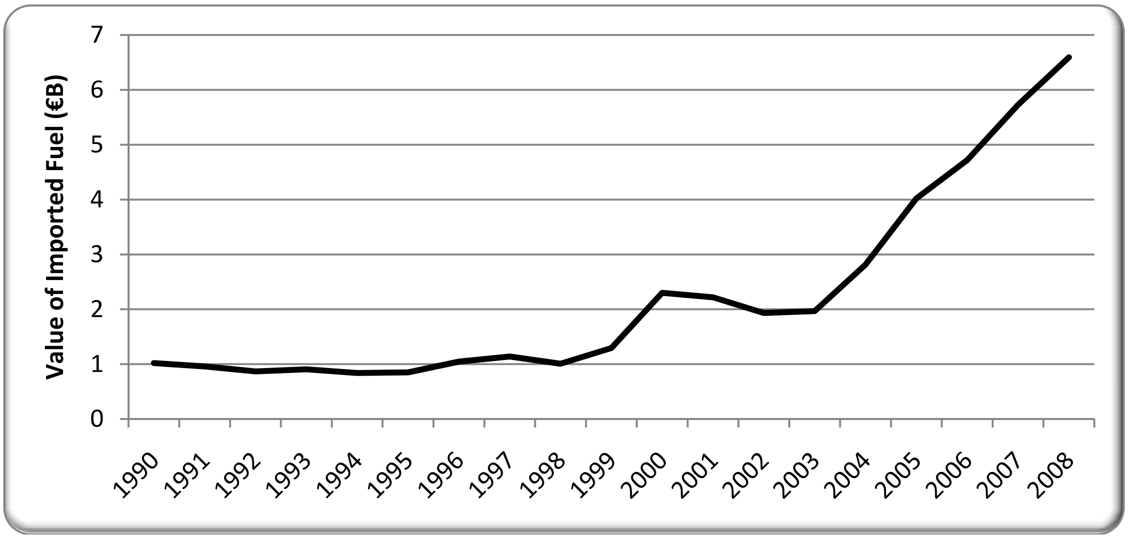


Figure 4-5: Value of imported fuel to Ireland from 1990 to 2008 [29].

On a global context Ireland's energy demands are relatively small, accounting for only 0.12% of total energy demand. In 2008 for example, Germany had a total energy demand of approximately 335 Mtoe/year in comparison to Ireland's demand of 16 Mtoe/year. This relatively small consumption is primarily due to Ireland's population, which is only 0.07% of the world's population. Hence, it is more appropriate to evaluate Ireland's energy position on a per capita basis. Figure 4-6 compares Ireland's total PES and CO_2 emissions to those for the World, individual countries, and the OECD region, while Figure 4-7 outlines Ireland's rank when compared to 137 other countries worldwide under various indices for PES, CO_2 emissions, energy production, and energy imports.

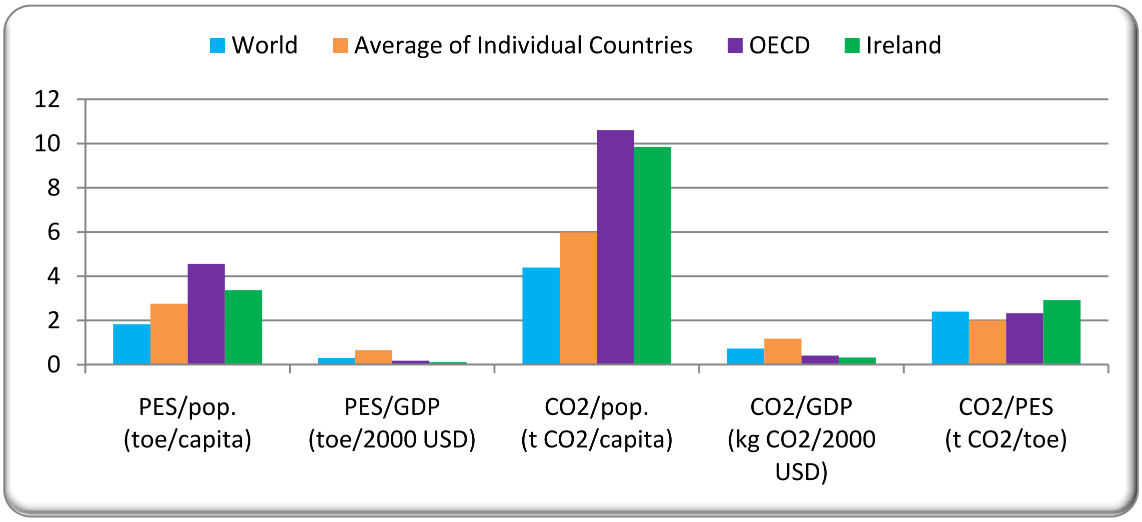


Figure 4-6: Energy indexes for the world, individual countries, the OECD region, and Ireland in 2008 [30].

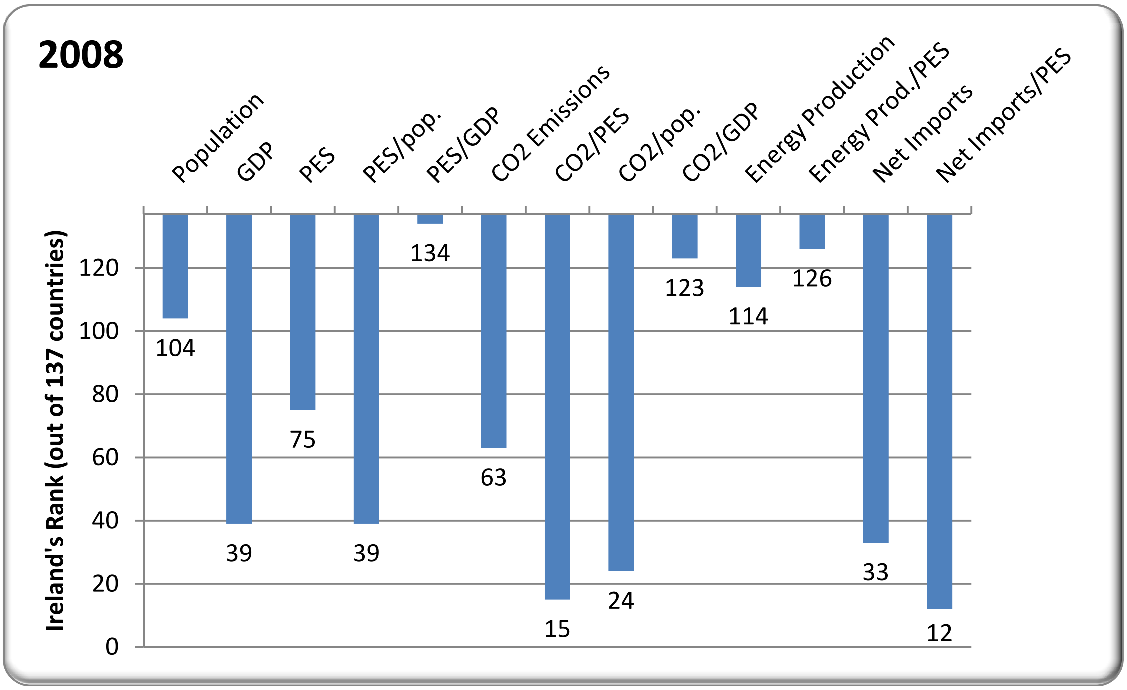


Figure 4-7: Ireland's rank out of 137 countries under various energy indexes in 2008 [30].

Figure 4-6 indicates that Ireland's PES/population is above average when compared to other countries, but it is less than the average consumption within the OECD region which suggests Ireland's consumption is low for a developed country. When assessed on a per GDP basis, Ireland's PES and CO_2 emissions are below those for the World, individual countries, and the OECD region. However, Figure 4-7 reveals that this is most likely due to Ireland's relatively high GDP in 2008, which was the 39th highest in the world. When Ireland's CO_2 emissions are assessed relative to its population, the results in Figure 4-6 indicate that they are approximately double those recorded for the World and the average of individual countries. Although Ireland's per capita CO_2 emissions are still lower than the OECD average, Figure 4-7 reveals that they are the 24th highest in the world. More significantly, Ireland's CO_2 emissions relative to its PES are above global, country, and OECD averages, at 2.92 t CO_2/toe (Figure 4-6), making Ireland the 15th largest emitter of CO_2/toe in the world (Figure 4-7).

Finally, the indices for energy security of supply in Figure 4-7 also display the vulnerability of the Irish energy system to global energy supply. When assessed relative to PES, Ireland is the 126th least self-sufficient country in the world and consequently, its net imports relative to its PES are the 12th highest in the world. This is specifically due to Ireland's extreme dependence on imported oil, as outlined earlier in Figure 4-4. Not only does this create risk, but the significant implications on Ireland's balance of payments have also been demonstrated in Figure 4-5 by Ireland's €6 billion/year expenditure on imported fuel each year [31]. By investing this money in domestic energy production, Ireland could improve its balance of payments, reduce risk, and increase its employment rates.

To conclude, in comparison to other developed countries, Ireland is a relatively low consumer of fuel and low emitter of CO_2. However, Ireland's CO_2 emissions relative to the energy it consumes are amongst the highest in the world and almost all of Ireland's energy is imported. Therefore, renewable energy could reduce Ireland's CO_2 emissions, while also improving its energy self-sufficiency.

4.2. Ireland's Renewable Energy Consumption and Potential

In 1990, Figure 4-8 indicates that Ireland supplied 2.3% of its total final consumption (TPC) using renewable energy, which was generated using biomass and hydro resources. During most of the 1990s, the renewable energy contribution in Ireland remained practically the same, until wind energy began to expand. From 1998 to 2008, wind energy increased its contribution to Ireland's TPC from approximately 0.3% to 2%, which correspondingly increased Ireland's total renewable energy contribution to 4.5% in 2008 (Figure 4-8).

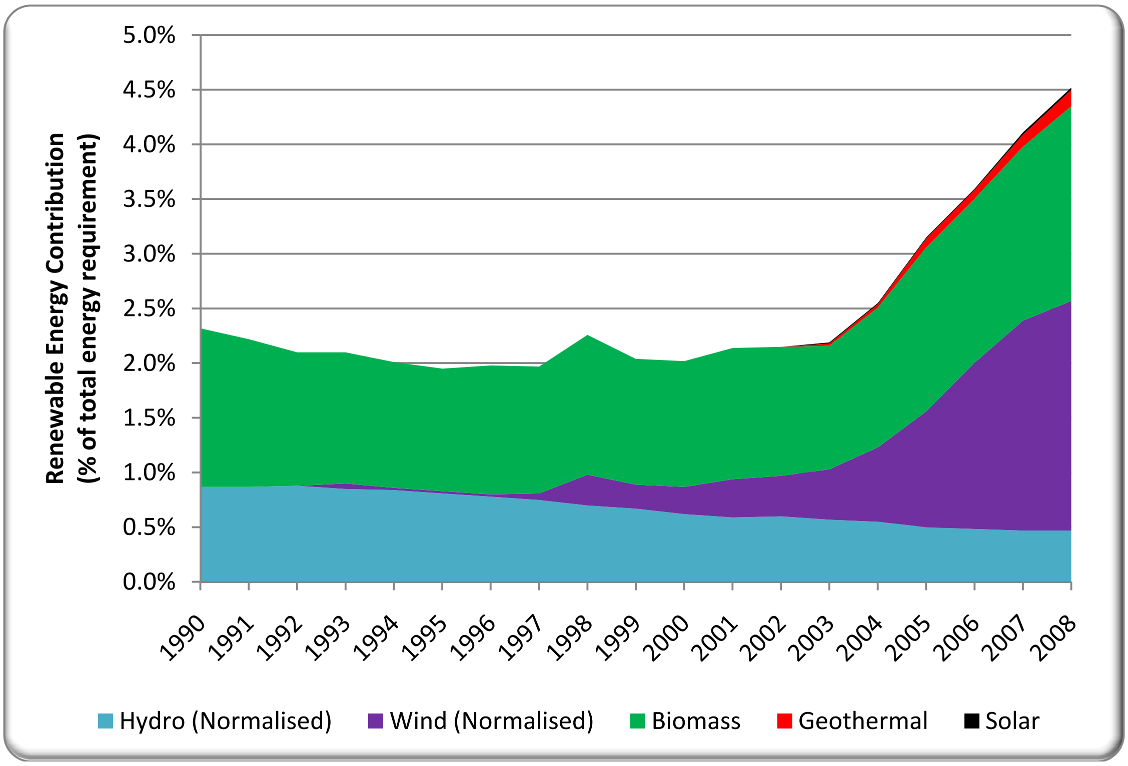
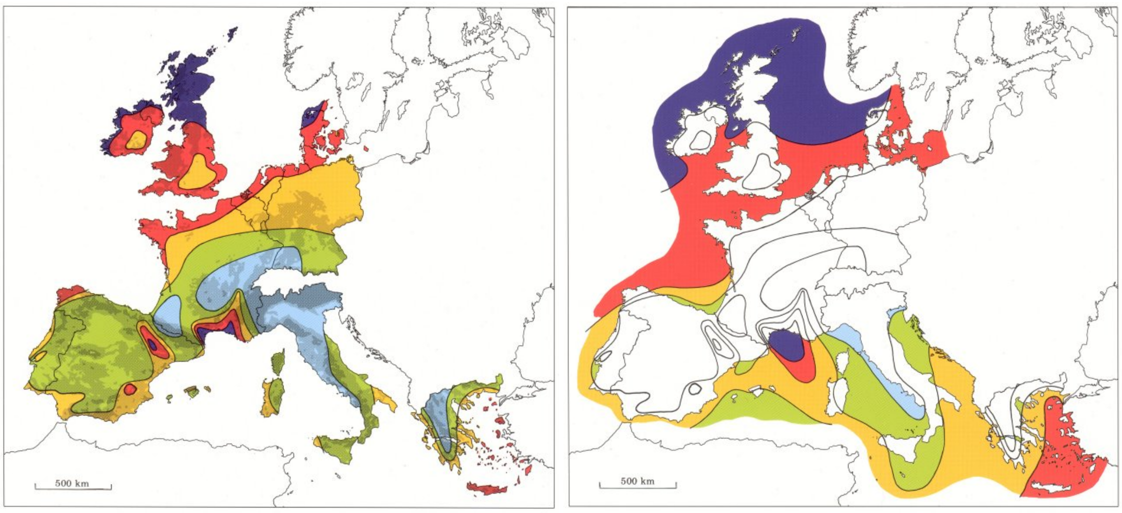


Figure 4-8: Renewable energy utilised in Ireland as a percentage of a total final consumption and divided by source [25]. Note that hydro is normalised to reflect the average hydro generation of the last 15 years and wind is normalised over the latest five years as per Directive 2009/28/EC.

Compared to other IEA member states, Ireland's utilisation of renewable energy is relatively poor. In fact, Ireland had the 5th lowest penetration of renewable energy in its energy system when compared to the 27 other IEA member states in 2008 [9]. From this comparison, it is evident that each country has introduced renewable energy into its energy mix in a different way. For example, Norway has predominately relied upon hydro power, Denmark has built a lot of wind energy, and Spain has focused on solar power. These sources have been utilised based on the resource available within each of these countries. Hence, to understand how Ireland can increase its renewable energy penetration, its renewable resources must be assessed.

To date, hydro power is currently the most utilised renewable energy within IEA member states [9]. There is 238 MW of hydro capacity currently installed in Ireland, which is approximately 3% of total generation capacity. However, this represents approximately 75% of total power available from Ireland's river resources [32] and hence, hydro power will always be a relatively small source of power in Ireland.

As outlined in Figure 4-8, wind energy has been growing substantially in Ireland since the late 1990s. Not only is this due to global developments in wind turbine technology, but also due to the excellent wind resource available in Ireland, which is illustrated in Figure 4-9. In total, the energy available from this wind resource is estimated based on technological constraints as 613 TWh/year [33] of which, approximately 55.5 TWh/year will be economically viable in 2020 [34, 35]. Since this is approximately 170% of the electricity demand forecasted for Ireland in 2020 [36], it is clear that wind power is a key resource if Ireland is going to increase its renewable energy penetration.



Wind resources[1] at 50 metres above ground level for five different topographic conditions										
	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Wind resources over open sea (more than 10 km offshore) for five standard heights										
	10 m		25 m		50 m		100 m		200 m	
	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}
	> 8.0	> 600	> 8.5	> 700	> 9.0	> 800	> 10.0	> 1100	> 11.0	> 1500
	7.0-8.0	350-600	7.5-8.5	450-700	8.0-9.0	600-800	8.5-10.0	650-1100	9.5-11.0	900-1500
	6.0-7.0	250-300	6.5-7.5	300-450	7.0-8.0	400-600	7.5- 8.5	450- 650	8.0- 9.5	600- 900
	4.5-6.0	100-250	5.0-6.5	150-300	5.5-7.0	200-400	6.0- 7.5	250- 450	6.5- 8.0	300- 600
	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 6.0	< 250	< 6.5	< 300

Figure 4-9: Onshore and offshore wind speeds in Europe [37, 38].

As Ireland has such as strong offshore wind resource, its wave energy resource is also relatively high. Not only has Europe one of the best wave energy resources in the world, but Ireland has one of the best wave energy resources in Europe, as displayed in Figure 4-10. Based on this resource and the capabilities of a Pelamis wave energy device [39], previous research estimated Ireland's theoretically available wave energy to be up to 28 TWh/year [40]. Even when this resource was refined to establish the 'accessible' wave resource in Ireland, it was predicted that wave energy could provide up to 20.76 TWh/year in Ireland [40], which is approximately 65% of the electricity demand forecasted for Ireland in 2020 [36]. Unlike wind, there is still uncertainty surrounding the capabilities of wave energy generators and therefore, although wave energy has the potential to be a significant renewable resource for Ireland, wind energy is a more attractive alternative in the immediate future.

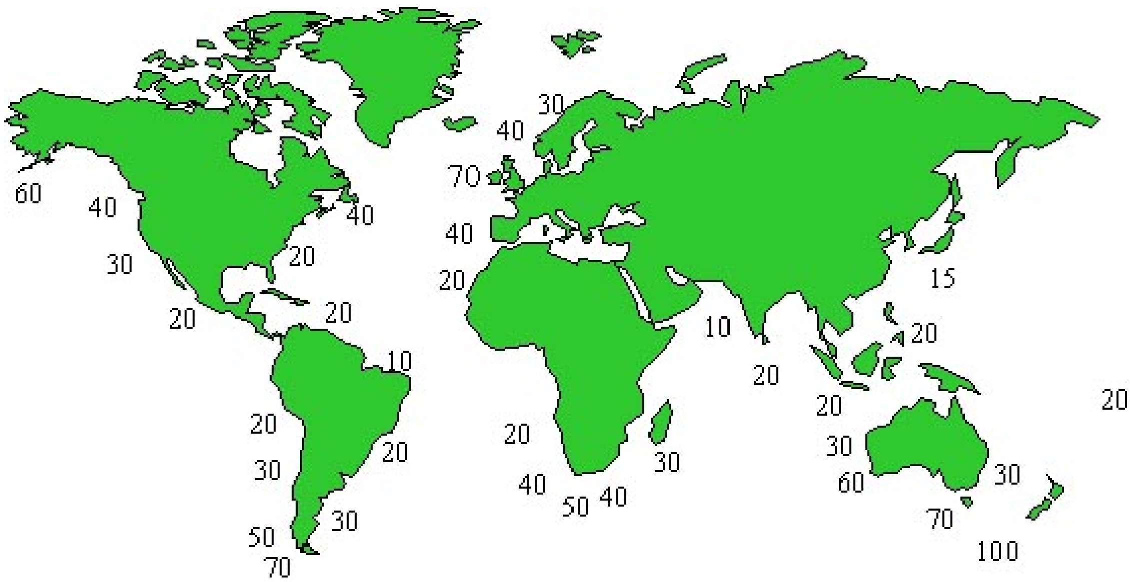


Figure 4-10: Global average theoretical wave power potential (kW/m) [41].

In relation to tidal power, Ireland is home to one of the most advanced developers of tidal energy in the world, OpenHydro [42]. Hence, even if tidal energy is not economically competitive with other generators at present, Ireland could benefit by being one of the first to utilise this resource. Theoretically, there is an estimated tidal resource of around 230 TWh/year available around the island of Ireland. However, due to the limitations of existing technology, restricted access to certain locations, and the condition of the sea bed, only 2.63 TWh/year of this is accessible [43], which is outlined in Figure 4-11. Due to its predictability and location near populated areas around Ireland, tidal energy is a unique renewable resource in Ireland which could provide almost 10% of Ireland's 2020 electricity demand.

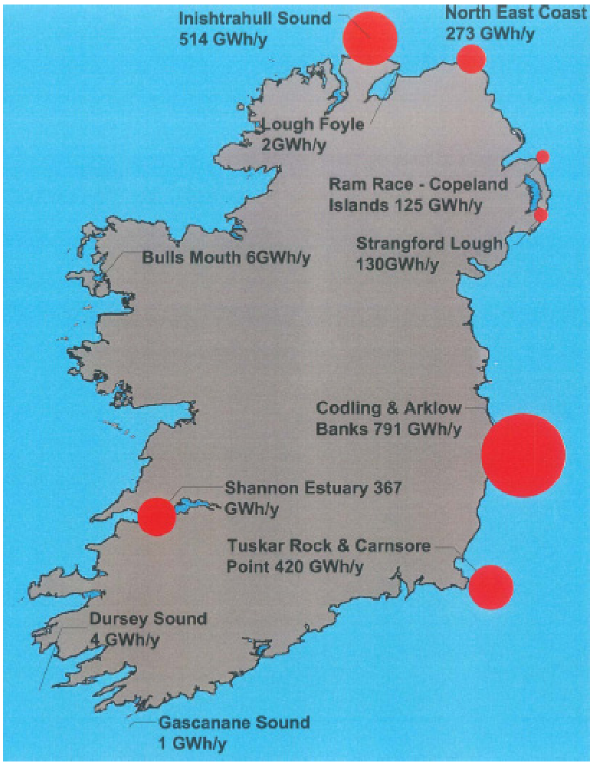


Figure 4-11: Accessible tidal energy resource around the island of Ireland [43].

Finally, agriculture is a prominent industry in Ireland and hence there are many sources of biomass that could be exploited. These include agricultural waste, energy crops, wood waste, landfill biogas, municipal waste, and sewage gas. From the literature, it was not possible to establish how much energy could be utilised from each of these resources. However, Corcoran *et al.* [44] calculated that if all suitable land was used for growing miscanthus energy crops in Ireland, then it would be possible to create 735 PJ (204 TWh) of energy each year. As displayed in Figure 4-12, this is approximately 6 TWh more than the PES forecasted for Ireland in 2020. Although this is not the accessible energy potential using biomass in Ireland, it clearly indicates that Ireland has a substantial biomass resource if it is required, especially considering the numerous other sources of biomass already mentioned that could also be utilised in addition to miscanthus energy crops.

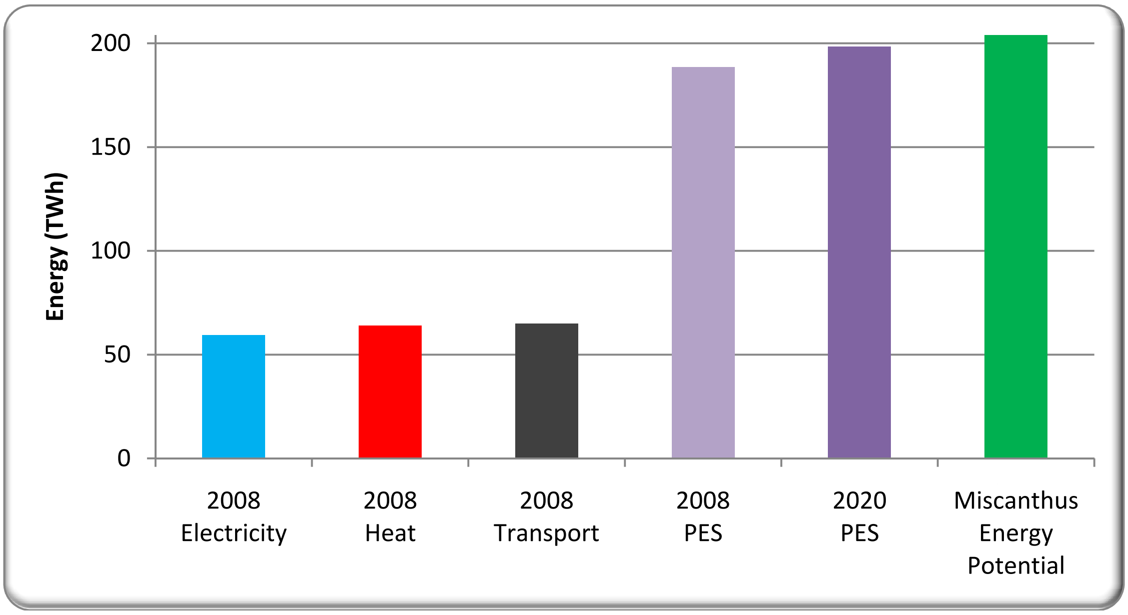


Figure 4-12: Energy feasible from miscanthus energy crops in Ireland compared to Ireland's actual 2008 and forecasted 2020 primary energy supply [25, 36, 44].

In summary, Ireland has a very significant supply of intermittent renewable energy for the production of electricity, as well as biomass which could be a direct replacement for fossil fuels. Since the use of biomass raises many other contentious issues, especially the debate relating to food production, it would be ideal if Ireland could maximise the use of its other intermittent renewable resources. Also, considering the abundance of these intermittent resources, which is summarised in Figure 4-13, utilising these resources before resorting to large-scale consumption of biomass is a pragmatic solution. Finally, from all of the renewable resources discussed, it is clear that Ireland's wind energy could be the ideal solution for increasing renewable energy utilisation. Wind turbines are a relatively mature technology and Ireland has more than enough wind to supply all of its forecasted electricity needs. Not only does this make Ireland an ideal laboratory for analysing energy storage, but this large-scale wind resource already plays a fundamental part in Ireland's current energy targets.

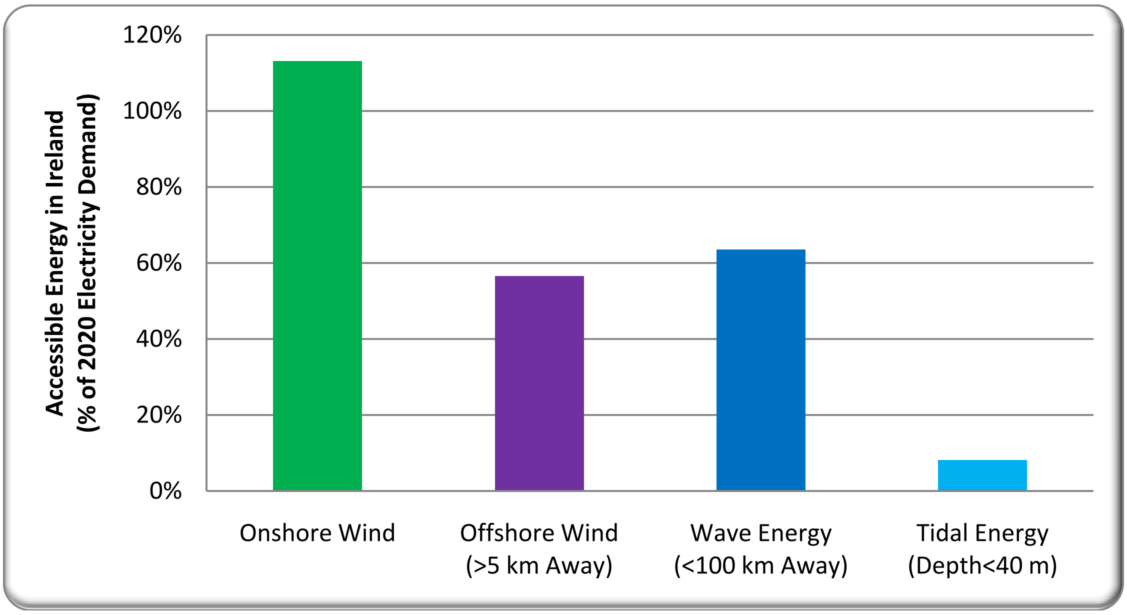


Figure 4-13: Accessible intermittent renewable energy resource in Ireland relative to forecasted 2020 electricity demand [34-36, 40, 43].

4.3. Ireland's Energy Targets

By 2020, Ireland has an obligation under European Union (EU) initiatives to supply 16% of its total primary energy consumption from renewable sources [45]. Also, the Kyoto protocol only allows Ireland to increase its GHG emissions by 13% relative to its 1990 levels [46], but in 2008 Ireland was approximately 20% above 1990 levels [47]. As a result, the Irish government set a number targets for energy in 2007 [48] which included: 30% of fuel must be from biomass at the three state-owned peat power plants by 2015, no oil and a maximum of 50% gas in electricity generation by 2020, combined heat and power (CHP) needs to be expanded to 400 MW by 2010 and 800 MW by 2020, 500 MW of ocean energy should be in operation by 2020, 15% of electricity from renewable sources by 2010 and 40% by 2020 (see Figure 4-14), 5% of heat demand must come from renewable sources by 2010 and 12% by 2020 (see Figure 4-14), 3% of transport from renewables by 2010 and 10% by 2020 (see Figure 4-14), and finally, a 20% reduction in overall energy demands by 2020 [49].

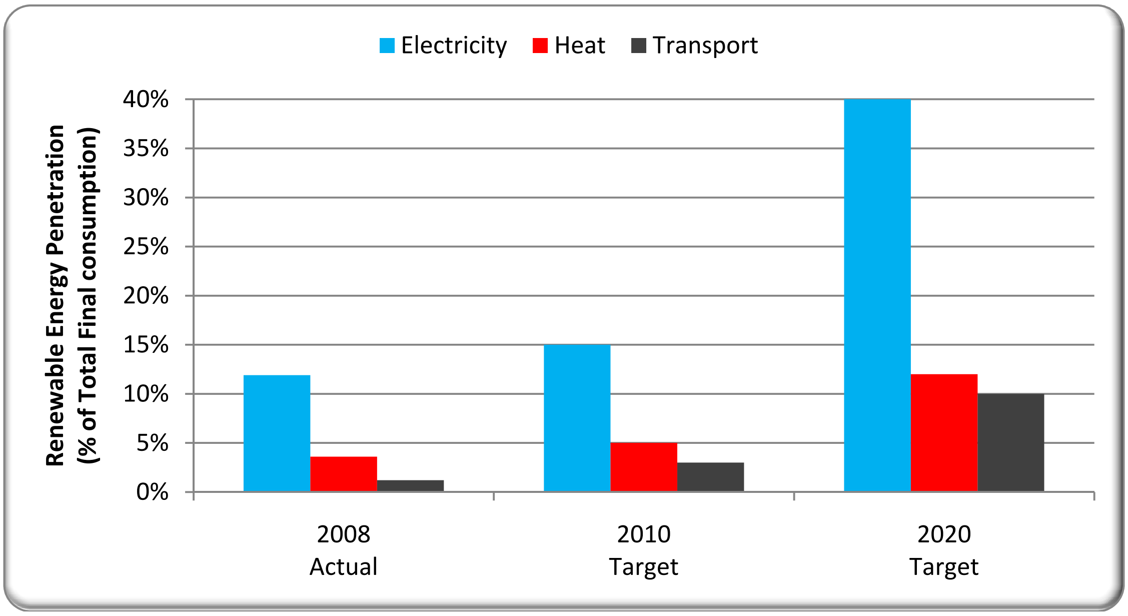


Figure 4-14: Actual and targeted renewable energy contribution in Ireland as a percentage of a total final consumption by sector [25].

Due to Ireland's significant wind energy potential which was discussed previously, this will be the primary resource utilised to achieve these targets. As outlined in Figure 4-15, Ireland is aiming for a wind penetration up to 37% by 2020, which is the highest penetration of wind energy proposed by any country within the EU. Therefore, Ireland will need to identify sources of flexibility within its energy system so this significant penetration of intermittent renewable energy can be accomplished. As there is practically no district heating in Ireland, the condensing power plants in Ireland only produce electricity. Therefore, there are a lot of hours where electricity storage would be able to directly replace power plant production (which is not the case in energy systems with a lot of CHP plants, such as Denmark [50]). As a result, electrical energy storage is an attractive option for increasing energy flexibility in Ireland based on the existing energy infrastructure. Consequently, evaluating the integration of wind energy using energy storage on the Irish energy system is not only an ideal case study for this research, but also a necessary one as Ireland's wind penetration increases.

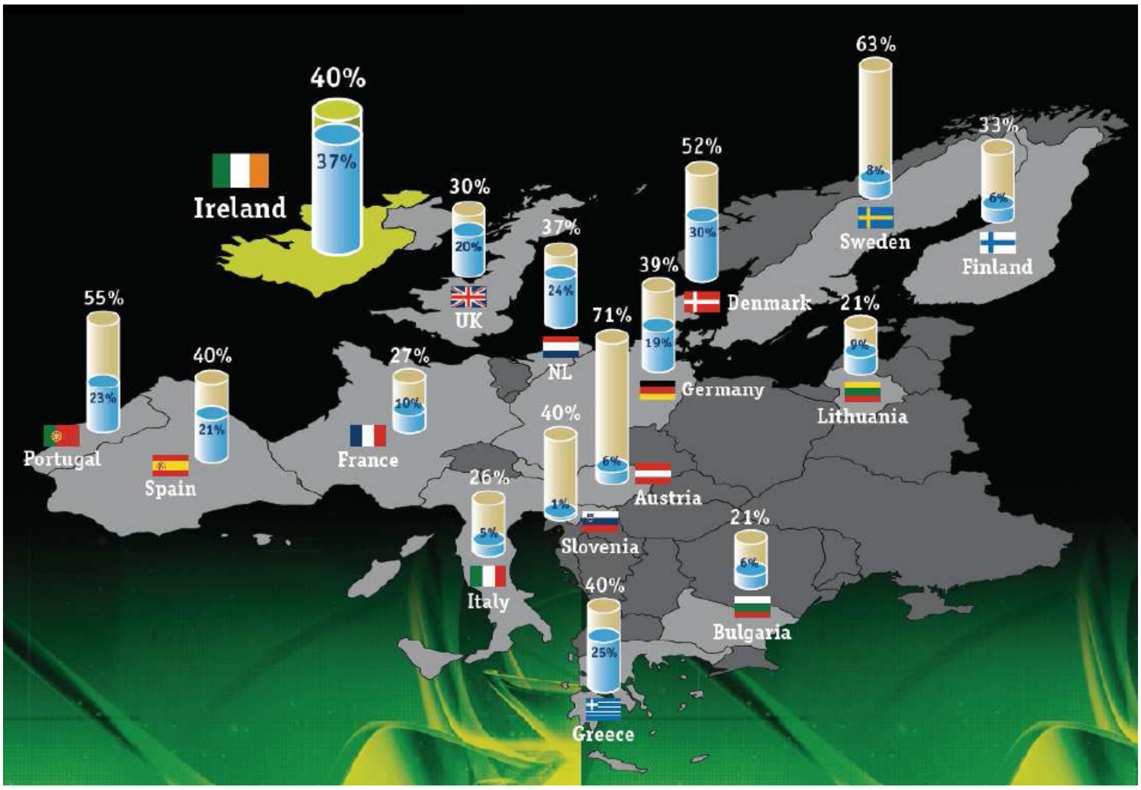


Figure 4-15: Renewable energy targets for individual EU member states for the electricity sector along with the corresponding wind penetration proposed [51].

4.4. Wind Energy Research in Ireland

A wide range of research relating to wind energy has evolved in Ireland due to its increasing penetrations of wind power in recent years. The following sections give a brief overview of this research which focuses on Ireland's wind resource, the implications of wind on the power system, electricity system analysis, demand side management, and energy storage.

4.4.1. Wind Resource in Ireland

Numerous studies have focused on the characteristics of the wind resource in Ireland. Bechrakis *et al.* [52] developed a method for analysing the wind energy potential at individual sites. Lang and McKeogh [53] developed a multi-scheme ensemble prediction tool for wind forecasting in Ireland and analysed its results on both a site-specific (51 wind farms) and a regional level. The authors concluded that for a 48-hour forecasting horizon, there is less than 7% error when this method is used to forecast wind generated electricity from all 51 wind farms together, but individual sites can have errors up to 21%, thus highlighting the benefits of aggregated wind forecasting. Doherty *et al.* [54] analysed the inclusion of wind forecasting in the dispatch of generators on an electricity market by using a typical 24-hour period on the All-Ireland electric grid as a case study. The implications of additional wind with and without wind forecasting were assessed by analysing the consequences for conventional generation, reserve levels, and resulting emissions. The authors concluded that the inclusion of wind forecasting during the dispatch of generators was the most promising strategy for facilitating wind on the Irish system. Leahy [55] investigated the implications of long periods of low wind speeds in Ireland during a time of high electricity demand by analysing data from December 2009 to January 2010 in Ireland. This was an extremely cold time in Ireland so electricity demand for heating was relatively high, but the data indicated that there were no notable effects on system demand or on electricity prices over this period. This was primarily due to a low total electricity demand caused by the economic recession in Ireland and also, because the cold spell corresponded with the holiday season. Hence, under normal economic conditions this could become a concern. Fusco *et al.* [56] investigated the potential correlation between wind and wave energy produced around the coast of Ireland, which was based on the predicted output from a 3.5 MW Vestas V90 wind turbine and a 750 kW Pelamis wave energy device. Results indicated a weak correlation between the two resources in the West and South-West of Ireland and hence, utilising wind and wave energy together at these locations could produce more reliable and predictable power. The authors concluded that this correlation lays the foundations for a more detailed quantification of its benefits and hence, they are not outlined here. Foley *et al.* [57] compared the wind speeds in Ireland, Scotland, England, and Wales, concluding that Britain may be able to balance its spatially variable wind resource better using the regional dispersion of wind farms within its own area rather than by interconnection with Ireland. The authors indicated that this could limit the system support available from interconnection between Ireland and Britain as wind energy increases in the future, which could be significant for the interconnector currently being constructed from Ireland to Wales. Overall, the research to date on the wind energy resource in Ireland outlines its variability, which needs to be accommodated for within the existing power system.

4.4.2. Impact of Wind Energy on the Power System

As wind penetrations increase, its unpredictability can have significant consequences on the dispatch of power plants and the stability of the electric grid. Therefore, studies have also focused these issues. Keatley and Hewitt [58] investigated the implications of increased cycling of power plants on the Irish electricity grid due to the introduction of the All-Ireland single electricity market (SEM) in 2007. The authors illustrated that some power plants have dropped down the merit order from baseload to mid-merit due to the SEM, which could dramatically reduce their lifetime due to increased creep and fatigue of components. In addition, the authors predicted that as more flexibility will be required as wind penetrations increase, it could lead to an over-reliance on gas fuelled power plants.

More specifically relating to the grid, Coughlan *et al.* [59] assessed the various wind turbine models available for power system stability studies from the perspective of the Irish TSO, EirGrid. For maximum benefit, the review indicated that generic models need to be developed between manufactures, model developers, and system operators, which should be validated using staged testing, have an agreed level of modelling error, and be incorporated into existing software. This would help the TSO achieve large-scale electricity generation using wind power. Doherty and O'Malley [60] developed a model to quantify the additional reserve required as wind energy is added to the All-Ireland electric grid, based on the probability of a generator tripping. The authors concluded that wind energy will not require any notable increase in expensive fast-acting reserve (< 1 hour), but may require additional reserve over large forecast horizons (several hours). Brownlees *et al.* [61, 62] compared the magnitude and frequency of power fluctuations from fixed-speed wind turbines and conventional generation to those experienced on the former interconnector between Northern Ireland and Ireland. Results indicated that there was a weak correlation between wind power oscillations and those on the interconnector, as they were being damped within the Northern Ireland electricity grid. Kennedy *et al.* [63] used the Northern Ireland electricity grid as a case study to compare the provision of spinning reserve to diesel generators for balancing significant short-falls of forecasted wind power. The results suggest that diesel generators are a more attractive option as they reduce system costs, can have relatively low CO_2 emissions if operated using biodiesel, and could provide network support if located in specific locations. Doherty *et al.* [64] analysed the impact of additional wind energy on the frequency of the All-Ireland electricity network, concluding that there will be significant frequency control challenges for the TSO when HVDC interconnection along with additional doubly-fed induction generators in wind turbines are introduced. Vittal *et al.* [65] assessed the impact of wind generation on the voltage stability of a power system. Using the 2013 All-Ireland electric grid with 2188 MW of wind as a case study, the results indicated that by utilising the control features found within doubly-fed induction generators, voltage stability could be improved in both transmission and distribution level buses of the electric grid, which would enable higher penetrations of wind energy without degrading the voltage stability of the system. Using a transmission expansion planning methodology, Rivera *et al.* [66] analysed the potential design of an offshore grid for Ireland which could accommodate up to 5294 MW of offshore wind power. The results indicated that an offshore grid should be meshed, there are synergies between onshore and offshore wind production specifically in congested areas, and AC grid technology is the most economically viable at present. These studies outline both the complexity and the significant implications associated with wind energy fluctuations. Consequently, to examine the economical and environmental cost of these fluctuations, as well as potential solutions for accommodating it, a wide range of research has also been carried out in electricity system analysis.

4.4.3. Electricity System Analysis in Ireland

To date, a number of electricity system analyses have already investigated the economic and environmental cost of integrating wind energy onto the Irish electric grid. In 2003, Gardner *et al.* [67] investigated the effects of additional wind energy in Ireland and identified that the most costly aspects of increasing the wind penetration are transmission reinforcement, wind curtailment, capital costs, and operating costs. In 2004, ESB National Grid [68] also analysed the costs and implications for conventional power plants associated with increasing the wind penetration in Ireland. The report concluded that increasing the wind penetration in Ireland from 0% to 11.7% would increase the total generation costs by €196M/year, while peaking and mid-merit power plants would require more frequent start-ups, need increased ramping, and have lower capacity factors. In 2006, Doherty *et al.* [69] developed a range of least cost generation portfolios for the All-Ireland electricity grid in 2020 for various discount rates, carbon taxes, and fuel price scenarios. For numerous scenarios the optimal wind capacity was the maximum assumed available, which was 3800 MW or 22% of the predicted electricity demand. Therefore, the authors concluded that even higher wind penetrations could be beneficial, but to analyse these a more detailed model is required which can assess wind curtailment and energy storage. Also in 2006, Denny and O'Malley [70] developed a least-cost dispatch model to identify if additional wind energy (0-2000 MW) would reduce GHG emissions on a forecasted 2010 All-Ireland electric grid. The results indicated that wind energy could reduce CO_2 by approximately 15% when 2000 MW was installed, but an additional incentive in the form of a €20/t CO_2 carbon tax was required to reduce SO_2 and NO_X emissions also. In 2007, Denny and O'Malley [71] used the PLEXOS environment [72] to create a model which could quantify the total net benefits of additional wind energy (0-4000 MW or 0-26.7% of electricity) on the All-Ireland electricity grid for the years 2010, 2015, and 2020. The authors concluded that additional interconnection and more flexible power plants would increase the net benefits of wind, by reducing the overall system costs.

In 2007, Meibom *et al.* [73, 74] modelled the Irish electricity grid for the year 2020 using the WILMAR Planning Tool [75]. The objective of this study was to identify the effects of large wind penetrations on the island of Ireland in relation to its overall operation, costs, and emissions. Meibom *et al.* concluded that a wind penetration of approximately 34% was feasible on the island of Ireland by 2020, which will reduce overall operation costs and the CO_2 emissions compared to 2007. Building on this work, numerous other studies have since been completed using the model developed with the WILMAR Planning Tool. Gubina *et al.* [76] developed a new scheduling tool which incorporates wind forecasting in the dispatch of plants on electricity markets. The Anemos wind-forecasting tool and the WILMAR Planning Tool were integrated with one another to create the WALT methodology, which will be tested in a future pilot project by the Irish TSO, EirGrid. Tuohy *et al.* [77] used the WILMAR Planning Tool to compare stochastic and deterministic modelling of the All-Ireland electric grid in 2020 with a 34% wind penetration. The results indicated that stochastic optimisation is 0.25% to 0.9% cheaper than deterministic optimisation. In addition, it was found that more frequent updating of the dispatch schedule for an electricity market will reduce the need for reserve. Troy *et al.* [78] used the WILMAR Planning Tool to analyse the operation of baseload power plants when wind energy is added to the Irish electricity grid. Three wind scenarios (2000 MW or 11% of demand, 4000 MW or 23%, and 6000 MW or 34%) were assessed on a forecasted 2020 All-Ireland electricity grid. The results indicated that additional wind energy will affect baseload plants differently depending on their characteristics. For the combined cycle gas turbine (CCGT) and coal plants which were considered in this study, CCGT units began to start-stop cycle more often and their capacity factor dropped, while coal units increased part-load operation and ramping. Alhajali *et al.* [79] also examined the impacts of wind variability on the 2020 All-Ireland electric grid as wind penetrations increased, but investigated if additional open cycle gas turbine (OCGT) power plants would improve the operation of the system. The authors concluded that the addition of OCGT could reduce system costs by up to 5% depending on the mix of plants, but interconnection to Britain is a vital component of the 2020 All-Ireland electric grid, as it reduces fuel costs by approximately 10-15%. Denny *et al.* [80] also used the WILMAR Planning Tool to assess interconnection from Ireland to Britain for the integration of 34% wind energy on the All-Ireland electricity network. The authors concluded that increased interconnection should reduce the price of electricity in Ireland and increase the security of the electric grid. Although Ireland would have lower CO_2 emissions, these would be counter-balanced by increased emissions in Britain. However, as well as interconnection, two other solutions for creating flexibility have also been researched in Ireland: demand side management and energy storage.

4.4.4. Demand Side Management

Due to the proposed rollout of smart meters across Ireland, many studies have also looked at demand side management (DSM) to aid the integration of large-scale wind penetrations in Ireland. McKenna *et al.* [81] simulated real-time load management in MATLAB to outline how an Irish local authority (Kerry County Council) could maximise the use of electricity from a 6.8 MW wind farm to meet its electricity requirements. Finn *et al.* [82] analysed the role of time-of-use and real-time-pricing tariffs for the domestic electricity market in Ireland. After forecasting electricity prices on the 2020 Irish electricity market with a 34% wind penetration, the authors concluded that due to the expected variability in pricing in 2020, a real-time-pricing tariff is more appropriate for increasing renewables on both the supply and demand side. Subsequently, this study also illustrated how real-time pricing could be used to reschedule the load of a domestic electric water heater over a 24-hour period. In a later study, Finn *et al.* [83] also investigated the implications of using day-ahead pricing predictions to demand side manage a load with an inherent energy loss due to rescheduling. Irish electricity market prices from 2008 and an electric water heater with a thermal storage in a domestic dwelling were used to form a case study. The results indicated that price optimised DSM has the potential to promote the use of wind generated electricity on the Irish electricity system, but discrepancies between day-ahead and final electricity prices could be a significant barrier. Savage *et al.* [84] also analysed the implications of using an electric heat load to integrate wind on the Northern Ireland electric grid, but as reserve by shutting down when there was shortages of wind supplied to the grid. Results indicate that thermal storage of electric heat loads provide an ideal buffer for counteracting over-predictions of wind power and if implemented, then wind forecasting should be included in the scheduling of power plants. Akmal *et al.* [85] assessed the benefits of heat pumps as a flexible load which could enable larger penetrations of wind power, by using the WILMAR model of the All-Ireland electric grid discussed earlier and a 34% wind penetration as a case study. Two operating strategies were considered: firstly, heat pumps were operated during off-peak hours and secondly, heat pumps were operated during hours of high wind generation. Although both strategies reduced system costs, the number of plant start-ups, and wind curtailment, the off-peak strategy was consistently better. Finally, Foley discussed Ireland's target for electric vehicles (EVs), which is 10% of road cars by 2020 [86]. In a future paper, the authors will outline how demand side managing EVs will enable larger penetrations of wind energy on the Irish electric grid, by modelling it on an hourly basis using the WASP-IV energy tool.

4.4.5. Energy Storage

Before this study began in 2007, there were no studies available for Ireland which simulated the integration of wind on the Irish energy system using large-scale energy storage on an hourly basis. However, numerous studies had analysed the benefits of energy storage in conjunction with a small number of wind farms. González *et al.* [87] analysed the operation of a hydrogen storage system for four wind farms (100 MW total capacity) in the South-West of Ireland utilising an electrolyser, compressor, and a hydrogen storage. The results indicated that significant cost-reductions for the hydrogen system, low average surplus wind electricity cost, and a high hydrogen market price are necessary for the economic viability of hydrogen storage. For a separate study, a demonstration project was initiated in 2007 to construct a vanadium-redox flow battery in conjunction with a 6 MW wind farm in Co. Donegal [88]. The initial economic analysis indicated that a 2 MW, 12 MWh battery would provide the greatest return and hence, these were the capacities defined for its construction, although it is unclear how the project has progressed since. In 2006, Allen *et al.* [89] developed a model using MATLAB-Simulink to investigate the operation of a single wind farm in conjunction with a PHES facility. The study analysed the operation of a 20 MW wind farm using a 30 minute time-step over a 1-year period in conjunction with two different PHES facilities, a 4 MW and a 6 MW. For each PHES considered, the model was run with various PHES storage capacities, up to a maximum of 500 MWh. Allen et al. discovered that the power variations from the wind-PHES system reduced as the power capacity and storage capacity of the PHES increased, until eventually a saturation point is reached.

Since this study began, there have been some significant developments in relation to PHES in Ireland. Firstly, in 2009 a new campaign was launched call “Spirit of Ireland” [90], which promoted the large-scale (>100 GWh) deployment of wind farms and PHES in Ireland. The PHES facilities in the proposal utilised U-shaped valleys along the Irish coastline as their upper reservoirs and the sea as their lower reservoirs. However, no detailed analysis of the size and economics of the proposal have been provided to date. Also, as mentioned earlier the All-Island Grid Study analysed the implications of a 34% wind penetration in Ireland by 2020. In this study, Meibom *et al.* [73, 74] found that the operation of energy storage on the Irish electricity grid didn’t change when wind power was increased to a penetration of 34% and hence, concluded that it was not necessary until the wind penetration surpassed this. Using the WILMAR Planning Tool, Tuohy and O'Malley [91] simulated the All-Ireland electricity grid with and without a 500 MW 5 GWh PHES facility for wind capacities between 3 GW and 15 GW, which is 17% to 80% of total electricity. The results indicated that the PHES plant did not have any impact on the operation of the system until the wind penetration exceeded 40%. Also, even though it reduced the operating costs of the system, the additional capital costs were too high to justify its construction. However, the authors did emphasise that future work should analyse the implications of different capacities and operating strategies for the PHES facility. In 2010 Nyamdash *et al.* [92] did this by analysing the implications of energy storage on the 2006 All-Ireland electricity grid with wind capacities of 1300 MW, 1950 MW, and 2550 MW. In this study, energy storage and wind power were simulated using three different operation strategies: one where the wind-hydro system provided a 24 hour baseload output and replaced baseload plant, a second where it charged for 12 hours at night and discharged for 12 hours during the day by replacing mid-merit plant, and thirdly, where it generated for 6 peak hours of the day and replaced peaking plant. Each operating strategy was analysed for a PHES power capacity ranging from 0 MW to 1800 MW. The results indicated that the baseload and peaking strategies increased the variability of wind, but the mid-merit strategy decreased it. Also, a subsequent economic assessment was carried out which indicated that the revenue made by the energy storage under all three strategies was not sufficient to make it an attractive investment, even when it was analysed as four different technologies: PHES, compressed air, battery, and flow battery. Therefore, the authors concluded that without any economic subsidy, energy storage would not be an attractive investment. Similarly, this research will also assess the role of PHES, but using a new methodology and different operating strategies to those proposed in existing studies.

4.5. Conclusions

This chapter has indicated that Ireland has an energy system which uses a lot of fossil fuel, is currently emitting more CO_2 than permissible under the Kyoto protocol, and is very dependent on energy imports. All of these concerns could be reduced if Ireland began to utilise its indigenous renewable energy resource which is currently only providing around 4.5% of PES, even though there is enough to supply all of Ireland's energy needs. In line with this, ambitious energy targets have been set by the Irish government, which include 40% of electricity, 12% of heat, and 10% of transport to be supplied using renewable energy by 2020. The primary resource which will be utilised to reach these targets is intermittent wind energy, which needs to provide approximately 34-37% of electricity in Ireland by 2020.

In line with this, a significant variety of research has been carried out in relation to the implementation and facilitation of Ireland’s wind energy target, which includes areas such as resource assessment, implications for the power system, energy modelling, demand side management, and energy storage. Most relevant to this research, is the work completed on electricity system analysis and energy storage in sections 4.4.3 and 4.4.5 respectively. This study will complement existing research by identifying PHES as a suitable energy storage technology for integrating Ireland’s wind, quantifying the freshwater PHES resource available in Ireland, simulating larger capacities and new operating strategies for PHES, analysing the implications of PHES for the entire Irish energy system, defining new alternatives to PHES, and proposing a new operating strategy so that PHES can maximise its profits on existing electricity markets. In line with this, the first task of this work investigates the various energy storage technologies currently available, to identify the most suitable technology for Ireland.

5. Review of Energy Storage Technologies

There are a wide variety of energy storage technologies currently available, each with its own specific capabilities, maturity, costs, and applications. Hence, the primary objectives of this literature review was to identify the various types of energy storage technologies that exist and subsequently, to assess their suitability as an aid for the integration of fluctuating renewable energy, especially in relation to the Irish energy system. This chapter summarises the results of this review, which is fully described in Appendix A.

In total, 11 different types of energy storage were assessed during the review. These were pumped hydroelectric energy storage (PHES), underground pumped hydroelectric energy storage (UPHES), compressed air energy storage (CAES), battery energy storage (BES), flow battery energy storage (FBES), flywheel energy storage (FES), supercapacitor energy storage (SCES), superconducting magnetic energy storage (SMES), a hydrogen energy storage system (HESS), thermal energy storage (TES), and electric vehicles (EVs). Each technology was analysed under the following key headings: how it works; advantages; applications; cost; disadvantages and future potential, so its suitability for the integration of fluctuating renewable energy could be assessed.

A detailed description and theoretical analysis of each storage technology can be found in Appendix A and hence, only a brief summary of their operation is provided here. PHES utilises two reservoirs of water at different vertical heights that are connected via a penstock. Typically these are freshwater facilities located on mountainous terrain, although recent proposals have been made based on seawater facilities [90, 93]. UPHES is based on the same concept as PHES, but the upper reservoir is located at ground level and the lower reservoir is located underground [94]. CAES operates in the same was as a conventional gas turbine. However, unlike a conventional gas turbine which uses 66% of its gas to compress air at the time of generation, CAES utilises off peak electricity to compress air and store it in an underground cavern until it is required. This reduces the gas required by approximately one third.

BES operates in the same way as conventional batteries, which exploit the chemical reactions that occur when two electrodes are immersed in an electrolyte. In the review, three different types were assessed: lead-acid, nickel-cadmium, and sodium-sulphur. Although FBES is also based on electrochemistry, its structure is very different to BES. Two electrolytes are stored in separate tanks, which react with one another when they are pumped to a cell stack. The power capacity is dependent on the size of the cell stack, while the storage capacity is dependent on the size of the electrolyte tanks. Once again, three different types were investigated: vanadium-redox, polysulphide-bromide, and zinc-bromine.

FES utilises the momentum within a mass which is spinning anywhere between 10,000 (low-speed) and 80,000 (high-speed) rpm. SCES functions in the same way as standard electronic capacitors, but on a much larger scale. SMES stores energy in the magnetic field created by the flow of direct current in a coil of wire. Typically, when current is passed through a wire it is dissipated as heat. However, if the wire used is kept in a superconducting state (i.e. cooled <150 K), zero resistance occurs and hence energy can be stored with practically no losses.

The HESS consists of three stages: creating, storing, and using hydrogen. Hydrogen can be created by extracting it from fossil fuels, reacting steam with methane, or by electrolysis using electricity. Subsequently, it can be stored as a gas by compressing it into containers or underground reservoirs, as a liquid by pressurising and cooling the gas, or in metal hydrides which absorb molecular hydrogen. Finally, the hydrogen can be used in an internal combustion engine or in a fuel cell.

Two distinct types of TES were assessed: air-conditioning thermal energy storage (ACTES) and a thermal energy storage system (TESS). ACTES uses off-peak electricity to power chillers which create blocks of ice. These ice blocks can then be used during the day as a cooling load for air conditioners. A TESS takes advantage of large hot water storage tanks and CHP plants which are typically used in district heating systems. Although multiple technologies must operate coherently with one another to ensure this system operates successfully, a simple example is described here using wind power, CHP, and thermal storage, to outline the fundamental operation of a TESS. When wind power production is low the CHP electrical and heat output is high and hence, too much heat is typically produced. Therefore, this excess heat is stored in hot water storage tanks. When wind power production is high the CHP output is low, too little heat is typically being produced. Therefore, heat is obtained from the hot water storage to account for the deficit.

Finally, a single EV has a power connection to the grid of approximately 5 kW and a storage capacity of approximately 50 kWh. Due to the number of cars in developed countries, EVs could act as an energy storage system for the grid, if there was a large-scale rollout and their capacities were aggregated. EVs can be classified under three primary categories: battery electric vehicles (BEV) which act as an additional load to the electricity network, smart electric vehicles (SEV) which charge when it is suitable for the electricity network, and vehicle to grid (V2G) which not only receive power from the grid, but also give power back.

Once the fundamental operation of each energy storage technology was identified, it was evident that there was a broad range of capacities feasible. As a result, they were grouped together based on the size of power and storage capacity that they can achieve. Four categories were created: devices with large power (>50 MW) and storage (>100 MWh) capacities; devices with medium power (1-50 MW) and storage capacities (5-100 MWh); devices with small power (<10 MW) and storage capacities (<10 MWh); and finally, a section on energy storage systems. These are energy storage technologies that were placed within the various categories defined:

1. PHES
2. UPHES
3. CAES

} Large Power and Storage Capacities

4. BES
5. FBES

} Medium Power and Storage Capacities

6. FES
7. SCES
8. SMES

} Small Power and Storage Capacities

9. HESS
10. TESS
11. EVs

} Energy Storage Systems

The characteristics of these storage technologies are outlined in Table 5-1 and their corresponding costs are displayed in Table 5-2. In addition, typical applications for the storage technologies are outlined in Table 5-3. The HESS, TESS, and EVs have unique characteristics as they are constructed from a range of different technologies and not just one single plant. As energy storage is only part of the system they are composed of, it is difficult to compare HESS, TESS, and EVs to the other energy storage technologies directly. Hence, documenting the costs and characteristics of these technologies is an area which will require further research in the future.

Table 5-1: Characteristics of various energy storage technologies [94-98].

Technology	Power rating	Discharge duration	Response time	Efficiency (%)	Parasitic losses	Lifetime	Maturity
Pumped hydro	100 – 4000 MW	4 – 12 h	sec - min	70 – 85	Evaporation	30 - 50 y	Commercial
Underground pumped hydro	100 – 4000 MW	4 – 12 h	sec - min	70 - 85	Evaporation	30 – 50 y	Concept
CAES (in reservoirs)	100 – 300 MW	6 – 20 h	sec - min	64	-	30 y	Commercial
CAES (in vessels)	50 – 100 MW	1 – 4 h	sec - min	57	-	30 y	Concept
Lead-acid battery	< 50 MW	1 min – 8 h	< ¼ cycle	85	Small	5 – 10 y	Commercial
Nickel-cadmium	< 50 MW	1 min – 8 h	n/a	60 - 70	~2 - 5%	3500 cycles	Commercial
Sodium sulphur battery	< 10 MW	< 8 h	n/a	75 – 86	5 kW/kWh	5 y	In development
Vanadium redox flow battery	< 3 MW	< 10 h	n/a	70 – 85	n/a	10 y	In test
Polysulphide bromide flow battery	< 15 MW	< 20 h	n/a	60 – 75	n/a	2000 cycles	In test
Zinc bromine flow battery	< 1 MW	< 4 h	< ¼ cycle	75*	Small	2000 cycles	In test / commercial units
Flywheels (low speed)	< 1650 kW	3 – 120 s	< 1 cycle	90	~1%	20 y	Commercial products
Flywheels (high speed)	< 750 kW	< 1 h	< 1 cycle	93	~3%	20 y	Prototypes in testing
Supercapacitor	< 100 kW	< 60 s	< ¼ cycle	95	-	10,000 cycles	Some commercial products
SMES (Micro)	10 kW – 10 MW	1 – 60 s	< ¼ cycle	95	~4%	30 y	Commercial
SMES	10 – 100 MW	1 – 30 min	< ¼ cycle	95	~1%	30 y	Design concept
Hydrogen (fuel cell)	< 250 kW**	As needed	< ¼ cycle	34 – 40*	n/a	10 – 20 y	In test
Hydrogen (engine)	< 2 MW**	As needed	Seconds	29 – 33*	n/a	10 – 20 y	Available for demonstration

*** AC-AC efficiency.**
****Discharge device. An independent charging device (electrolyser) is required.**

Table 5-2: Costs of various energy storage technologies [94-98].

	Capital cost			O&M cost				
Technology	Power related cost ($/kW)	Energy related cost ($/kWh)	BOP ($/kWh)	Fixed ($/kW-y)	Variable (c$/kWh)	Cost certainty	Environmental issues	Safety issues
Pumped hydro	600 – 2000	0 – 20	Included	3.8	0.38	Price list	Reservoir	Exclusion area
Underground pumped hydro	n/a	n/a	n/a	3.8	0.38	Estimate	Reservoir	Exclusions area
CAES (in reservoirs)	425 – 480	3 – 10	50	1.42	0.01	Price quotes	Gas emissions	None
CAES (in vessels)	517	50	40	3.77	0.27	Estimate	Gas emissions	Pressure vessels
Lead-acid battery	200 – 580	175 – 250	~50	1.55	1	Price list	Lead disposal	Lead disposal, H_2
Nickel-cadmium	600 – 1500	500 – 1500	n/a	n/a	n/a	Estimate	Toxic cadmium	Toxic cadmium
Sodium sulphur battery	259 – 810	245	~40	n/a	n/a	Project specific	Chemical handling	Thermal reaction
Vanadium redox flow battery	1250 – 1800	175 – 1000	n/a	n/a	n/a	Project specific	Chemical handling	Chemical handling
Polysulphide bromide flow battery	1000 – 1200	175 – 190	n/a	n/a	n/a	Project specific	Chemical handling	Chemical handling
Zinc bromine flow battery	640 – 1500	200 – 400	Included	n/a	n/a	Project specific	Chemical handling	Chemical handling
Flywheels (low speed)	300	200 – 300	~80	n/a	n/a	Price list	-	Containment
Flywheels (high speed)	350	500 – 25,000	~1000	7.5	0.4	Project specific	-	Containment
Supercapacitor	300	82,000	10,000	5.55	0.5	Project specific	-	-
SMES (Micro)	300	72,000	~10,000	26	2	Price quotes	-	Magnetic field
SMES	300	2000	~1500	8	0.5	Estimate	-	Magnetic field
Hydrogen (fuel cell)	1100 – 2600	2 – 15	n/a	10	1	Price quotes	-	-
Hydrogen (engine)	950 – 1850	2 – 15	n/a	0.7	0.77	Price list	Emissions	-

Table 5-3: Technical suitability of energy storage technologies to different applications [96, 99-101].

	Storage Technology	Pumped hydro	Underground pumped hydro	Compressed air	Lead-acid batteries	Advanced batteries	Flow batteries	Flywheels	Supercapacitors	Superconducting magnetic	Hydrogen fuel cell	Hydrogen engine
Storage Application												
Transit and end-use ride-through					X		X	X	X	X	X	
Uninterruptible power supply					X	X	X	X			X	X
Emergency back-up		X	X	X	X	X	X				X	X
T&D stabilisation and regulation		X	X	X	X		X			X	X	
Load levelling		X	X	X	X	X	X				X	X
Load following		X	X	X	X	X	X				X	X
Peak generation		X	X	X	X	X	X	X			X	X
Fast response spinning reserve		X	X	X	X	X	X	X			X	X
Conventional spinning reserve		X	X	X	X	X	X	X			X	X
Renewable integration		X	X	X	X	X	X	X			X	
Renewables back-up		X	X	X	X	X	X				X	

To chose a suitable energy storage technology based on the characteristics outlined in Table 5-1, Table 5-2, and Table 5-3, existing research on the integration of wind was also reviewed. By looking at the energy storage technologies used during island investigations, it was apparent that very large storage capacities are necessary to obtain high wind penetrations. Bakos [102] and Kaldellis [103] concluded that a storage capacity in the region of 1 to 3 days of the energy system's power requirement is necessary to obtain a wind penetrations above 90%. Although larger energy systems will probably require less energy storage than island systems, primarily due to the possibilities of creating flexible loads such as electric vehicles or demand side management, these island case studies indicate that large-scale energy storage will most likely be necessary for large wind penetrations. Therefore, the scale of energy storage necessary for Ireland to integrate large penetrations of wind energy reduced the energy storage technologies feasible to PHES, UPHES, and CAES.

Studies indicate that PHES is the most utilised and mature large-scale energy storage technology currently available, but its major drawback is the lack of suitable sites [104-106]. In theory UPHES could benefit from the maturity of PHES as it uses a number of similar components, but it is still only at the conceptual stage of development and hence, the definition of a suitable site is still even vague. Finally, not only does the feasibility of CAES rely on the availability of suitable locations, but it will also depend on the price and availability of gas within future energy systems. In addition, although CAES is classified as a mature technology, there are currently only two facilities constructed worldwide.

In conclusion, it is evident that large-scale energy storage facilities all share one key issue: the availability of suitable locations. However, UPHES and CAES utilising vessels are still only concepts and thus unproven, while CAES using underground reservoirs is often considered a mature technology, but there are currently only two facilities operating worldwide. In comparison, there is over 90 GW of PHES at over 240 facilities currently in operation, as well as 7 GW of additional plants planned in Europe alone over the next eight years [99]. Therefore, based on the scale, maturity, and future outlook, it was concluded that PHES is most likely large-scale energy storage technology feasible for the integration of wind energy on Irish energy system. Consequently, the literature was reviewed again to identify the potential for suitable PHES sites and the benefits of additional PHES on an energy system, as discussed in chapter 6.

6. Pumped Hydroelectric Energy Storage

This chapter gives a more detailed over of the PHES technology including its operation, applications, costs, disadvantages, current development, and future prospects. Subsequently, a summary of the existing literature in relation to the location of suitable PHES sites and the integration of wind energy using PHES is provided.

6.1. Overview of Technology

PHES consists of two large reservoirs located at different elevations and a number of pump/turbine units, as displayed in Figure 6-1. Typically during off-peak electrical demand, water is pumped from the lower reservoir to the higher reservoir where it is stored until it is needed. Once required, usually during peak electrical production, the water in the upper reservoir is released through the turbines which are connected to generators that thus produce electricity. Therefore, during production a PHES facility operates in a similar way to a conventional hydroelectric system.

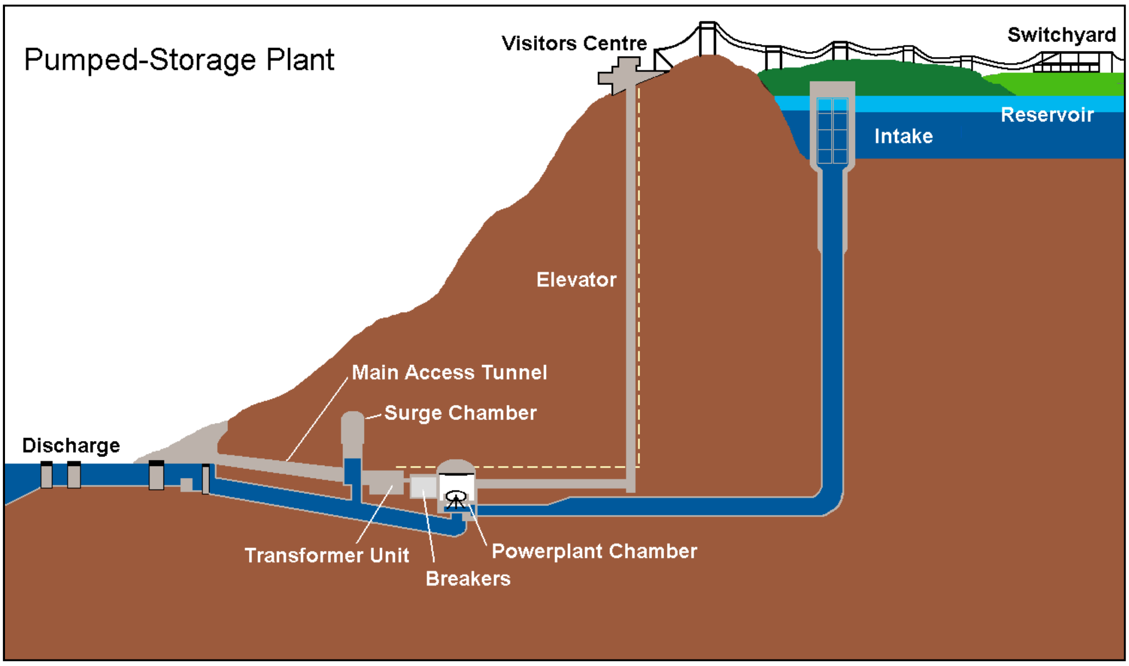


Figure 6-1: Layout of a pumped hydroelectric energy storage facility [107].

The round-trip efficiency of modern pumped storage facilities is in the region of 70% - 85%. The efficiency is typically limited by the efficiency of the pump/turbine unit used in the facilities [96], which is currently being improved through the use of variable speed machines. Until recently, PHES units have always used fresh water as the storage medium. However, in 1999 the 30 MW PHES facility displayed in Figure 6-2 was constructed using seawater as the storage medium [93]: corrosion was prevented by using paint and cathodic protection. A typical PHES facility has 300 m of hydraulic head (the vertical distance between the upper and lower reservoir). The power capacity (kW) is a function of the flow rate and the hydraulic head, whilst the energy stored (kWh) is a function of the reservoir volume and hydraulic head. To calculate the mass power output of a PHES facility, the following relationship can be used [94]:

$$P_{Capacity} = \rho g Q H \eta \tag{1}$$

Where $P_{Capacity}$ is the power capacity in watts, ρ is the mass density of water in kg/m^3, g is acceleration due to gravity in m/s^2, Q is discharge through the turbines in m^3/s, H is the effective head in m, and η is the pumping or turbine efficiency. To evaluate the storage capacity of the PHES the following must be used [108]:

$$C_{Storage} = \frac{\rho g H V \eta_{Generation}}{3.6x10^3} \tag{2}$$

Where $C_{Storage}$ is storage capacity in watt-hours, V is volume of water that can be drained from the reservoir in m^3, and $\eta_{Generation}$ is the generating efficiency. It is evident that the power and storage capacities are respectively dependent on the head and the volume of the PHES. It is typically cheaper to construct a facility with a large hydraulic head and small reservoirs, than to construct a facility of equal capacity with a small hydraulic head and large reservoirs. This is based on a number of factors such as: less material needs to be removed to create the reservoirs required, smaller piping is necessary, and the pump/turbine is physically smaller. Hence, facilities are usually designed with the greatest hydraulic head possible rather than the largest upper reservoir possible. Currently, there is over 90 GW in more than 240 PHES facilities around the world, which is roughly 3% of the world's global generating capacity. Each individual facility can store from 30 MW to 4000 MW and up to 15 GWh of electrical energy [96].

Figure 6-2: Photograph of a pumped hydroelectric storage facility using seawater [93].

As well as large storage capacities, PHES also has a fast reaction time which makes it ideal for the integration of fluctuating renewable energy. Facilities can have a reaction time as short as 10 minutes or less from complete shutdown (or from full reversal of operation) to full power [95]. In addition, if kept on standby, full power can even be reached within 10 to 30 seconds. Also, with the recent introduction of variable speed machines, PHES systems can now be used for frequency regulation in both pumping and generation modes (this has always been available in generating mode). This allows PHES units to absorb power in a more cost-effective manner that not only makes the facility more useful, but also improves the efficiency by approximately 3% [95]. PHES can also be used for peak generation and black starts due to its large power capacity and sufficient discharge time.

The cost of PHES ranges from $600/kW [96] to upwards of $2000/kW [95], depending on a number of factors such as size, location and connection to the power grid. In order to make a PHES facility economically viable, it is usually constructed on a large scale. Although the cost per kWh of storage is relatively economical in comparison to other techniques, this necessity for large-scale projects results in a very high initial construction cost, thus detracting investment in PHES e.g. Bath County storage facility in the United States which has a power capacity of 2,100 MW cost $1.7 billion in 1985. Due to the design requirements of a PHES facility, the ultimate drawback is its dependence on specific geological formations that is; two large reservoirs with a sufficient amount of hydraulic head between them must be located within close proximity to build a PHES system. However, as well as being rare these geological formations normally exist in remote locations such as mountains, where construction is difficult and the power grid is not present. Hence, there is a 300+% variation in costs associated with PHES facilities. In recent times, development has focused on the upgrading of old PHES facilities with new equipment such as variable speed devices, which can increase capacity by 15% to 20% and efficiency by approximately 3% without the high initial construction costs. However, over the next few years a resurgence of new PHES facilities is expected, with over 7 GW planned in Europe alone [99]. Consequently, before embarking on the research carried out in this study, a review of existing literature was carried out to identify how suitable sites were being located for PHES and if its ability to integrate fluctuating renewable energy had been documented.

6.2. Review of Existing Research

As mentioned earlier, PHES is a very mature and well-established technology which was introduced in the early 20th century [109]. As a result, there is very little research being published surrounding the development of the technology itself, with any studies focusing on technical improvements usually relating to site-specific problems such as those that have recently been reported for Chinese [110], Korean [111], and American [112] facilities. Furthermore, although a lack of suitable sites is usually perceived as the most significant barrier to the development of PHES [104-106], there is very little research carried out on this issue. Studies have been carried out to locate small run-of-the-river hydro projects [113-115] and large hydropower facilities [116-119], but these studies do not specify which sites would be suitable for PHES. The two studies which have investigated suitable sites for PHES were completed manually using maps, by Levine [120, 121] who analysed the state of Colorado in the USA and by Black [122], who searched for seawater PHES around the coast of Britain and Northern Ireland [122]. As a lack of suitable sites was such as key issue for PHES, it was concluded from the literature review that a tool should be developed which could identify suitable locations for the construction of PHES. Therefore, this was the first aim of this study, which is examined in chapter 7.

With very little research on the technical development and suitability of sites for PHES, current research is primarily focused on the dispatch of PHES, especially in relation to the utilisation of wind energy and its role on electricity markets. Hence, these are discussed in detail in the following sections.

6.2.1. PHES and Wind Energy

Numerous studies have been carried out in recent times analysing the potential wind penetration feasible by introducing a PHES facility, especially on island[6] electric-grids. In 2003 Bakos [102] analysed the benefits of introducing a PHES on Ikaria island in Greece using the computer simulation outlined in Figure 6-3.

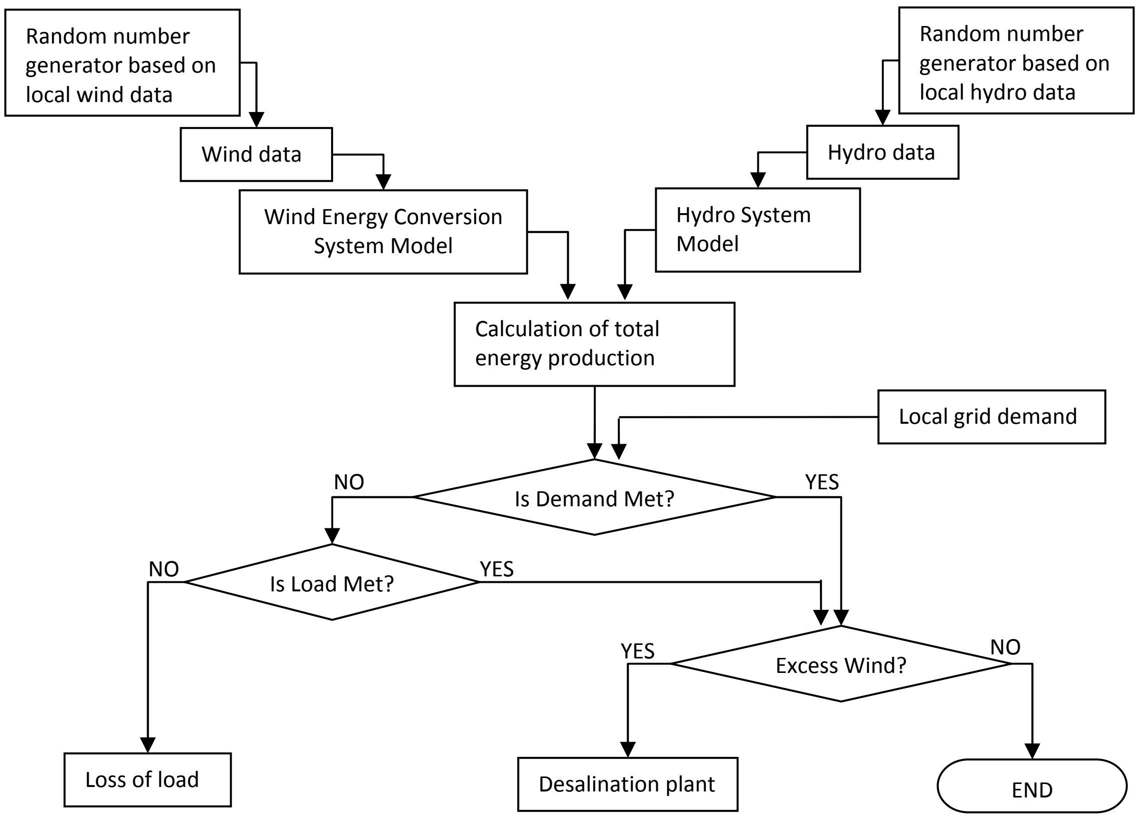


Figure 6-3: Flow chart of the computer simulation used by Bakos to analyse the potential of a PHES facility on Ikaria island in Greece [102].

This was followed by a variety of island studies that created simulations of wind-PHES hybrids [103, 123-140]. In general, the objectives of these simulations were quiet similar: to analyse a system without PHES, subsequently analyse a system with PHES and finally, identify if the benefits of the PHES were worthy of the costs associated with it. A number of intriguing conclusions were made during these studies. Bakos [102] concluded that electricity on Ikaria island could be generated cheaper using a wind-PHES system than using conventional generation. Theodoropoulos *et al.* [123] stated that the amortization period for a PHES facility on Ikaria island (Greece) is only four to five years. Castronuovo and Peças-Lopes [124] concluded that a small wind-PHES hybrid system in North Portugal would produce more

[6] Island electricity systems refer to small-scale stand-alone energy systems where the installed generating capacity is usually between 1 and 100 MW.

revenue each year than the same system without the PHES facility, and they also investigated various tariffs to improve the profits from a wind-PHES system [125]. Anagnostopoulos and Papantonis [126, 127] defined the capacities for a PHES facility at which it became economically viable, and also identified a new pumping configuration for a PHES facility in a wind-PHES hybrid system. Bueno and Carta developed a very detailed wind-PHES model [128] which was used to study a wind-PHES system on the Spanish island of El Hierro [129]. This study simulated the wind-PHES under various operating strategies and concluded that the most economic one was, to define a maximum percentage of electricity allowed from wind energy and to supply the rest using PHES where possible. If the PHES could not be used, then supply was met using conventional generation. Bueno and Carta's wind-PHES model was later used to identify the most economical capacities for a PHES facility in the Gran Canaria [130]. Caralis and Zervos [131] identified the PHES capacities required to make wind-PHES facilities feasible on the Greek islands of Crete, Lesvos, and Serifos, stating that up to 72%, 79% and 83% of the energy for these islands respectively could come from the wind-PHES facilities proposed. Katsaprakakis *et al.* [132] analysed the effects of a PHES plant on all the various types of thermal generation within the energy system of two Greek islands: Crete and Rhodes. The authors concluded that for an island electrical system with an energy cost of approximately €0.15/kWh, a PHES will always be attractive, between €0.05/kWh and €0.15/kWh a PHES may be an attractive investment, and below €0.05/kWh a PHES system is not expected to improve the power system. Papathanassiou *et al.* [133] also developed a model of a wind-PHES system which was used to identify the optimum capacities [133], operation strategies [134], and economic viability [135] of various wind-PHES units, concluding that they are not an economical option unless specific tariffs are in place to support their operation. Segurado *et al.* [136] identified how PHES could be used in conjunction with water desalination to achieve a 30% wind penetration on S. Vicente Island in Cape Verde. Kaldellis has been involved in a variety of island studies which analysed the feasibility of different wind-storage systems for various Aegean Archipelago Islands [103, 137-139]. The results indicated that sodium-sulphur batteries were the most economical storage device for islands with an annual electricity demand less than 90 MWh and peak demand less than 300 kW. However, for larger islands up to an annual demand of 200 GWh and peak of 50 MW, PHES was not only the most economical storage technology for integrating wind power, but it was a cheaper alternative to conventional fossil fuel based generation. In addition, Kaldellis *et al.* [140] also demonstrated how the size of the PHES used to integrate wind energy onto island energy systems can affect the amount of wind energy utilised and the operation of the system. In summary, this variety of island studies completed outlines the range of key issues which can be altered within a wind-PHES system such as size, operation, cost, and the mix on other technologies. Hence, it is unclear how the conclusions drawn during these island studies can be translated onto national[7] electricity systems.

Although PHES and wind energy has been assessed extensively on island electric grids, there has been much less research carried in relation to national electric grids. Benitez *et al.* [141] analysed the impacts of additional wind capacity on the Alberta electricity network in Canada, concluding that when PHES is added in conjunction with wind power, it can provide most of the peak load requirements of the system and thus, peak-load gas generators are no longer required. Dursun and Alboyaci [142] carried out a detailed review of previous wind-PHES studies and outlined how this solution could be incorporated in the Turkish energy system, by utilising the mountainous areas around the Black Sea and the electrical infrastructure to other hydro facilities. Black and Strbac [143, 144] examined the benefits of PHES on the British energy system with a wind penetration of 20%, which equates to an installed wind capacity of 26 GW. After paying particular attention to reserve requirements and systems costs, the authors concluded that the value of PHES is very dependent on the flexibility of the conventional generation also on the system. The results also indicated that energy storage could reduce system costs, wind curtailment, and the amount of energy required for conventional generation. Krajačić *et al.* [145] analysed how Portugal could achieve a 100% renewable electricity system where wind and PHES played a key role. On a system with a maximum peak demand of 8777 MW, the authors indicated that approximately 6000 MW and 4500 GWh of storage is required, hence outlining the scale of storage necessary for integrating large-scale wind penetrations. As outlined in section 4.4.5, two previous studies [91, 92] also assessed the implications of PHES for increased wind penetrations on the All-Ireland electricity grid, with both concluding that the additional investment required for PHES exceeded the corresponding reduction in operating costs of the system.

In summary, the majority of island studies conclude that PHES reduces operating costs and increases the wind penetrations feasible. However, studies completed on national electric grids are more ambiguous and hence, it is difficult to assess if the results from the island studies are relevant to national energy systems. Therefore, this research will contribute to this debate by quantifying the maximum wind penetrations feasible on the Irish electric grid for

[7] National electricity systems refer to large-scale interconnected energy systems where the installed generating capacity is usually above 1 GW.

various capacities of PHES, by then investigating the economic savings associated with this additional wind energy, and also by comparing PHES to alternative technologies, while not only considering the electricity sector, but the heat and transport sectors also. The details and results from these analyses are outlined in chapter 8.

6.2.2. PHES and Electricity Markets

The dispatch of energy storage on deregulated electricity markets is another significant area of research in recent years. As a merchant unit, an energy storage facility will earn most of its revenue from the sale of electricity to the market [92, 146]. However, there is many ways that an energy storage facility can make a profit on these markets and hence, it is still unclear how they should be operated especially with increasing amounts of wind energy. Furusawa *et al.* analysed energy storage as a demand side management tool utilising electricity prices for domestic scale consumers [147]. Sioshansi *et al.* investigated the arbitrage value of small-scale energy storage for the PJM market in the USA [148], while Walawalkar and Mancini analysed the potential of sodium-sulphur batteries and flywheel energy storage systems in New York state's electricity market [149]. Kazempour *et al.* [150] completed an economic comparison between emerging (sodium-sulphur battery) and traditional (PHES) electric energy storage technologies assuming perfect pricing foresight one week in advance. Kazempour *et al.* created a scheduling tool for a group of hydro plants supplemented by a PHES facility [151], while Figueiredo and Flynn [108] optimised the size of two specific PHES plants in Alberta, Canada based on electricity arbitrage profits. Kanakasabapathy *et al.* [152, 153] created a bidding strategy for PHES based on day-ahead market prices, but assumed that pumping always takes place before generation, which may not be suitable for all electricity markets. Bathurst and Strbac [154] simulated the dispatch of an energy storage facility on day-ahead markets in conjunction with a wind farm, concluding that there is an optimal capacity of energy storage for maximising profits from a wind farm on energy markets. For the 10 MW wind farm considered by the authors, a 6 MW 36 MWh storage captured almost all of the additional revenue feasible from the addition an energy storage facility. Zhao and Davison [155] examined the dispatch of PHES facilities with water inflows on electricity markets, concluding that the dispatch of facilities with small inflows is very dependent on the daily variation in electricity prices, but for facilities with large inflows the dispatch is more dependent on water management and maximising the power generated by the facility.

In summary, there have been numerous studies that analysed the dispatch of PHES under very specific circumstances which do not reflect the procedures followed by PHES on some deregulated markets, including the Irish market. This includes a group of plants together [151], pumping always ahead of generation [152, 153], dispatch in conjunction with a single wind farm [154], and PHES plants with inflows [155]. Consequently, the final part of this research analyses a range of realistic operation strategies for a PHES on a deregulated electricity market like Ireland's, which is documented in chapter 9.

6.3. Conclusions

PHES is clearly a well-established, mature, and effective energy storage technology. As a result, there is very little research currently being published which focuses on the technology itself, but instead recent studies are typically related to the utilisation of wind energy in conjunction with PHES and the dispatch of PHES on deregulated electricity markets. The findings from this literature review are in agreement with those outlined by Wilson *et al.* [156], who identified a number of key issues that needed to be addressed for the development of electricity energy storage including the size, location, and market structure required for them. Hence, this study will add to the existing PHES literature by:

1. Developing a tool which will locate suitable locations for the construction of new freshwater PHES facilities and applying it to Ireland (chapter 7).
2. Identifying the additional wind energy feasible on the Irish energy system due to the addition of different PHES capacities (section 8.3).
3. Assessing the economic implications of additional wind and PHES on the Irish energy system (section 8.4).
4. Comparing PHES to alternative technologies which could also reduce the costs of operating the Irish energy system (section 8.4.4).
5. Creating new dispatch strategies for PHES on the Irish deregulated electricity market, which will maximise its profits when utilising electricity price arbitrage (chapter 9).

The results from these investigations will not only illustrate the feasibility, implications, and potential operation of PHES on existing energy systems, but they will also establish how PHES compares to completely different alternatives, which is often overlooked in existing research.

7. The Potential for Additional PHES in Ireland

As outlined in section 6.2, it is widely believed that suitable locations to construct PHES facilities are limited and hence it is one of the most crucial factors when evaluating its feasibility. Consequently, to quantify the potential PHES resource in Ireland, the number of suitable locations remaining had to be identified. Therefore, this chapter doesn't focus on the benefits of PHES, but instead the focus is on whether or not PHES is still technically a feasible option. Existing research carried out to identify suitable locations has usually been done manually with the aid of maps and therefore, it has been limited to specific areas [120, 121] or seawater facilities [90, 122, 157]. Although seawater PHES was successfully demonstrated when the first facility was built in 1999 [93], its capacity was only 30 MW compared to the 480 MW [157] and 100+ GWh [90] seawater sites that are currently being proposed for Ireland. As a result, there are still concerns surrounding the effects of these seawater facilities in relation to the technology itself and the surrounding landscape. In comparison, freshwater PHES has been in use for over 100 years and is thus a proven and well-established technology. Therefore, this study tried to establish the freshwater PHES resource in Ireland and to do so, a program was created that can scan a user-specified terrain and identify if there are technically suitable locations for the construction of freshwater facilities. The following chapter is an overview of the work reported in Appendix B and Appendix C.

7.1. Methodology

After assessing a range of geographic information system (GIS) tools for the development of the program, Atlas Computers' Survey Control Centre (SCC) was chosen [158]. The SCC is a unique land survey and modelling package which has been in development for 18 years. The inclusion of very advanced tools, such as dynamic cut to fill balancing, meant it was ideally suited for manipulating terrain and identifying if a suitable PHES site existed. Therefore, in this study an add-on module was developed which utilised the functionality of the SCC, but searched for PHES facilities specifically.

To begin, suitable terrain data was required. After an initial search, 'Digital Terrain Model' (DTM) data files were sourced from Ordinance Survey Ireland (OSI) [159], that provide a regular grid of x, y, and z points, at 10 m intervals for any area in Ireland. This data can be imported into the SCC software and processed to form a Delaunay Triangulated Irregular Network model (TIN). A TIN model displays the x, y, and z data as a 3D terrain that can then be analysed using different constraints (TIN modelling and its applications are discussed further in

Hjelle [160]). The add-on PHES module for the SCC utilised the TIN model to find adjacent polygonal areas of acceptable flatness, A_U and A_L, with a minimum acceptable vertical separation, *H*, and a maximum acceptable horizontal separation, *d*, as portrayed in Figure 7-1. The program created could only identify regular shaped polygons as the areas for the reservoirs, and hence a circle was chosen.

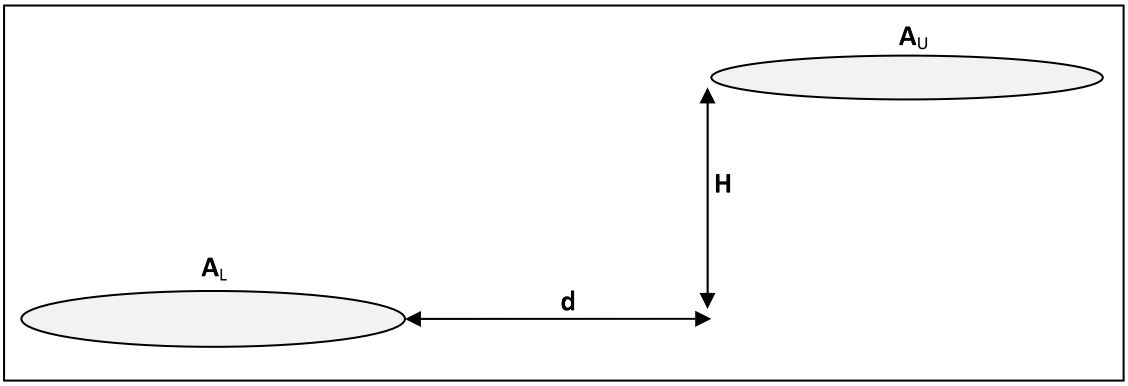


Figure 7-1: Area and parameters utilised by the SCC computer program to search for PHES.

The upper and lower reservoir areas identified by the program had to be flat. Flatness in this case is specified in terms of the maximum allowable 'cut' and 'fill' excavation volumes, E_U and E_L, which are required to construct a polygon at an arbitrary datum, where the software selects an optimal value for that datum. In other words, the level of flatness required was specified by quantifying the maximum amount of earth that could be moved in order to make the site flat, *E*, as displayed in Figure 7-2. The earth that needs to be moved to make the area flat must be obtained within the investigated site i.e. the circular area. There was an E value for the upper reservoir, E_U, and an E value for the lower reservoir, E_L.

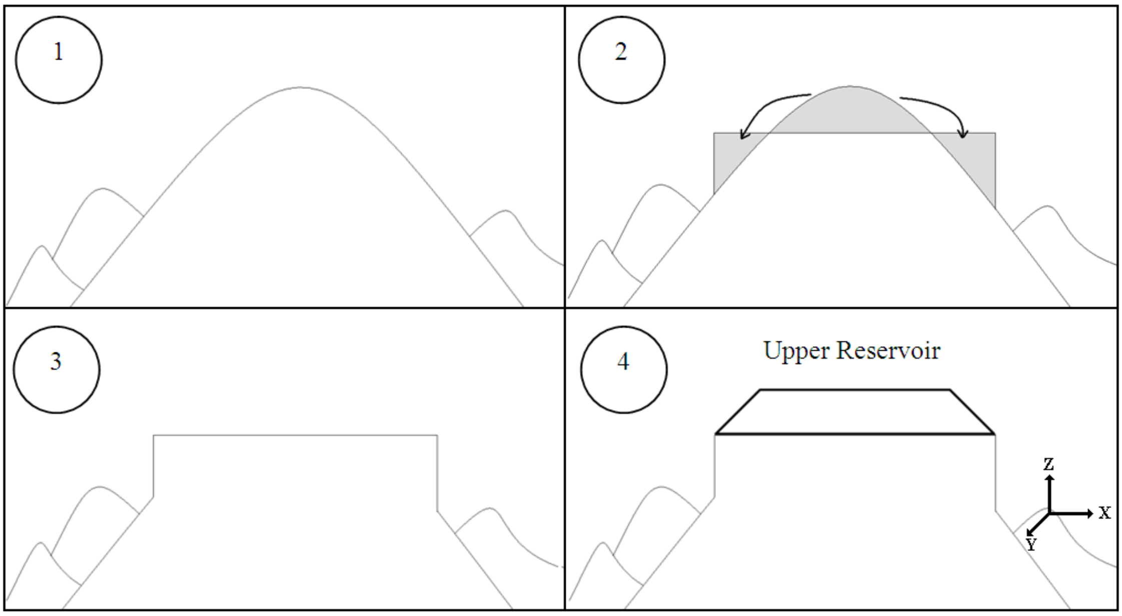


Figure 7-2: Earth moving procedure within the program to make the investigated area flat for PHES.

Initially, the search was iterated at a specified plan interval, *FR*, in the x and y axes over the entire area being analysed for potential lower reservoir sites. On finding such a site, the border of that site was searched radially for upper reservoir sites over a specified interval, *SR*. Determining 'flatness' required modelling the polygon representing the reservoir area, and vertically searching over a specified interval, *SV*, for an optimal datum where the volumes of cut and fill material to be excavated to construct the reservoir were the same. Thus the parameters required for each search are displayed in Table 7-1 below.

Table 7-1: Parameters used by the SCC software to identify potential PHES facilities.

Name	Symbol	Unit
Polygon area for upper reservoir	A_U	m^2
Polygon area for lower reservoir	A_L	m^2
Minimum acceptable vertical separation	H	m
Maximum acceptable horizontal separation	d	m
Flatness / maximum excavation volume for upper reservoir	E_U	m^3
Flatness / maximum excavation volume for lower reservoir	E_L	m^3
Grid search interval for lower reservoir	FR	m
Radial search interval for upper reservoir	SR	m
Vertical search tolerance for 'flatness'	SV	m

To verify the PHES algorithm worked as designed, a series of test cases were created that comprised of artificially generated terrain data similar to that displayed in Figure 7-3. Boundary value analysis [161] was employed to produce a suitable set of test cases. These test terrains were generated containing locations where all search criteria were met, to ensure the search worked as anticipated. Subsequently, additional test cases where all but one of the search criteria were met, were also created in order to ensure that the algorithm did not produce any false positives. Multiple versions of each test case were generated at either side of the boundaries of each parameter under test, to verify the search tolerances were working correctly.

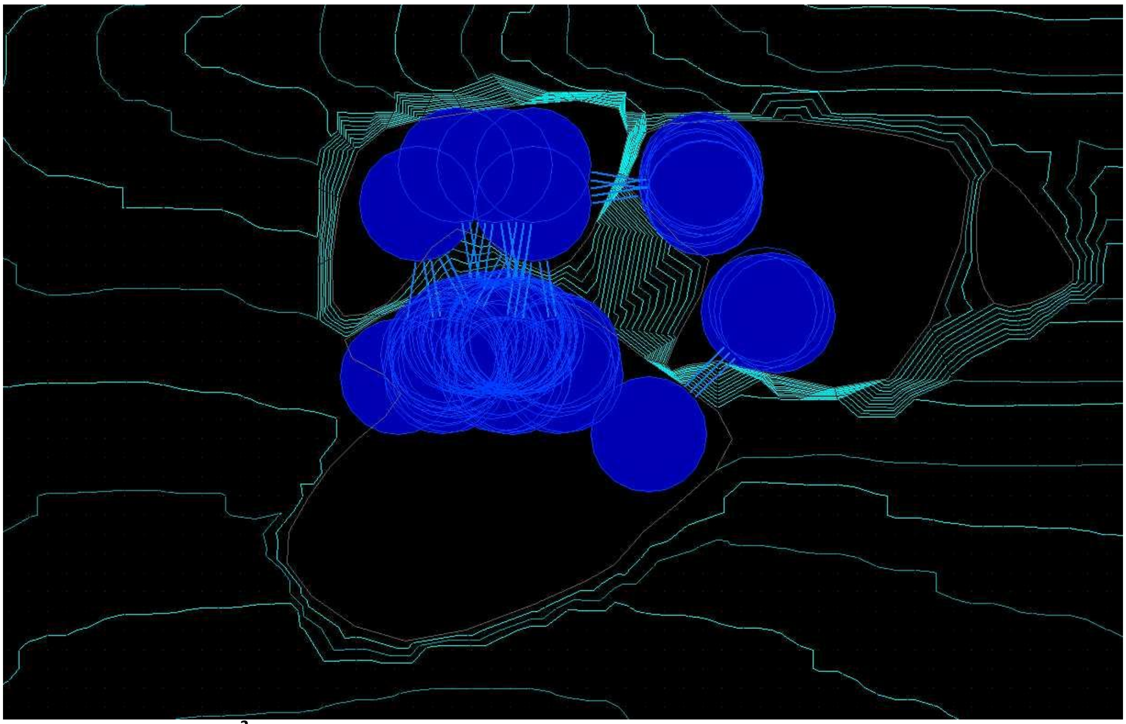


Figure 7-3: A 1 km^2 artificially created terrain for testing the PHES module in the SCC software.

Once testing was completed using artificial data, the software was then tested on an existing PHES site, Turlough Hill, which is the only freshwater PHES in Ireland (see Figure 7-4a). As displayed in Figure 7-4b, the program identified numerous positive results at this site indicating that the program was functioning correctly. In addition, the results could be combined with one another, which is displayed in Figure 7-4c, to create an accurate representation of the maximum potential reservoir that could be constructed at that site. Based on the results obtained during this testing phase, it was concluded that the program was operating correctly.

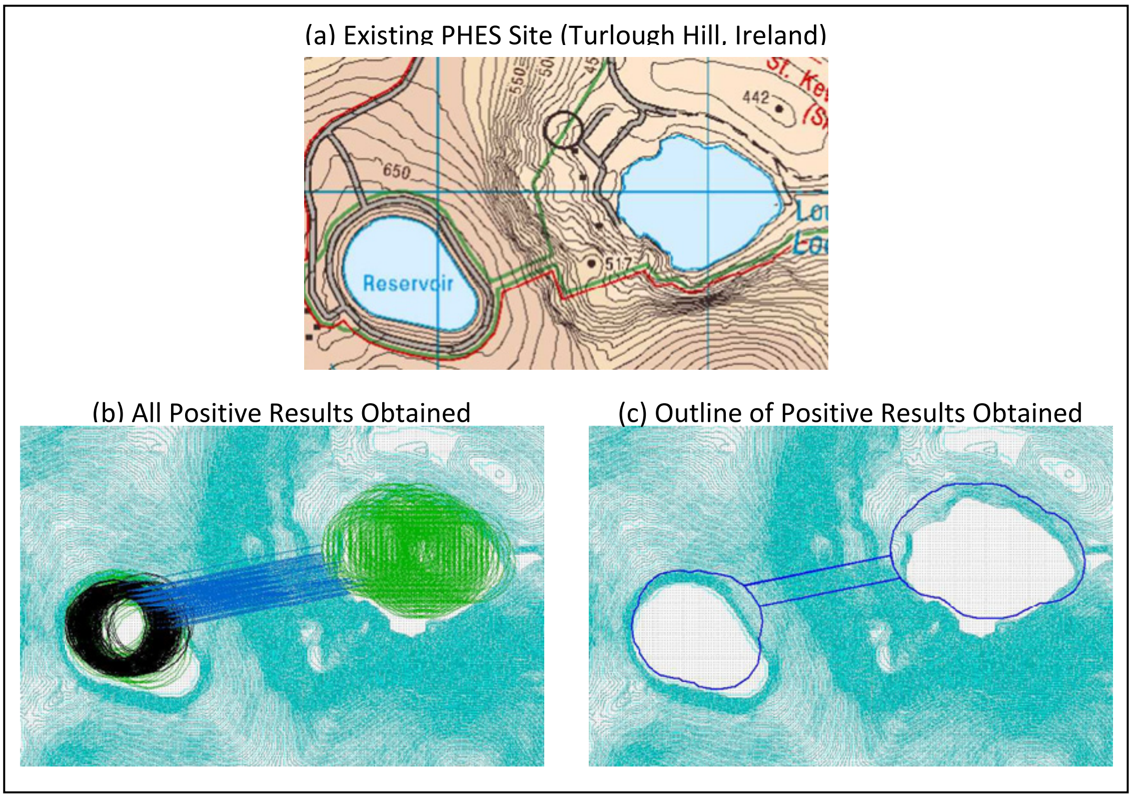


Figure 7-4: Results obtained (b, c) when the new program was tested on an existing PHES facility: Turlough Hill in Ireland (a).

7.2. Capacity and Cost Calculator

The SCC software is specifically designed to identify locations which have suitable topographical conditions for constructing PHES and hence, a separate program was designed to convert these results into PHES capacities and costs, which is displayed in Figure 7-5. The underlying equations used in the calculator for the power and storage capacities are Equations 1 and 2, which have been discussed in section 6.1. Six different variables are required to calculate the power and storage capacities using these equations. However, the program assumes that reservoirs can be constructed at a site because it can be made flat. To do so, a reservoir wall must be constructed similar to that displayed in Figure 7-6. Therefore, the reservoir volume, V, must be calculated using the reservoir area, A_L or A_U, and the assumed reservoir wall height, R_H from:

$$V = AR_H \tag{3}$$

Consequently, there are now seven variables necessary to convert the results from the SCC software into PHES capacities, which are displayed in Table 7-2. Two of these, A and H, are outputs from the SCC software, while two others, g and ρ, are constants. Therefore, assumptions had to be developed for the volumetric flow rate, Q, the height of the reservoir wall, R_H, and the round-trip efficiency of the PHES, η_{PHES}.

Energy Storage Capacity & Cost Calculator		
Capacity and Cost of Energy Storage		
Pump Capacity	**213**	MW
Turbine Capacity	**213**	MW
Storage Capacity	**2489**	MWh
Total Annual Costs	**11.732**	M€/year
Geological Parameters of Energy Storage Facility		
Head	250	m
Area of Reservoir	120,000	m^2
Height of Reservoir	35	m
Volume of Reservoir	4,200,000	m^3
Density of Water	1000	kg/m^3
Acceleration Due to Gravity	9.81	m/s^2
Technical Parameters of the Technologies		
Penstock Flow Rate	100	m^3/s
Pump Efficiency	87%	%
Generation Efficiency	87%	%
Financial Parameters		
Lifetime	40	years
Interest Rate	6%	(Fixed Repayment Loan)
Annual Fixed O&M Costs	1.5%	% of Annual Investment
Capital Cost of Pump	0.250	M€/MW
Capital Cost of Turbine	0.250	M€/MW
Capital Cost of Storage	15.000	M€/GWh
Total Investment		
Pump	53.342	M€
Turbine	53.342	M€
Storage	37.339	M€
Total	**144.023**	**M€**
Annual Loan Repayments (Million €/year)		
Pump	3.545	M€/year
Turbine	3.545	M€/year
Storage	2.482	M€/year
Total	**9.572**	**M€/year**
Annual Fixed Operation & Maintenance Costs (Million €/year)		
Pump	0.800	M€/year
Turbine	0.800	M€/year
Storage	0.560	M€/year
Total	**2.160**	**M€/year**

Figure 7-5: User-interface of the Energy Capacity and Cost Calculator.

Figure 7-6: PHES upper reservoir (of Taum Sauk PHES in the USA) with a man-made reservoir wall [162].

Table 7-2: Variables used for converting the program parameters into energy capacities.

Variable	Symbol	Value	Unit
Reservoir area	A	-	m^2
Head	H	-	m
Volumetric flow rate through pump/turbine unit	Q	-	m^3/s
Reservoir-wall height	R_H	-	m
Volume of water that can be utilised	V	-	m^3
Acceleration due to gravity	g	9.81	m/s^2
Density of water	ρ	1000	kg/m^3
Round-trip efficiency of PHES	η_{PHES}	-	-

To establish realistic assumptions, the parameters at existing PHES facilities were investigated [163]. The flow rate is dependent on the size of the turbine and penstock with typical values ranging from 50 m^3/s to 150 m^3/s. In relation to reservoir height, existing man-made reservoirs have been constructed in excess of 20 m. For example, Coo-Trois-Ponts PHES in Belgium has a reservoir wall that is 47 m high, Revin PHES in France has a reservoir that is 20 m high, and Turlough Hill PHES in Ireland has a reservoir that reaches heights up to 30 m. Finally, pump and turbine efficiencies are not only dependent on the technology used, but also on the way the PHES facility is operated i.e. as a grid asset or as a merchant unit [92]. Due to the broad range of parameters that could be correctly assumed for the flow rate, wall height, and efficiencies when calculating potential capacities at suitable locations, a range of parameters were included in the calculator, which are outlined in Table 7-3. These are pre-defined values which can be selected from the green cells displayed in Figure 7-5. This enables the user to evaluate the sensitivity of a site based on typical parameters found at existing PHES facilities. Note that the parameters are not related to one another in any way. A minimum value for the penstock flow rate could be combined with a maximum height for the reservoir wall. Therefore, the user can specify the value for each parameter individually. Once a user has inputted the results from the PHES search and selected values from the pre-defined parameters, the power and storage capacity of that site are displayed in the yellow boxes of the calculator, which are again illustrated in Figure 7-5.

Table 7-3: Predefined parameters included in the Energy Capacity and Cost Calculator (see green cells in Figure 7-5).

Parameter	Minimum	Medium	Maximum
Height of Reservoir (m)	20	35	50
Penstock Flow Rate (m^3/s)	50	100	150
Pump Efficiency (%)	82	87	92
Generation Efficiency (%)	82	87	92
Lifetime (years)	30	40	50
Real Interest Rate (%)	3	6	9

The orange inputs in Figure 7-5 are used for evaluating the costs of a PHES facility. These are fully editable as costs can vary substantially with each site and also over time. However, as outlined in Table 7-3 predefined values have been included for the lifetime, *n*, and the interest rate, *i*, within the calculator. The annual repayment costs, I_{Annual}, are calculated based on the unit investment cost (I) and capacity (C) for the pump (P), turbine (T), and storage (S), as well as the fixed operation and maintenance costs, $O\&M_{Fixed}$, according to Equation 4 below.

$$I_{Annual} = \left(I_{Pump}C_{Pump} + I_{Turbine}C_{Turbine} + I_{Storage}C_{Storage}\right)\left\{\left[\frac{i}{1-(1+i)^{-n}}\right] + O\&M_{Fixed}\right\} \quad (4)$$

Finally, none of the blue inputs in the calculator can be edited to ensure the validity of the results produced by the software. However, it is important that a user understands the accuracy of their inputs when using the calculator. A disclaimer and a full list of instructions is provided in the calculator software, which can be downloaded from [164].

7.3. Results and Discussion

Firstly, an initial analysis (which is discussed in detail in Appendix B) was carried out on a 20 km x 40 km area in Ireland which is illustrated in Figure 7-7. The region analysed was limited due to the costs associated with purchasing the required data files and the cost of computer processing time for completing the analysis. Three different searches were completed over this area using the parameters illustrated in Table 7-4.

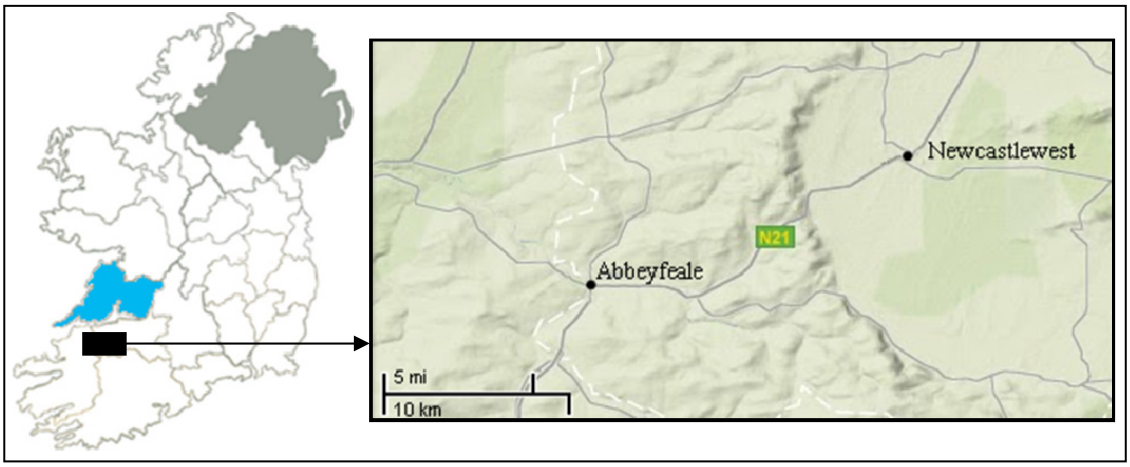


Figure 7-7: Black area was searched for the initial analysis completed with the software and County Clare is highlighted in blue, which was also searched afterwards.

Table 7-4: Parameters used for the three different searches carried out during the initial analysis.

Parameter	First Search	Second Search	Third Search	Unit
A_U	120,000	180,000	70,000	m^2
A_L	120,000	120,000	70,000	m^2
H	200	150	200	m
d	1000	1000	1000	m
E_U	300,000	400,000	200,000	m^3
E_L	300,000	300,000	200,000	m^3
FR	50	50	40	m
SR	10	10	10	m
SV	0.5	0.5	0.5	m

Using these parameters, five potential PHES sites were identified, which are illustrated in Figure 7-8. For the purposes of this initial investigation, the capacity of all sites were calculated using the same efficiency, flow rate, and reservoir wall height that exists at Ireland's only PHES facility, Turlough Hill. The average annual round-trip efficiency of Turlough Hill in 2007 was 63.9% [165], so a pump efficiency of 80% and a generating efficiency of 80% were assumed. The flow rate at Turlough Hill is 113 m^3/s and the upper reservoir was constructed at a maximum height of 30 m [166]. Based on these assumptions, it was calculated that the five sites identified in this initial search had a combined capacity of approximately 700 MW and 9 GWh. One specific site, which is highlighted in green in Figure 7-8, had a capacity of approximately 180 MW and 1.5 GWh. Considering the capacity of Turlough Hill is 292 MW and 1.7 GWh, the scale of the sites identified are significant for the Irish electric grid. In addition, it is worth noting that the area analysed here was only 800 km^2, which is approximately 1% of the total island of Ireland [167, 168].

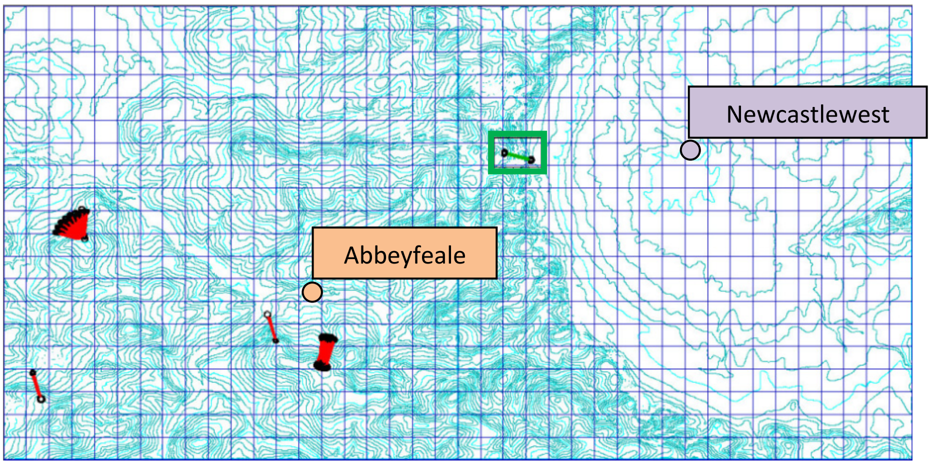


Figure 7-8: Potential PHES sites identified after the initial analysis using the parameters displayed in Table 7-4. The green site was found in the first search and the red sites in the second search.

In summary, the primary goal of this initial analysis was to identify the frequency and scale of freshwater PHES sites in Ireland. After locating five potential sites of such significant scale within only 1% of the island of Ireland, the initial analysis indicated that large-scale freshwater PHES is technically feasible in Ireland.

Based on the positive results in the initial analysis, funding was secured to carry out a more elaborate search of County Clare in Ireland, which is discussed in detail in Appendix C. County Clare has a total area of approximately 3150 km^2 and is highlighted in Figure 7-7. The search was carried out in line with the "Strategic Wind Farm Development Areas" contained in the Clare Wind Energy Strategy [169], so the county was divided into the following sections and given this preference (see Figure 7-9):

1. Strategic Areas (Blue).
2. Acceptable in Principle (Green).
3. Open to Consideration (White).

Although areas defined as "Not Normally Permissible (Red)" were included in the search, results within this area were deemed unacceptable.

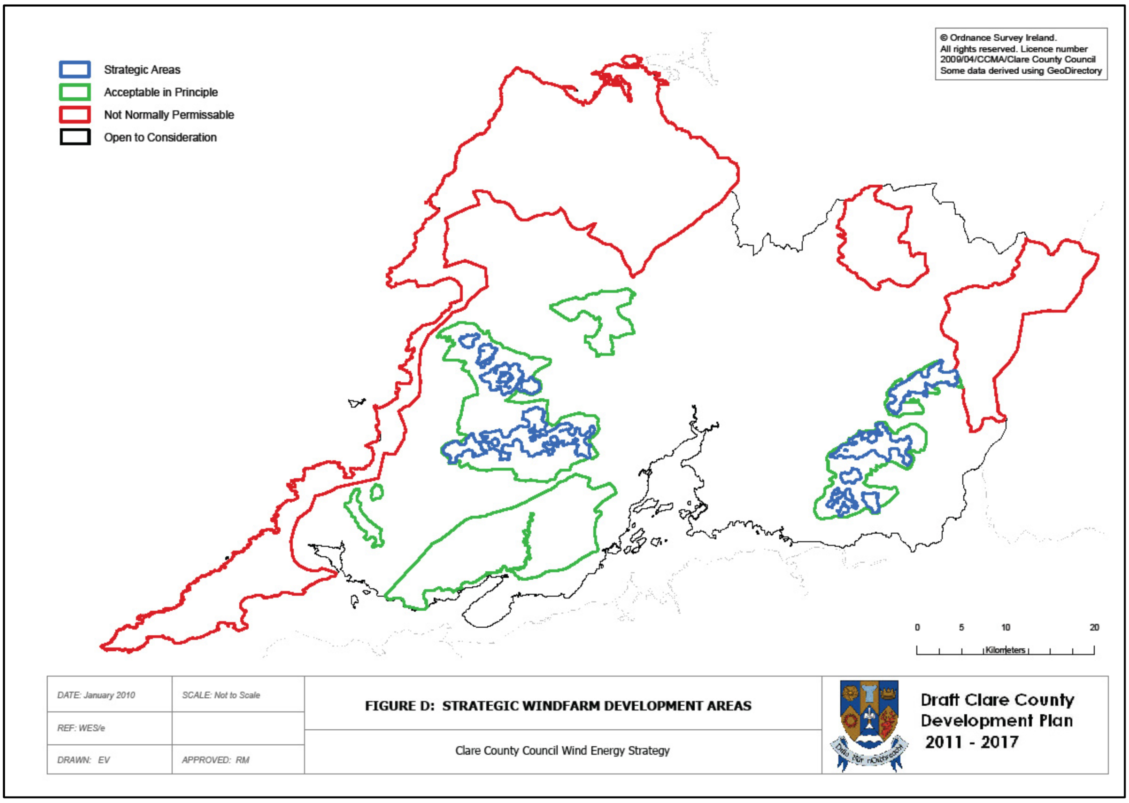


Figure 7-9: Division of County Clare for the PHES search.

A detailed list of the search criteria used by the software to search County Clare for PHES sites is provided in Table 7-5. To locate potential reservoir sites that were shaped liked irregular polygons, initial searching was carried out using circles of 100 m in radius, and where multiple adjacent sites were found these were combined. After being combined, if the multiple adjacent sites did not meet the area criteria specified in Table 7-5, then they were discarded.

Table 7-5: Search criteria specified to identify potential locations for PHES in County Clare.

Parameter	Symbol	Value	Unit
Area (minimum) of upper reservoir	A_U	120,000	m^2
Area (minimum) of lower reservoir	A_L	120,000	m^2
Height (minimum) between reservoirs	H	200	m
Distance (horizontal) between reservoirs	d	3000	m
Flatness at upper reservoir (maximum earth to be moved to make a flat base)	E_U	500,000	m^3
Flatness at lower reservoir (maximum earth to be moved to make a flat base)	E_L	500,000	m^3
Vertical search tolerance for “flatness”	SV	0.5	m
Radial search interval for upper reservoir	SR	3	m
Grid search interval for lower reservoir	FR	50	m

Based on the technical criteria defined, 14 separate locations were identified that had suitable parameters for the construction of PHES in County Clare. However, due to the area restrictions, only 8 of these locations were classified as acceptable, which are outlined in Figure 7-10. It should be noted that a range of different upper and lower reservoir combinations could be chosen at each location identified. Therefore, although 8 locations have been identified in this search, there are a much greater number of individual PHES facilities that could be constructed.

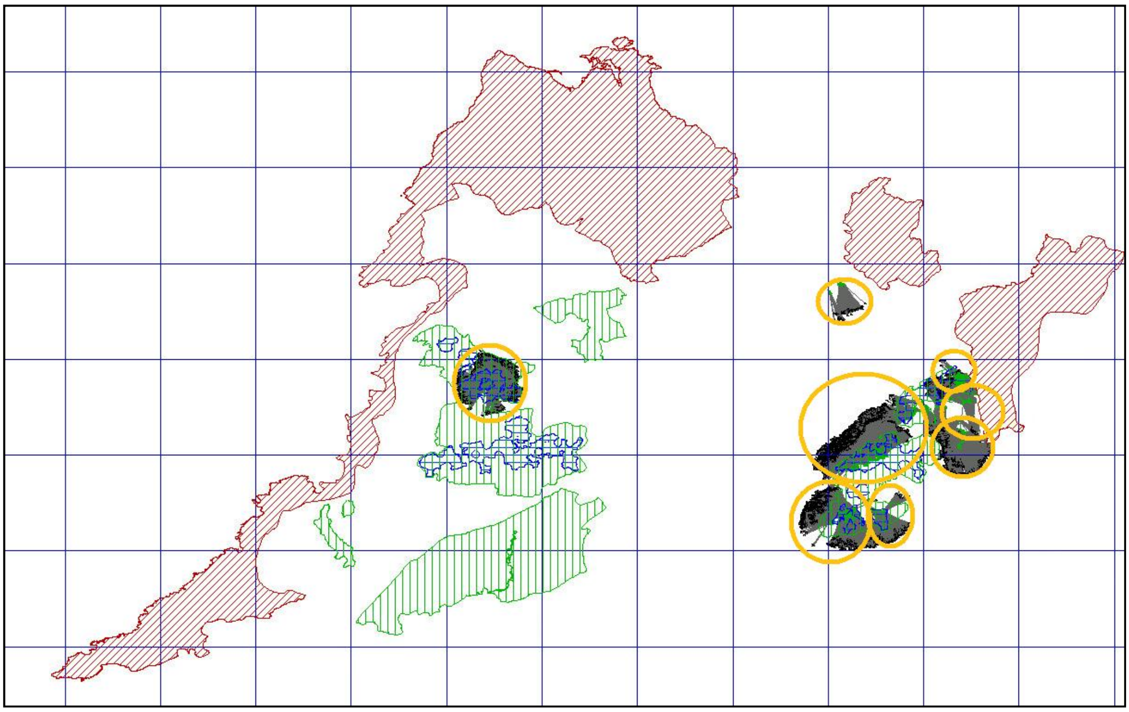


Figure 7-10: Potential freshwater PHES sites found within acceptable areas of County Clare.

To examine the type of sites which are available in County Clare, the initial sites were limited to those with a head greater than 250 m. As outlined in Figure 7-11, this reduced the number of potential locations to 5. Then, three unique sites were chosen from the remaining five locations for further analysis. One site was chosen from Area 1 of Figure 7-11 as it was the only site which was entirely located in the area of strategic interest for wind farm development and hence it was called “TotalArea”. The site chosen in Area 2 had the largest reservoir area found and was called “BigReservoir”. Finally, the site in Area 3 had the largest vertical head identified and was named “BigHead”. Due to these unique characteristics, the capacities feasible at these three sites will illustrate the range of PHES capacities feasible in County Clare.

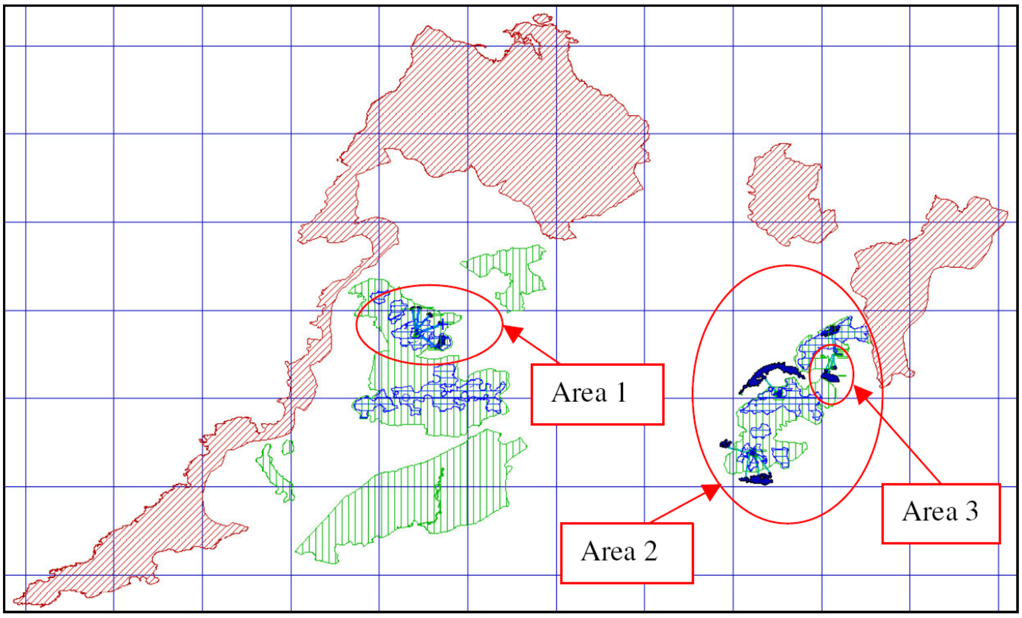


Figure 7-11: Potential PHES sites found within acceptable areas of County Clare with a head greater than 250 m.

The size and cost of these PHES facilities were assessed using the calculator in Figure 7-5. In addition, a detailed discussion and a sensitivity analysis are available in Appendix C for each of the three sites. In summary, the maximum capacity that could be constructed at each of these three sites is displayed in Table 7-6. Once again, compared to Ireland's current PHES capacity of 292 MW and 1.7 GWh, the PHES facilities feasible in County Clare are very big, especially in relation to their potential storage capacities. The largest power capacity feasible at a single site in County Clare was estimated at 570 MW, which is almost double the existing PHES capacity in Ireland, while the total power capacity at the three sites could be approximately 1300 MW.

Table 7-6: Capacities for a selection of PHES facilities found in County Clare based on the max technical parameters defined in Table 7-3*.

Capacity Results	TotalArea	BigReservoir	BigHead
Pump Capacity (MW)	405	340	570
Turbine Capacity (MW)	405	340	570
Storage Capacity (GWh)	15.4	22.5	12.7

***These are indicative values only based on existing PHES facilities. Hence, new facilities could vary.**

Similarly, the maximum storage capacity at one site was estimated at 22.5 GWh, which is over 13 times the existing storage capacity in Ireland. However, it is unlikely that a storage capacity this large would ever be profitable, so for the economic analysis a smaller storage capacity corresponding to a 12 hour discharge was assumed. As displayed in Table 7-7, the total annual investment costs for the three PHES facilities would be approximately €20-30M/year for a power capacity of approximately 300-600 MW and a storage capacity of 4-7 GWh respectively.

This corresponds to a total investment over the lifetime of the facilities of approximately €230-390 million. It is worth stressing once again that these cost calculations are based on typical construction costs and borrowing costs which have previously been reported [96, 170]. Therefore, they are indicative only and the actual costs could vary substantially depending on the site-specific construction costs and the financial parameters agreed for the construction of this facility.

Table 7-7: Cost of the selected PHES facilities found in County Clare based on a 6 hour discharge and the medium economic parameters defined in Table 7-3*.

Capacity Results	TotalArea	BigReservoir	BigHead
Pump Capacity (MW)	405	340	570
Turbine Capacity (MW)	405	340	570
Storage Capacity (GWh)	4.9	4.1	6.8
Cost Results	TotalArea	BigReservoir	BigHead
Total Annual Costs (€M/year)	23	19	32
Total Investment (€M)	276	230	387

***These are indicative values only based on existing PHES facilities. Hence, new facilities could vary.**

7.4. Conclusions

In total, five potential sites were located when an 800 km^2 area of Ireland was searched during the first analysis with the program. Due to their cumulative estimated power capacity of approximately 700 MW and 8.6 GWh, it is evident that the program is capable of identifying potential freshwater PHES sites. In addition, the program is capable of identifying sites that may otherwise go unnoticed, as it can identify sites after the earth has been modified. To supplement the PHES search program, a spreadsheet calculator has also been created which can convert the PHES search results into estimated capacities and costs, based on predefined assumptions for a number of key variables.

Using both the PHES search program and the calculator, a detailed search and analysis of potential freshwater PHES sites in County Clare was carried out. Overall 14 locations were identified in County Clare where freshwater PHES facilities could be constructed, but only 8 of these were in acceptable areas of the county. After analysing three potential PHES facilities which could be constructed at these locations, it was estimated that one site alone in County Clare could have a power capacity up to 570 MW and a storage capacity up 22.5 GWh, at a total investment cost of approximately €230-390M. However, the specific capacities and costs determined are not the most significant results from this chapter. Instead it is the scale and frequency of technically feasible PHES sites which can be constructed in Ireland. In total, 19 separate locations have already been established after searching approximately 5% of the island of Ireland. Therefore, the most significant conclusion from this chapter is that Ireland has a significant freshwater PHES resource and the availability of technical suitable sites is no longer a limiting factor. This outcome is in agreement with a very recently published article, which assessed the feasibility of PHES in the United States [171]. Here, Yang and Jackson concluded that "the main limiting factors for PHES appear to be environmental concerns and financial uncertainties rather than the availability of technically feasible sites" [171]. As a result, the next stage in this research will try to examine the implications of additional PHES (chapter 8) and how PHES can be accommodated on deregulated electricity markets (chapter 9).

8. The Implications of Additional PHES in Ireland

So far, this research concluded in chapter 5 that PHES is the most likely large-scale energy storage technology to be deployed for the integration of fluctuating renewable energy, while it is evident from chapter 7 that PHES is still technically a feasible option for Ireland. Therefore, the next objective in this research is to investigate the implications of adding PHES to the Irish energy system. Implications in this research refer to two key issues: technical and economical. From a technical perspective, the objective is to identify how much additional wind power can be added to the Irish energy system with the introduction of large-scale energy storage. From an economic perspective, the objective is to calculate if the fuel savings realised from the additional wind power feasible as a result of energy storage, will pay for the initial investment costs required to construct them. This chapter is a summary of the work completed in Appendices D, E, F, and G.

8.1. Methodology

A broad range of issues need to be considered when evaluating the implications of PHES on an energy system including the size, operation, output, and costs of the energy system and all of its components. Due to the complexity of the problem proposed, the range of technologies that need to be considered, and the methodologies proposed in other similar studies [89, 102, 103, 123-138, 140], it was evident that a computer tool[8] would be necessary to answer the questions proposed in this chapter. Therefore, the first task was to carry out a review of existing computer tools, to identify if there were any which could be used to model the implications of PHES on the Irish energy system.

Appendix D gives a detailed account of the review which was completed to identify a suitable computer tool. It outlines the methodology undertaken to assess each energy tool, the corresponding results, provides an individual description about each of the energy tools reviewed, and gives a sample of the existing studies completed using each of the tools. Therefore, these will not be discussed in detail here, but instead the results and primary conclusions are discussed.

[8] Energy tools are used to create energy models: Therefore, a computer program discussed here is referred to as a 'tool', which can be used to create various types of models.

8.1.1. Review of Energy Tools

To obtain a detailed understanding of the energy tools analysed, a survey was completed (using SurveyXact [172]) and distributed to a number of tool developers: a short summary of the survey can be seen in Appendix D. In summary, the survey consisted of five sections:

A. Background information: an insight into the background of the respondent.
B. Users: who and how many people were using the tool, and how the tool could be obtained?
C. Tool properties: basic characteristics about the type of tool in question.
D. Applications: what applications *can* the tool be used for and what applications is it *typically* used for?
E. Case studies: how was the tool previously used with a specific focus on renewable energy?
F. Further information: the respondents provided a description of the tool in their own words, listed the tools they had previously known before this review, and answered general queries about the process of this study.

After the surveys were answered and returned by the tool developers, the results were used to generate a range of tables which compared the tools along with a detailed description of each one. The tables act as a directory by providing a concise overview of each tool, while the paragraphs (which are available in Appendix D) provide a more in depth discussion where further information is required.

Initially, 68 energy tools were considered for the review, but as displayed in Table 8-1 only 37 of these were included in the final analysis. Table 8-1 also provides the most appropriate web-link available, along with a brief description of a typical application for each energy tool reviewed. The organisations responsible for each of the 37 tools reviewed, along with their availability, and number of downloads/sales are displayed in Table 8-2. From discussions with the tool developers, it became apparent that there is no common language shared amongst them which classifies the different types of energy tools. Consequently, to ensure that the tools were described correctly, a common language was created and distributed to the developers. Seven different tool types were defined, which can be used exclusively or collectively to describe an energy tool. The energy tool types are:

1. A simulation tool simulates the operation of a given energy system to supply a given set of energy demands. Typically a simulation tool is operated in hourly time-steps over a one-year time period.
2. A scenario tool usually combines a series of years into a long-term scenario. Typically scenario tools function in time-steps of one year and combine such annual results into a scenario of typically 20 to 50 years.

3. An equilibrium tool seeks to explain the behaviour of supply, demand, and prices in a whole economy or part of an economy (general or partial) with several or many markets. It is often assumed that agents are price takers and that equilibrium can be identified.
4. A top-down tool is a macroeconomic tool using general macroeconomic data to determine growth in energy prices and demands. Typically top-down tools are also equilibrium tools (see 3).
5. A bottom-up tool identifies and analyses the specific energy technologies and thereby identifies investment options and alternatives.
6. Operation optimisation tools optimise the operation of a given energy system. Typically operation optimisation tools are also simulation tools (see 1) optimising the operation of a given system.
7. Investment optimisation tools optimise the investments in an energy system. Typically optimisation tools are also scenario tools (see 2) optimising investments in new energy stations and technologies.

These definitions were then used to define each tool reviewed, which is illustrated in Table 8-3. The different types of analyses that can be completed with each of the tools are displayed in Table 8-4. Also, the energy sectors considered by each tool along with the renewable energy penetrations already simulated are shown in Table 8-5. By combining the details in Table 8-1 to Table 8-5 with the detailed descriptions in Appendix D, a suitable tool can be identified for different investigations. These investigations vary from small renewable penetrations where they do not influence the energy system significantly, to penetrations where renewables begin to compete with conventional production and even to penetrations where renewable technologies replace conventional technologies.

Table 8-1: Tools considered in the review and the status of their inclusion in the final analysis.

Considered and Included [website]: Description of a typical application		Considered but Not Included	
AEOLIUS [173]: Power plant dispatch simulation tool	BALMOREL [174]: Open source electricity and district heating tool	BESOM	CEEM
BCHP Screening Tool [175]: Assesses CHP in buildings	COMPOSE [176]: Techno-economic single project assessments	CEPEL	CHP Capacity Optimizer
E_4cast [177]: Tool for energy projection, production, and trade	EMCAS [178]: Creates techno-economic models of the electricity sector	CHPSizer	CO2BD
EMINENT [179]: Early stage technologies assessment	EMPS [180]: Electricity systems with thermal/hydro generators	DER-CAM	DIMES
EnergyPLAN [181]: User friendly analysis of national energy systems	energyPRO [182]: Techno-economic single project assessments	DREAM	E3database
ENPEP-BALANCE [183]: Market-based energy system tool	GTMax [184]: Simulates electricity generation and flows	EFOM	Elfin
H_2RES [185]: Energy balancing models for Island energy systems	HOMER [186]: Techno-economic optimisation for stand-alone systems	Endur	GmbH
HYDROGEMS [187]: Renewable and H_2 stand-alone systems	IKARUS [188]: Bottom-up cost-optimisation tool for national systems	GREET	H2A Analysis
INFORSE [189]: Energy balancing models for national energy systems	In*vert* [190]: Simulates promotion schemes for renewable energy	HUD CHP Screening Tool	HyDIVE
LEAP [191]: User friendly analysis for national energy systems	MARKAL/TIMES [192]: Energy-economic tools for national energy systems	HYPRO	HyTrans
MESAP PlaNet [193] Linear network models of national energy systems	MESSAGE [194]: National or global energy systems in medium/long term	MENSA	MOREHyS
MiniCAM [195, 196]: Simulates long-term, large-scale global changes	NEMS [197]: Simulates the US energy market	NESSIE	PSAT
ORCED [198]: Simulates regional electricity-dispatch	PERSEUS [173]: Family of energy and material flow tools	PSR	Ready Reckoner
PRIMES [199]: A market equilibrium tool for energy supply and demand	ProdRisk [200]: Optimises operation of hydro power	Samplan	SEDS
RAMSES [201]: Simulates the electricity and district heating sector	RETScreen [202]: Renewable analysis for electricity/heat in any size system	SGM	TESOM
SimREN [203]: Bottom-up supply and demand for national energy systems	SIVAEL [204]: Electricity and district heating sector tool	UREM	
STREAM [205]: Overview of national energy systems to create scenarios	TRNSYS16 [206]: Modular structured models for community energy systems		
UniSyD3.0 [207]: National energy systems scenario tool	WASP [208]: Identifies the least-cost expansion of power plants		
WILMAR Planning Tool [75]: Increasing wind in national energy systems			

Table 8-2: Tool information and the number of users in terms of downloads/sales.

Tool	Organisation (Link)	Availability	Downloads / Sales
	Very High Number of Users		
RETScreen	RETScreen International (http://www.retscreen.net/)	Free to Download	>200000
HOMER	National Renewable Energy Laboratory and HOMER Energy LLC (www.homerenergy.com)	Free to Download	>28000
LEAP	Stockholm Environment Institute (http://www.energycommunity.org/)	Commercial / Free for developing countries and students	>5000
BCHP Screening Tool	Oak Ridge National Laboratory (http://www.ornl.gov/)	Free to Download	>2000
energyPRO	Energi-Og Mijødata (EMD) International A/S (http://www.emd.dk/)	Commercial	>1000
	High Number of Users		
EnergyPLAN	Aalborg University (http://www.energyplan.eu/)	Free to Download	100-1000
In*vert*	Energy Economics Group, Vienna University of Technology (http://www.invert.at/)	Free to Download	100-1000
MARKAL/TIMES	Energy Technology Systems Analysis Program, International Energy Agency (http://www.etsap.org/)	Commercial	100-1000
MESSAGE	International Institute for Applied Systems Analysis (http://www.iiasa.ac.at/)	Free / Simulators must be purchased	100-1000
ORCED	Oak Ridge National Laboratory (http://www.ornl.gov/)	Free to Download	100-1000
TRNSYS16	The University of Wisconsin Madison (http://sel.me.wisc.edu/trnsys/)	Commercial	100-1000
WASP	International Atomic Energy Agency (http://www.iaea.org/OurWork/ST/NE/Pess/PESSenergymodels.shtml)	Commercial / Free to IAEA member states	100-1000
	Medium Number of Users		
EMCAS	Argonne National Laboratory (http://www.dis.anl.gov/projects/emcas.html)	Commercial	20-50
EMPS	Stiftelsen for Industriell og Teknisk Forskning (SINTEF) (http://www.sintef.no/)	Commercial	20-50
ENPEP-BALANCE	Argonne National Laboratory (http://www.dis.anl.gov/projects/Enpepwin.html)	Free to Download	20-50
GTMax	Argonne National Laboratory (http://www.dis.anl.gov/projects/Gtmax.html)	Commercial	20-50
	Low Number of Users		
AEOLIUS	Institute for Industrial Production, Universität Karlsruhe (http://www-iip.wiwi.uni-karlsruhe.de/)	Commercial	1-20
COMPOSE	Aalborg University (http://www.socialtext.net/energyinteractivenet/index.cgi?compose)	Free to Download	1-20
IKARUS	Research Centre Jülich, Institute of Energy Research (http://www.fz-juelich.de/ief/ief-ste/index.php?index=3)	Commercial / Earlier versions are free	1-20
INFORSE	The International Network for Sustainable Energy (http://www.inforse.org/europe/Vision2050.htm)	Distributed to non-governmental organisations	1-20
Mesap PlaNet	seven2one (http://www.seven2one.de/de/technologie/mesap.html)	Commercial	1-20
NEMS	Office of Integrated Analysis and Forecasting, Energy Information Administration (http://www.eia.doe.gov/)	Free / Simulators must be purchased	1-20
PERSEUS	Institute for Industrial Production, Universität Karlsruhe (http://www-iip.wiwi.uni-karlsruhe.de/)	Commercial: only sold to large European utilities	1-20
ProdRisk	Stiftelsen for Industriell og Teknisk Forskning (SINTEF) (http://www.sintef.no/Home/)	Commercial	1-20
RAMSES	Danish Energy Agency (http://www.ens.dk/)	Projects completed for a fee	1-20
SIVAEL	Energinet.dk (http://www.energinet.dk/en/menu/Planning/Analysis+models/Sivael/SIVAEL.htm)	Free to Download	1-20
EMINENT	Instituto Superior Técnico, Technical University of Lisbon (http://carnot.ist.utl.pt/~eminent2/)	To be decided	0
PRIMES	National Technical University of Athens (http://www.e3mlab.ntua.gr/)	Projects completed for a fee	0
	Number of Users is Not Specified as it is Not Monitored		
BALMOREL	Project Driven with a users network and forum around it (http://www.balmorel.com/)	Free to Download (Open Source)	Not Specified
E4cast	Australian Bureau of Agricultural and Resource Economics (http://www.abare.gov.au/)	Commercial	Not Specified
H2RES	Instituto Superior Técnico and the University of Zagreb (http://powerlab.fsb.hr/h2res/)	Internal Use Only	Not Specified
HYDROGEMS	Institutt for energiteknikk (http://www.hydrogems.no/)	Commercial / Free for TRNSYS Users	Not Specified
MiniCAM	Pacific Northwest National Laboratory (http://www.globalchange.umd.edu/)	Free to Download Once Contacted	Not Specified
SimREN	Institute of Sustainable Solutions and Innovations (http://www.isusi.de/theerjreport.html)	Projects completed for a fee	Not Specified
STREAM	Ea Energy Analyses (http://www.ea-energianalyse.dk/)	Free to Download Once Contacted	Not Specified
UniSyD3.0	Unitec New Zealand (http://www.unitec.ac.nz/)	Contact Prof. Jonathan Leaver: jleaver@unitec.ac.nz	Not Specified
WILMAR Planning Tool	Risø DTU National Laboratory for Sustainable Energy (http://www.wilmar.risoe.dk/)	Commercial	Not Specified

Table 8-3: Type of each tool reviewed.

Tool	Type						
	Simulation	Scenario	Equilibrium	Top-Down	Bottom-Up	Operation Optimisation	Investment Optimisation
AEOLIUS	Yes	-	-	-	Yes	-	-
BALMOREL	Yes	Yes	Partial	-	Yes	Yes	Yes
BCHP Screening Tool	Yes	-	-	-	Yes	Yes	-
COMPOSE	-	-	-	-	Yes	Yes	Yes
E4cast	-	Yes	Yes	-	Yes	-	Yes
EMCAS	Yes	Yes	-	-	Yes	-	Yes
EMINENT	-	Yes	-	-	Yes	-	-
EMPS	-	-	-	-	-	Yes	-
EnergyPLAN	Yes	Yes	-	-	Yes	Yes	Yes
energyPRO	Yes	Yes	-	-	-	Yes	Yes
ENPEP-BALANCE	-	Yes	Yes	Yes	-	-	-
GTMax	Yes	-	-	-	-	Yes	-
H2RES	Yes	Yes	-	-	Yes	Yes	-
HOMER	Yes	-	-	-	Yes	Yes	Yes
HYDROGEMS	-	Yes	-	-	-	-	-
IKARUS	-	Yes	-	-	Yes	-	Yes
INFORSE	-	Yes	-	-	-	-	-
In*vert*	Yes	Yes	-	-	Yes	-	Yes
LEAP	Yes	Yes	-	Yes	Yes	-	-
MARKAL/TIMES	-	Yes	Yes	Partly	Yes	-	Yes
Mesap PlaNet	-	Yes	-	-	Yes	-	-
MESSAGE	-	Yes	Partial	-	Yes	Yes	Yes
MiniCAM	Yes	Yes	Partial	Yes	Yes	-	-
NEMS	-	Yes	Yes	-	-	-	-
ORCED	Yes	Yes	Yes	-	Yes	Yes	Yes
PERSEUS	-	Yes	Yes	-	Yes	-	Yes
PRIMES	-	-	Yes	-	-	-	-
ProdRisk	Yes	-	-	-	-	Yes	Yes
RAMSES	Yes	-	-	-	Yes	Yes	-
RETScreen	-	Yes	-	-	Yes	-	Yes
SimREN	-	-	-	-	-	-	-
SIVAEL	-	-	-	-	-	-	-
STREAM	Yes	-	-	-	-	-	-
TRNSYS16	Yes	Yes	-	-	Yes	Yes	Yes
UniSyD3.0	-	Yes	Yes	-	Yes	-	-
WASP	Yes	-	-	-	-	-	Yes
WILMAR Planning Tool	Yes	-	-	-	-	Yes	-

Table 8-4: Type of analysis conducted by each tool reviewed.

Tool	Geographical Area	Scenario Timeframe	Time-Step	Specific Focus
1. National Energy System Tools				
1.1. Time-Step Simulation Tools				
Mesap PlaNet	National/State/Regional	No Limit	Any	-
TRNSYS16	Local/Community	Multiple Years	Seconds	-
HOMER	Local/Community	1 Year*	Minutes	-
SimREN	National/State/Regional	No Limit	Minutes	-
EnergyPLAN	National/State/Regional	1 Year*	Hourly	-
SIVAEL	National/State/Regional	1 Year*	Hourly	-
STREAM	National/State/Regional	1 Year*	Hourly	-
WILMAR Planning Tool	International	1 Year*	Hourly	-
RAMSES	International	30 Years	Hourly	-
BALMOREL	International	Max 50 Years	Hourly	-
GTMax	National/State/Regional	No Limit	Hourly	-
H2RES	Island	No Limit	Hourly	-
MARKAL/TIMES	National/State/Regional	Max 50 Years	Hourly, Daily, Monthly using user-defined time slices	-
1.2. Sample periods within a year				
PERSEUS	International	Max 50 Years	Based on Typical Days with 36 to 72 slots for one year	-
UniSyD3.0	National/State/Regional	Max 50 Years	Bi-weekly	-
RETScreen	User Defined	Max 50 Years	Monthly	-
1.3. Scenario Tools				
E4cast	National/State/Regional	Max 50 Years	Yearly	-
EMINENT	National/State/Regional	1 Year*	None / Yearly	-
IKARUS	National/State/Regional	Max 50 Years	Yearly	-
PRIMES	National/State/Regional	Max 50 Years	Years	-
INFORSE	National/State/Regional	50+ Years	Yearly	-
ENPEP-BALANCE	National/State/Regional	75 Years	Yearly	-
LEAP	National/State/Regional	No Limit	Yearly	-
MESSAGE	Global	50+ Years	5 Years	-
MiniCAM	Global and Regional	50+ Years	15 Years	-
2. Tools with a Specific Focus				
2.1. Time-Step Simulation Tools				
AEOLIUS	National/State/Regional	1 Year*	Minutes	Effects of fluctuating renewable energy on conventional generation
HYDROGEMS	Single-Project Investigation	1 Year*	Minutes	Renewable energy and hydrogen stand-alone systems
energyPRO	Single-Project Investigation	Max 40 Years	Minutes	Single power plant analysis
BCHP Screening Tool	Single-Project Investigation	1 Year*	Hourly	Combined heat and power
ORCED	National/State/Regional	1 Year*	Hourly	Dispatch of electricity
EMCAS	National/State/Regional	No Limit	Hourly	Electricity markets
ProdRisk	National/State/Regional	Multiple Years	Hourly	Hydro power
COMPOSE	Single-Project Investigation	No Limit	Hourly	CHP with electric boilers or heat pumps
2.2. Sample periods within a year				
EMPS	International	25 Years	Weekly (With a load duration curve representing fluctuations within the week)	Hydro power
WASP	National/State/Regional	Max 50 Years	12 Load Duration Curves for a year	Power plant expansion on the electric grid
2.3. Scenario Tools				
In*vert*	National/State/Regional	Max 50 Years	Yearly	Heat sector
NEMS	National/State/Regional	Max 50 Years	Yearly	US Energy Markets

***Tools can only simulate one year at a time, but these can be combined to create a scenario of multiple years.**

Table 8-5: Energy sectors considered and renewable energy penetrations simulated by each tool reviewed.

	Energy Sectors Considered			Renewable-Energy Penetrations Simulated	
Tool	**Electricity Sector**	**Heat Sector**	**Transport Sector**	**100% Electricity Simulated**	**100% Renewable Energy System**
Reports available detailing these renewable-energy penetrations					
EnergyPLAN	Yes	Yes	Yes	Yes	Yes
INFORSE	Yes	Yes	Yes	Yes	Yes
Mesap PlaNet	Yes	Yes	Yes	Yes	Yes
H2RES	Yes	Yes	Partly	Yes	Yes
SimREN	Yes	Yes	Partly	Yes	Yes
energyPRO	Yes	Partly	-	Yes	Partly*
HOMER	Yes	Yes	-	Yes	Partly*
TRNSYS16	Yes	Yes	-	Yes	Partly*
PERSEUS	Yes	Yes	Partly	Yes	-
MESSAGE	Yes	Yes	Yes	-	-
NEMS	Yes	Yes	Yes	-	-
Reports NOT available detailing these renewable-energy penetrations					
LEAP	Yes	Yes	Yes	Yes	Yes
In*vert*	Yes	Yes	Partly	Yes	Yes
EMPS	Yes	-	-	Yes	Partly*
ProdRisk	Yes	-	-	Yes	Partly*
RETScreen	Yes	Yes	-	Yes	Partly*
MiniCAM	Yes	Partly	Yes	Yes	-
SIVAEL	Yes	Partly	-	Yes	-
COMPOSE	Yes	Yes	Yes	-	-
ENPEP-BALANCE	Yes	Yes	Yes	-	-
IKARUS	Yes	Yes	Yes	-	-
MARKAL/TIMES	Yes	Yes	Yes	-	-
PRIMES	Yes	Yes	Yes	-	-
E4cast	Yes	Yes	Partly	-	-
STREAM	Yes	Yes	Partly	-	-
EMINENT	Yes	Yes	-	-	-
UniSyD3.0	Yes	Partly	Yes	-	-
WILMAR Planning Tool	Yes	Partly	Partly	-	-
BALMOREL	Yes	Partly	-	-	-
GTMax	Yes	Partly	-	-	-
RAMSES	Yes	Partly	-	-	-
HYDROGEMS	Yes	-	-	-	-
ORCED	Yes	-	Partly	-	-
EMCAS	Yes	-	Partly	-	-
WASP	Yes	-	-	-	-
AEOLIUS	Yes	-	-	-	-
BCHP Screening Tool	-	-	-	-	-

*Have simulated a 100% renewable energy penetration in all the sectors they consider.

From this review it is evident that there is a wide range of different energy tools available which are diverse in terms of the regions they analyse, the technologies they consider, and the objectives they fulfil. Out of the 37 energy tools which were reviewed in detail, EnergyPLAN was chosen for this study for a number of key reasons. Firstly, it is a very user-friendly tool and hence the initial training period required to begin using the model is usually less than one month. In addition, online training is available and EnergyPLAN can be downloaded from its website [181]. Also, in the programming of EnergyPLAN, any procedures which would increase the calculation time have been avoided. For example, it uses deterministic modelling as opposed to stochastic, so with the same input it will always come to the same result. Also, EnergyPLAN is based on analytical programming as opposed to iterations, dynamic programming, or advanced mathematical tools. This makes the calculations direct and the tool very fast when performing calculations. As a result, the computation of one year requires only a few seconds on a normal computer, even in the case of complicated national energy systems. Therefore, it is ideal for analysing a wide range of alternatives against one another. Furthermore, the results created in EnergyPLAN are published within academic journals and many of these were closely related to the objectives of this study, such as analysing the integration of wind power [209] and the feasibility of large-scale energy storage [50, 210, 211]. Finally, one of the most distinguishing features within EnergyPLAN was the fact that it considered the three primary sectors of any national energy system: electricity, heat, and transport. As fluctuating renewable energy such as wind power becomes more prominent within energy systems, flexibility will become a vital consideration, which is the primary attraction of PHES. However, one of the most accessible methods of creating flexibility within an energy system is the integration of the electricity, heat, and transport sectors using technologies such as CHP, heat pumps, electric vehicles, and hydrogen. Therefore, although PHES is only used in the electricity sector, the construction of a PHES facility also impacts technologies which operate within the heat and transport sectors. In addition, alternative sources of flexibility to PHES depend on the consideration of the heat and transport sectors. Therefore, as the objective of this study is to evaluate the implications of PHES and compare it to alternatives on the Irish energy system, it is vital that all three sectors are considered and hence, EnergyPLAN was ideal for this analysis.

8.1.2. EnergyPLAN

EnergyPLAN has been developed and expanded on a continuous basis since 1999 at Aalborg University in Denmark. Approximately ten versions of EnergyPLAN have been created and it has been downloaded by more than 1200 people. The current version can be downloaded for free along with a range of training material from the EnergyPLAN website [181]. The training period required can take a few days up to a month, depending on the level of complexity required.

EnergyPLAN is a user-friendly tool designed in a series of tab sheets and programmed in Delphi Pascal. Input is defined by the user in terms of technologies and cost specifications. The main purpose of the tool is to assist the design of national or regional energy planning strategies on the basis of technical and economic analyses of the consequences of implementing different energy systems and investments. It encompasses the whole national or regional energy system including heat and electricity supplies as well as the transport and industrial sectors. All thermal, renewable, storage, conversion, and transport technologies can be modelled by EnergyPLAN. The tool is a deterministic input/output tool and, as outlined in Figure 8-1, general inputs are demands, renewable energy sources, energy station capacities, costs, and a number of optional regulation strategies for import/export and excess electricity production. Outputs are energy balances and resulting annual productions, fuel consumption, import/export of electricity, and total costs including income from the exchange of electricity. EnergyPLAN uses an hourly time step in its simulation so it is able to analyse the influence of fluctuating renewable energy sources on the system, as well as weekly and seasonal differences in electricity and heat demands and water inputs to large hydro power systems. EnergyPLAN simulates a one year time-period in total, although several analyses each covering one year may be combined to create longer scenarios. In the interest of speed, EnergyPLAN is aggregated in its system description instead of modelling each individual station and component, e.g. in EnergyPLAN district-heating systems are aggregated and defined as three principle groups. Also, EnergyPLAN provides a choice between different regulation strategies for a given system instead of incorporating a specific institutional framework. Therefore, the system can not only be optimised based on costs, but also based on its operation so that investments can be compared based on their socio-economic gains.

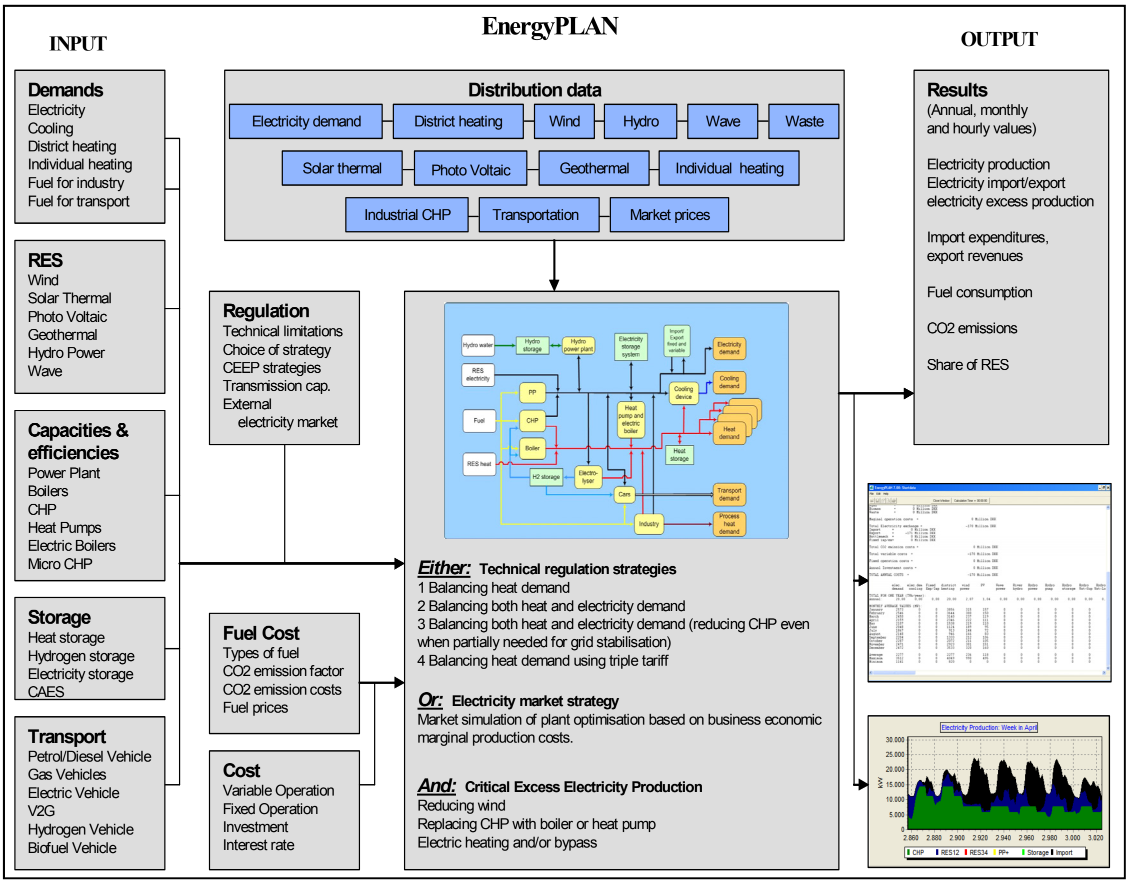


Figure 8-1: The structure of the EnergyPLAN tool.

Previously, EnergyPLAN has been used to analyse the large-scale integration of wind [209] as well as optimal combinations of renewable energy sources [212], management of surplus electricity [213], the integration of wind power using V2G electric vehicles [214], the implementation of small-scale CHP [215], integrated systems and local energy markets [216], renewable energy strategies for sustainable development [217], the use of waste for energy purposes [218], the potential of fuel cells and electrolysers in future energy systems [219, 220], the potential of thermoelectric generation in thermal energy systems [221], and the effect of energy storage [222], with specific work on compressed air energy storage [50, 210, 211] and the thermal energy storage system [223, 224]. In addition, EnergyPLAN was used to analyse the potential of CHP and renewable energy in Estonia, Germany, Poland, Spain, and the Britain [225]. Other publications can be seen on the EnergyPLAN website [181], while an overview of the work completed using EnergyPLAN is discussed by Lund [226]. Finally, EnergyPLAN has been used to simulate a 100% renewable energy system for the island of Mljet in Croatia [227] and the entire country of Denmark [228-232].

8.2. Modelling the Irish Energy System

After concluding that EnergyPLAN was the most suitable energy tool, the next step was to create a reference model of the Irish energy system based on an historical year. This was to ensure that EnergyPLAN is capable of accurately modelling the Irish energy system. As this work began in 2008, the most recent complete year of data available was for 2007 and hence, this was chosen as the reference year.

In summary EnergyPLAN requires two specific types of data: an annual production/demand and a corresponding hourly distribution of that annual value. The foundation for the annual data is the national energy balance which is usually available in every country. In Ireland, this is developed by the Sustainable Energy Authority of Ireland (SEAI), so a detailed breakdown of the 2007 Irish energy balance is available from their website [165] and in Appendix E. The relevant data for this study from the 2007 energy balance is displayed in Table 8-6, which displays the total annual energy requirement and consumption for each fuel within each sector of the energy system. Although some of these needed to be manipulated to satisfy the EnergyPLAN inputs, many could be taken directly.

For the distribution data, hourly values must be obtained based on historical records or theoretical assumptions. This data is then indexed by the EnergyPLAN software so it can be manipulated for an alternative scenario. For example, in Table 8-7 the historical output of a 100 MW wind farm is used to simulate the predicted output from a 400 MW wind farm and in Figure 8-2, the Irish electricity demand for January 2007 is manipulated to represent hypothetical demands of 1.5 TWh, 1 TWh, and 0.5 TWh.

To construct a new model in EnergyPLAN, over 100 separate pieces of data relating to the Irish energy system were required. As the construction of the model is not critical here, the details of the technical data used and economical assumptions made are described in detail in Appendix E and F. Instead, the most important outcome for this study is the accuracy of the model after it was constructed.

Table 8-6: Energy balance for the Irish energy system in 2007 (last updated by SEAI on the 21st October 2009): for all data, see reference [165] or Appendix E.

2007 Energy Balance **Units = ktoe**	**Coal**	**Peat**	**Oil**	**Jet Kerosene**	**Gasoline / Petrol**	**Gasoil / Diesel /DERV**	**Natural Gas**	**Renewables**	**Hydro**	**Wind**	**Wave**	**Biomass**	**Solar**	**Geothermal**	**Electricity**	**TOTAL**
Primary Energy Requirement	*1508*	*701*	*9047*	*1043*	*1920*	*3885*	*4293*	*467*	*57*	*168*	*0*	*239*	*1*	*1*	*-114**	*16130*
Power Plant Consumption	1124	431	368				2737	33				33				4660[#]
Power Plant Production	460[€]	181[€]	116[€]				1307[€]	237	57	168	0	12				2064[#]
Transmission & Distribution Losses															229	229
Total Final Energy Consumption	*374*	*272*	*8604*	*1043*	*1920*	*3885*	*1584*	*213*				*211*	*1*	*1*	*2224*	*13271*
Industry	140		1015			178	655	152				152			729	2691
Transport			5659	1043	1920	2695	0	21				21			4	5685
Residential	208	272	1127			230	593	24				30	1	1	693	2917
Commercial/Public Services	26		551			530	336	8							749	1670
Agricultural			252			252	0	7				7			48	308

***Negative sign indicates an electricity net import.**
[#]Figure represents fossil fuel power plants only.
[€]This was not available in the energy balance and hence it was obtained from [21].

Table 8-7: Sample of how a distribution is indexed and subsequently used in EnergyPLAN.

Time (h)	Output from a 100 MW Wind Farm (MW)	Index Data		Using Indexed Data to Simulate a 400 MW Wind Farm	
		Fraction	Decimal		
1	20	20/100	0.2	0.2*400	80
2	30	30/100	0.3	0.3*400	120
3	60	60/100	0.6	0.6*400	240
4	100	100/100	1.0	1.0*400	400
5	80	80/100	0.8	0.8*400	320
6	40	40/100	0.4	0.4*400	160

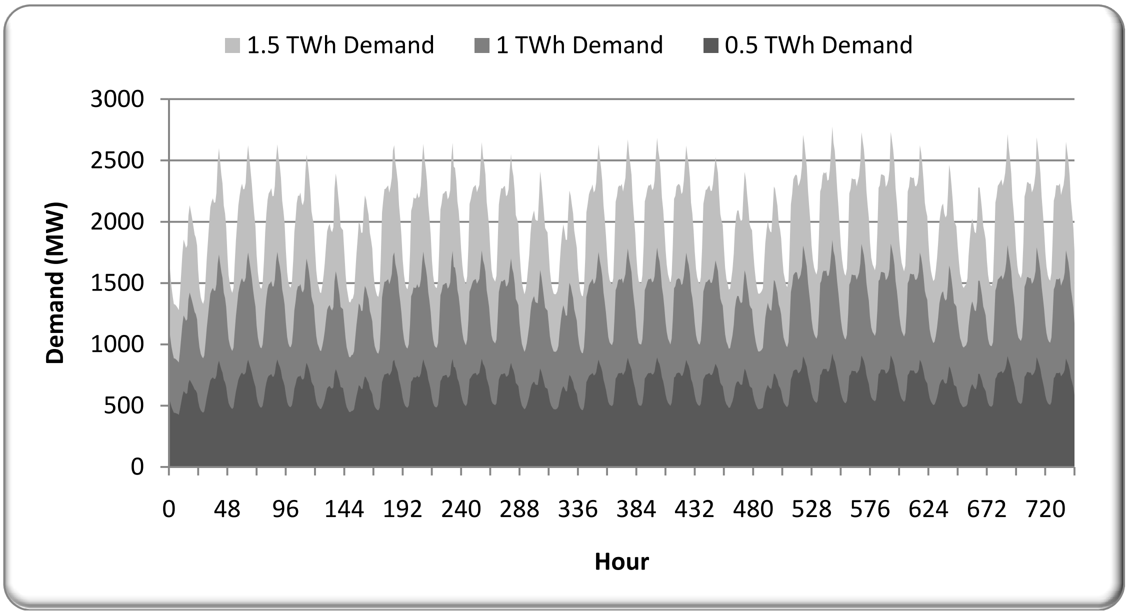


Figure 8-2: One sample distribution being modified by the total electricity demand required over the 30 day period (based on the Irish electricity demand in January 2007 [23]). This illustrates how data is manipulated in EnergyPLAN.

To validate the model, a comparison was made between the results from the EnergyPLAN model and the actual figures from 2007. The first parameter that was compared was the electricity demand. The total electricity generated for 2007 (28.5 TWh), including a 1.31 TWh net import were being simulated correctly in the model. Also, the distribution of the electricity generated over the year was also being simulated correctly, as indicated by the average monthly electricity demands displayed in Table 8-8.

Table 8-8: Comparison of average monthly electricity demands obtained from the EnergyPLAN model and actual values for Irish energy system in 2007.

Month	Average Monthly Electricity Demand (MW)		Difference (MW)	Difference (%)
	Actual 2007	EnergyPLAN 2007		
January	3564	3559	-5	-0.14
February	3576	3573	-3	-0.09
March	3414	3386	-28	-0.82
April	3079	3084	5	0.18
May	3029	3025	-4	-0.14
June	2991	2970	-21	-0.71
July	2937	2947	10	0.34
August	2964	2960	-4	-0.15
September	3094	3105	11	0.36
October	3279	3281	2	0.07
November	3515	3508	-7	-0.20
December	3531	3519	-12	-0.35

Once it was verified that the electricity demand was being simulated correctly, the electricity produced from various units was compared. As seen in Table 8-9, the total electricity generated from the various production units is very similar in both the actual 2007 figures [165] and the results from the reference model. The only significant difference occurred for wind power production, which is most likely attributed to the 8.5% variation in installed wind capacity at the beginning and end of 2007[9]. As power plants contributed such a large proportion of the electricity supply, a further comparison was made for them.

Table 8-9: Comparison between electricity produced for Ireland in 2007 and in the EnergyPLAN simulation.

Production Unit	2007 Production [165] (TWh)	EnergyPLAN Production 2007 (TWh)	Difference	
			TWh	%
Power Plants	23.56	23.54	0.02	0.08
Onshore Wind	1.88*	1.86	0.06	3.20
Offshore Wind		0.08		
Industrial CHP	0.93	0.93	0.00	0.00
Hydro Power	0.66	0.65	-0.01	-1.52

***Onshore and offshore data could not be obtained separately.**

Power plant production could not be compared individually because EnergyPLAN aggregates the power plants within an energy system and consequently, the production from each power plant is not available from the results. Therefore, electricity production was not compared for each power plant, but instead the annual fuel consumed by each fuel type of power plant was compared. From Table 8-10 it is clear that the model provides an accurate representation of

[9] There was an 8.5% increase in wind capacity in Ireland in 2007 from 723.8 MW to 785.2 MW.

the power plants on the Irish energy system in 2007, as the largest difference that occurred was 0.47%.

Table 8-10: Comparison between the fuel consumed in power plants for Ireland in 2007 and in the EnergyPLAN simulation.

Power Plant	2007 Production [165] (TWh)	EnergyPLAN Production 2007 (TWh)	Difference	
			TWh	%
Natural Gas	29.10	29.23	0.13	0.45
Coal	18.08	18.16	0.08	0.44
Oil	4.28	4.30	0.02	0.47
Biomass	0.28	0.28	0.00	0.00

After the electricity sector was analysed, the heat and transport sectors were compared with the reference model. However, all heat in Ireland is produced by individual boilers and all transport is powered by conventional vehicles. Therefore, due to the lack of integration between the sectors in the Irish energy system, no hourly simulations are necessary in the heat or transport sectors. The only input required is the annual fuel requirements which are used as inputs in EnergyPLAN. Therefore, comparing the EnergyPLAN results with the actual data from 2007 would result in no difference, as it would be the same data. Therefore, for the heat and transport sectors, the accuracy of the model needs to be based on the assumptions made while constructing the input data, not on the figures produced by the model, which are outlined in detail in Appendix E.

Next the total fuel consumption within the Irish energy system is compared with those calculated in EnergyPLAN. As seen in Table 8-11, the total fuel consumptions from actual 2007 figures and from the reference model are very similar for all fuels: the largest relative difference occurred for biomass at 2.17%.

Table 8-11: Comparison between the total fuel consumed in Ireland in 2007 and in the EnergyPLAN simulation.

Fuel	2007 Fuel Consumption (TWh)	EnergyPLAN Fuel Consumption (TWh)	Difference	
			TWh	%
Oil	105.22	104.44	-0.78	-0.74
Natural Gas	49.92	50.41	0.49	0.98
Coal/Peat	25.70	25.76	0.06	0.23
Biomass	2.77	2.83	0.06	2.17
Renewables	2.54	2.59	0.05	1.97

Finally, the actual CO_2 emissions for Ireland in 2007 were compared with those from the EnergyPLAN simulation. The total energy-related CO_2 emissions for Ireland in 2007 were calculated as 46.8 Mt using fuel consumptions from [165] and emission factors from [21], as seen in Table 8-12. In comparison, EnergyPLAN calculated the CO_2 emissions for Ireland in

2007 as 47.21 Mt. This is 0.88% (0.41 Mt) higher than those calculated from the statistics, and thus indicates that the reference model provided an accurate representation of the Irish energy system.

Table 8-12: CO_2 emissions for Ireland in 2007 and CO_2 emissions from the EnergyPLAN simulation.

Fuel	Consumption [165] (TWh)	CO_2 Emission Factor [21] (kg/GJ)	CO_2 Emitted (Mt)
Gasoil	45.188*	73.30	11.92
Electricity	25.867	150.83	14.05
Gasoline	22.325	70.00	5.63
Natural Gas	18.424*	57.10	3.79
Jet Kerosene	12.134	71.40	3.12
Kerosene	10.620	71.40	2.73
Coal	4.354*	94.60	1.48
Fuel Oil (Residual Oil)	4.295*	76.00	1.18
Coke	3.637	100.80	1.32
Sod Peat	2.167	104.00	0.81
LPG	1.853*	63.70	0.42
Peat Briquettes	0.992	98.90	0.35
Naphtha	0.012	73.30	0.003
Total			46.80

***Excludes fuel required for electricity generation.**

After completing the comparison between the reference model and the actual 2007 figures, it was concluded that the model was capable of accurately modelling the Irish energy system as the largest difference recorded was 2.17%. Therefore, the EnergyPLAN tool could be used to assess the implications of large-scale energy storage in Ireland. However, to do so a future model of the Irish energy system was required instead of the 2007 historical reference.

In line with this, a new model of the Irish energy system was developed based on the year 2020. For the most part, the technical and economical assumptions from the 2007 reference model, which are outlined in Appendices E and F, were applied to the 2020 model also. However, the annual consumption and demand data were taken from the 2020 reference projected by the Irish energy authority, SEAI [36]. More specifically, the 2020 model was based on SEAI's "White Paper Plus" scenario for 2020, which is outlined in Table 8-13. The total electricity demand assumed was approximately 34 TWh with an average demand of approximately 3400 MW, a peak of approximately 5500 MW, and a minimum demand of approximately 1900 MW. In addition, the installed capacity assumed for each technology is outlined in Table 8-14. Using this new 2020 model of the Irish energy system, the technical and economical consequences of PHES could be assessed in relation to the integration of wind power.

Table 8-13: Projected energy balance for the Irish energy system in 2020 (White Paper Plus Scenario) [36].

2020 White Paper Plus Energy Balance **Units = ktoe**	**Coal**	**Peat**	**Oil**	**Jet Kerosene**	**Gasoline / Petrol**	**Gasoil / Diesel /DERV**	**Natural Gas**	**Renewables**	**Hydro**	**Wind**	**Wave**	**Biomass**	**Solar**	**Geothermal**	**Electricity**	**TOTAL**
Primary Energy Requirement	*606*	*483*	*8721*	*800*	*1873*		*3916*	*2481*	*91*	*718*	*118*	*1450*	*20*	*84*	*-127**	*16080*
Power Plant Consumption	373	338	345				2397	500				500				3453[#]
Power Plant Production	137	120	118				1356	1109	91	718	118	183				1732[#]
Transmission & Distribution Losses															242	242
Total Final Energy Consumption	*233*	*146*	*8376*	*800*	*1873*		*1519*	*1055*				*950*	*20*	*84*	*2447*	*13776*
Industry	98		877				778	345				345			630	2728
Transport			5933	800	1873	3259	0	464				464			95	6492
Residential	112	146	1210				516	103				141	20	84	648	2734
Commercial/Public Services	23		60				225	143							998	1448
Agricultural			296												76	373

***Negative sign indicates an electricity net import.**
[#]Figure represents fossil fuel power plants only.

Table 8-14: Predicted capacities on the Irish electric grid in 2020 [36].

Technology	Installed Capacity (MW)
Coal Power Plants	845
Peat Power Plants	346
Open Cycle Gas Turbines	1091
Combined Cycle Gas Turbines	3013
Waste Incineration	89
Wind Turbines	3100
Wave Powers	500
Hydroelectricity	260
Interconnection	580

When simulating PHES in EnergyPLAN during this study, the primary focus was to integrate the maximum feasible wind penetration (MFWP) and hence, a technical optimisation was used. For a technical optimisation, PHES is charged during hours when critical excess electricity production (CEEP)[10] occurs in the energy system (i.e. if $e_{CEEP} > 0$) [181]. In this case the electricity demand for the PHES pump (e_{Pump}) is found as the minimum value in Equation 5, which considers the CEEP, e_{CEEP}, the available space in the PHES facility ($C_{Storage} - s_{PHES}$), and the maximum capacity of the PHES pump, C_{Pump}. Subsequently, the energy stored in the PHES facility after operating the pump is calculated using Equation 6, where s_{PHES} is the current volume of energy stored in the PHES facility and η_{Pump} is the pump efficiency:

$$e_{Pump} = min\left[e_{CEEP}, \frac{C_{Storage} - S_{PHES}}{\eta_{Pump}}, C_{Pump}\right] \tag{5}$$

$$s_{PHES} = s_{PHES} + \left(e_{Pump} * \eta_{Pump}\right) \tag{6}$$

Conversely, the PHES is discharged when it is possible to replace power plant production with power from the PHES facility (i.e. if $e_{PP} > 0$) [181]. Therefore, the electricity produced by the turbine, $e_{Turbine}$, is found as the minimum value in Equation 7, which considers the power plant capacity which can be replaced, e_{pp}, the current energy available in the PHES facility, s_{PHES}, and the maximum capacity of the PHES turbine, $C_{Turbine}$. Subsequently, the volume of energy remaining in the PHES after operating the turbine is identified using Equation 8, where $\eta_{Generation}$ is the generating efficiency:

$$e_{Turbine} = min[e_{PP}, (S_{PHES} * \eta_{Generation}), C_{Turbine}] \tag{7}$$

[10] CEEP is the amount of excess electricity produced that could not be used in the energy system. The consequences of CEEP are forced export (if adequate interconnection capacity exists) or stopping the wind turbines to reduce production (curtailment).

$$s_{PHES} = s_{PHES} - \frac{e_{Turbine}}{\eta_{Generation}} \quad (8)$$

In summary, where possible the simulation will use wind power directly to satisfy the electricity demand, but when grid constraints prevent this, the PHES stores the excess wind power so it can be used at a later time. Two primary assumptions were made in order to ensure the electricity grid operated in a stable fashion. Firstly, it was assumed that the minimum output from electrical power plants was never below 700 MW during each hour simulated and secondly, as recommended by the Irish TSO [233], 30% of the electricity production during each hour had to be supplied from grid stabilising units such as thermal power plants and hydro stations. Finally, a full and detailed explanation of the equations and operating principals associated with the EnergyPLAN tool is available from the EnergyPLAN website [181].

8.3. The Technical Implications of PHES

As outlined in section 6.2.1 earlier, some of the key issues identified from the literature in relation to the integration of wind using PHES included its operation, size, and cost. Therefore, in this section the first two of these key issues, operation and size, were assessed by simulating various types and capacities of PHES on the 2020 Irish energy system with increasing penetrations of wind power. The results here were identified using version 8.3 of EnergyPLAN.

8.3.1. Operation

Historically, PHES facilities have typically been constructed with a single penstock system as they were designed to maximise electricity generation from baseload power plants i.e. by charging during the night when electricity prices were low (due to a high percentage of baseload power) and discharging during the day when electricity prices were high (due to a high electricity demand). However, if energy storage devices are designed especially to integrate fluctuating renewable energy, there may be additional benefits, especially in relation to grid stabilisation, when using PHES that can charge and discharge at the same time. This can be achieved in a single PHES facility by installing two penstocks, as displayed in Figure 8-3, or also by installing multiple single penstock PHES facilities on the same energy system i.e. one can charge while the other is discharging at the same time. By using a double penstock system, the PHES introduces even more flexibility onto the energy system which could aid the integration of wind power. Therefore, both of these operating strategies were used to simulate a 2500 MW and 25 GWh PHES facility on the 2020 Irish energy system.

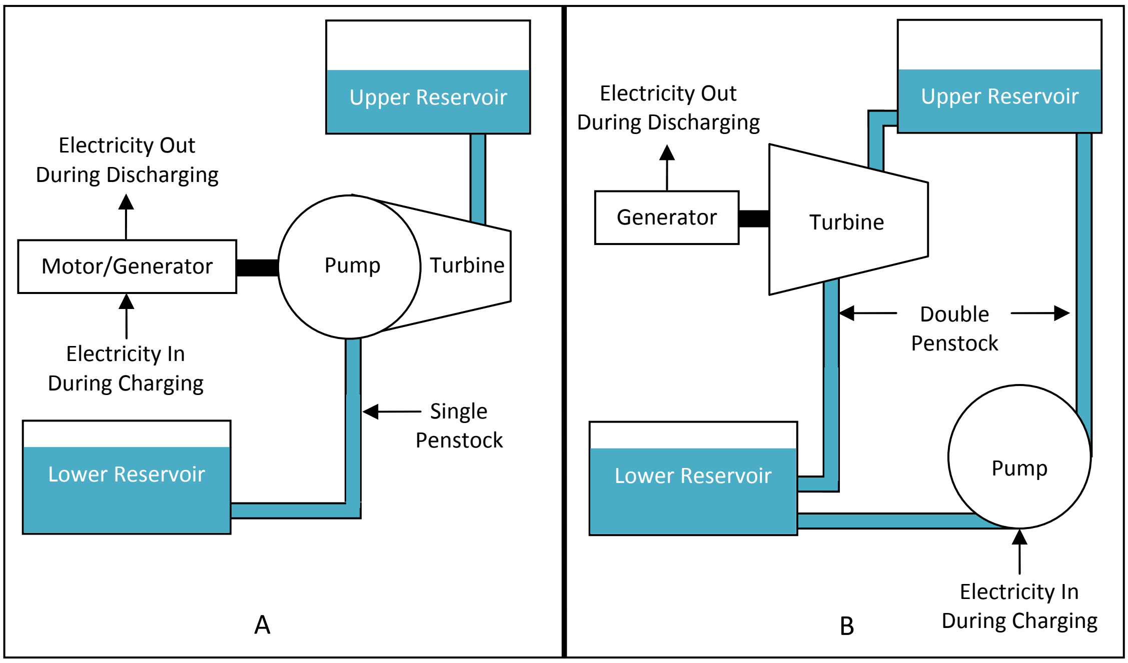


Figure 8-3: One PHES facility with (A) a single penstock system and (B) a double penstock system.

The CEEP recorded for both operating strategies when wind power is added to the Irish energy system is outlined in Figure 8-4, while Figure 8-5 displays the corresponding PES and CO_2 emissions. These results illustrate that PHES can reduce the amount of excess electricity created with the introduction of wind power, while also reducing the corresponding PES and CO_2 emissions. Also, it is evident from Figure 8-4 and Figure 8-5 that when the PHES facility operates as a double penstock system, there is less CEEP, PES, and CO_2 compared to the single penstock operating strategy. To identify the cause of this, the hourly operation of the system was analysed.

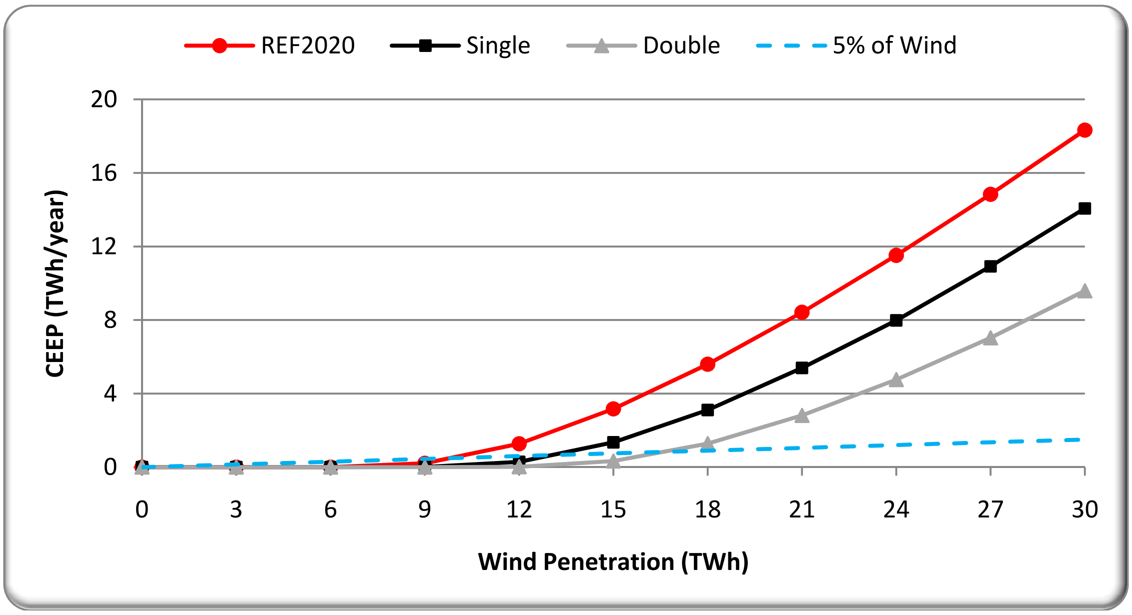


Figure 8-4: CEEP when a 2500 MW / 25 GWh single PHES and a 2500 MW / 25 GWh double PHES is added to the 2020 Irish energy system for wind penetrations of 0% to 100% (0-30 TWh) of electricity demand. The 5% of wind limitation displayed is used to define a maximum feasible wind penetration.

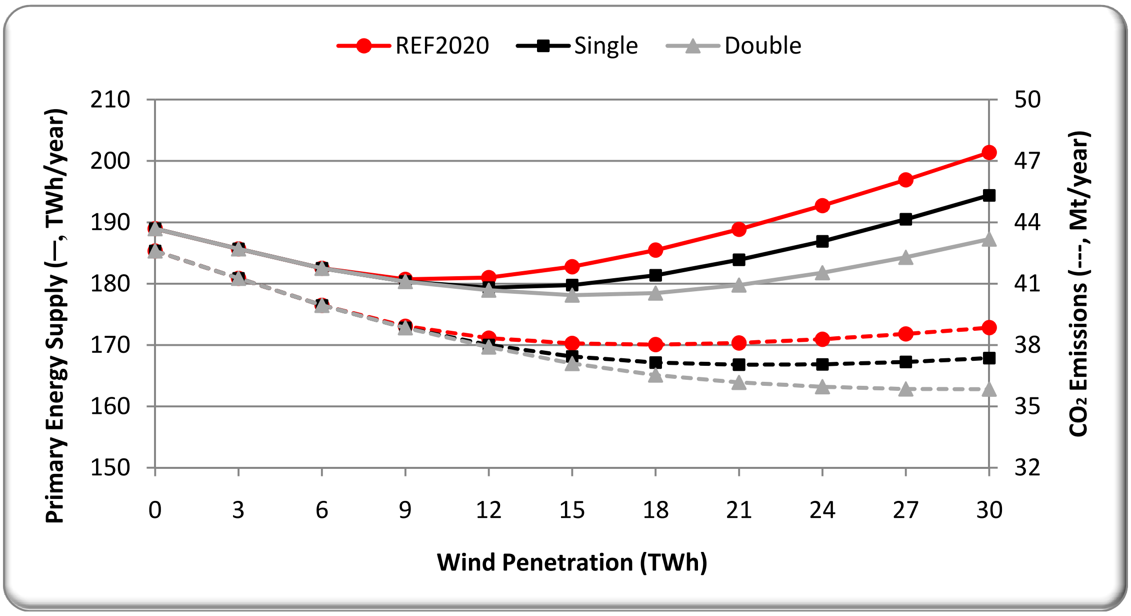


Figure 8-5: Primary energy supply and CO_2 emissions when a 2500 MW / 25 GWh single and double penstock system is added to the 2020 Irish energy system, for wind penetrations of 0% to 100% (0-30 TWh) of electricity demand.

From these hourly values it became apparent that the grid stabilisation constraints were significantly limiting the effectiveness of the single penstock PHES. The primary objective of adding PHES is to minimise excess electricity production (i.e. reduce CEEP) and use it to replace thermal power production (i.e. reduce PES). However, as 30% of the production must come from grid stabilising units during each hour, wind power cannot always be used directly so it must be sent to the PHES facility. During these hours of excess wind, the single PHES cannot be used to provide grid stabilisation as it is being charged by the wind power and hence, the power plants (PP) must operate to provide grid stabilisation. Therefore, a single penstock PHES has to reduce CEEP and use the power plants to meet demand (Figure 8-6, Option A), or dump the CEEP and replace the power plant production (Figure 8-6, Option B). However, as displayed in Figure 8-6, both of these options will result in lower wind penetrations and correspondingly higher fuel consumption. In contrast, a double penstock system enables the PHES to store excess wind energy while at the same time providing ancillary services to the grid, which is also displayed in Figure 8-6. Therefore, during these hours a double penstock PHES facility can store CEEP by charging, while at the same time it can be discharged to replace power plant production (until such point that power plant production has reached its minimum limit, which was 700 MW in this study). This is the root cause for the lower CEEP, PES, and CO_2 emissions recorded in Figure 8-4 and Figure 8-5. To further demonstrate this, a snapshot from the simulation has been taken.

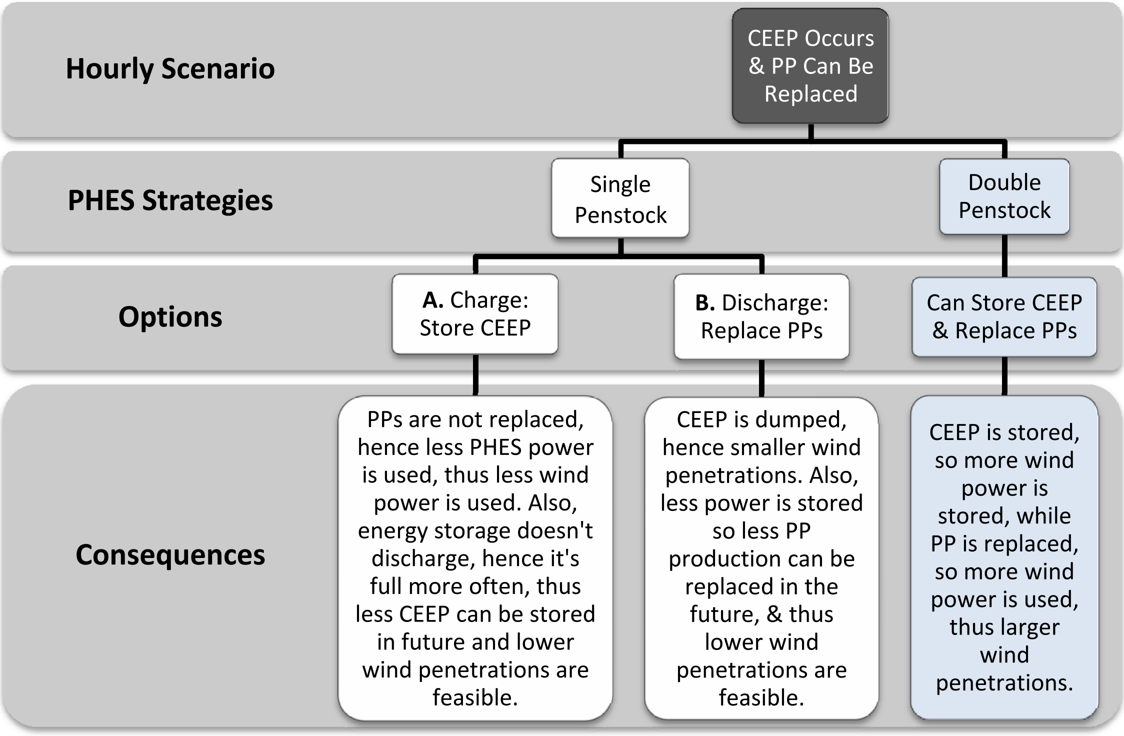


Figure 8-6: Consequences of using a single and double penstock system for PHES facilities when integrating wind power.

Figure 8-7 and Figure 8-8 demonstrate how a single and double penstock system operate in the simulation when there is excess wind production and power plant generation at the same time. In this snapshot, there is a 4000 MW demand on the electric grid. To maintain grid stability, 30% of this must come from synchronous generation in the form of power plants, which is 1285 MW. Therefore, only 2715 MW of wind power can be delivered onto the grid.

With the single penstock system in Figure 8-7, the TSO has two options in this scenario: either charge the PHES with the excess wind production or discharge the PHES to replace power plant production. Both of these decisions will result in negative consequences. If the single PHES is charged with the excess wind, then power plants will be required to provide grid stability, thus burning fossil fuels. If the single PHES is discharge, then the power plants can be replaced, but the excess wind production must now be curtailed. In contrast, with the double penstock system in Figure 8-8, the TSO could perform both of these tasks at the same time by using either a PHES with two penstocks or by operating multiple single PHES as a double penstock system. If multiple PHES units were used to create a double penstock system, as displayed in Figure 8-8, then the TSO would not only need to monitor the operation of the grid, but also the water levels in the PHES reservoirs at its disposal.

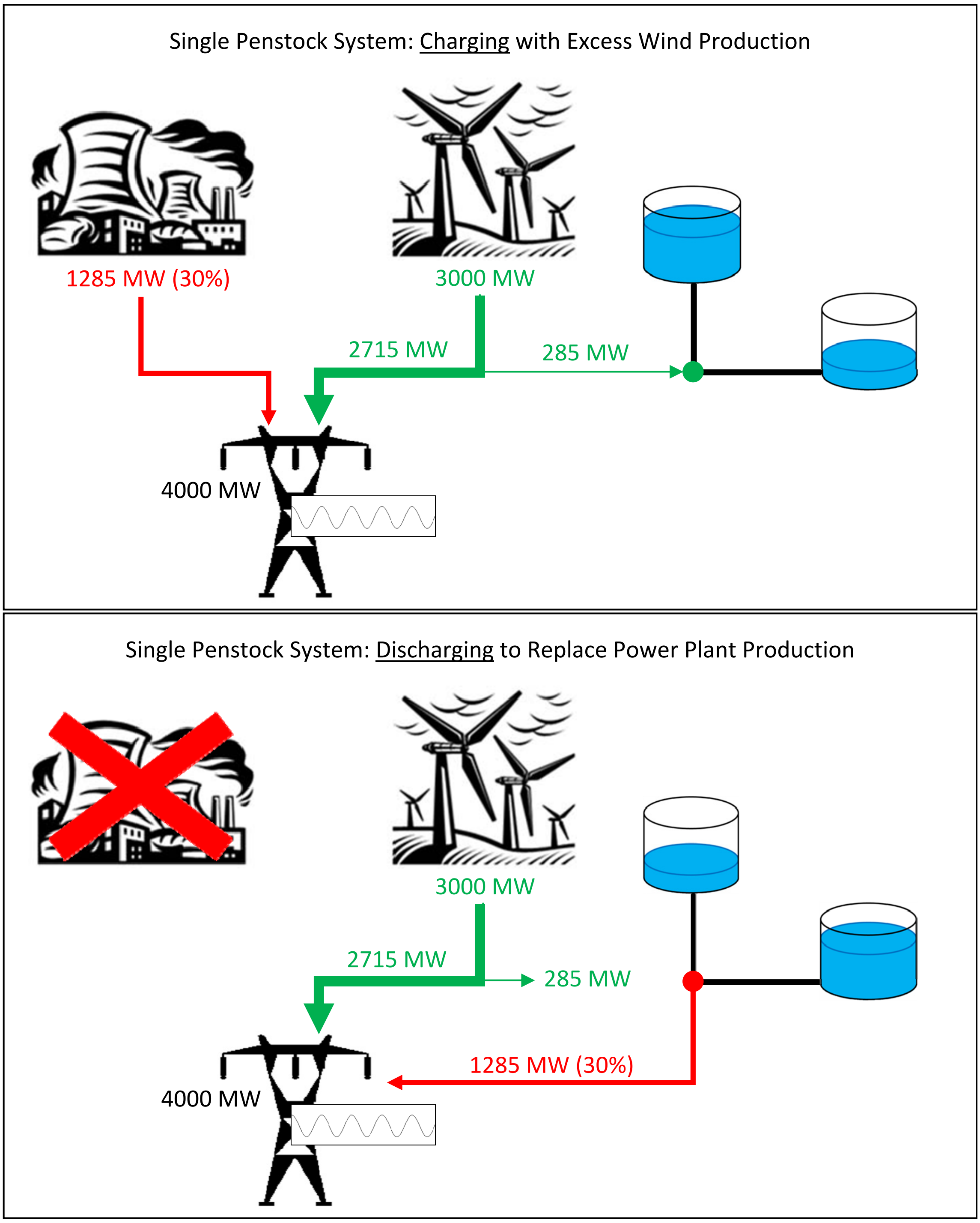


Figure 8-7: Instantaneous operation of a single penstock system (charge & discharge mode) when there is a demand of 4000 MW and a wind production of 3000 MW. Note: 30% of production must be generated from synchronous units at all times to maintain grid stability.

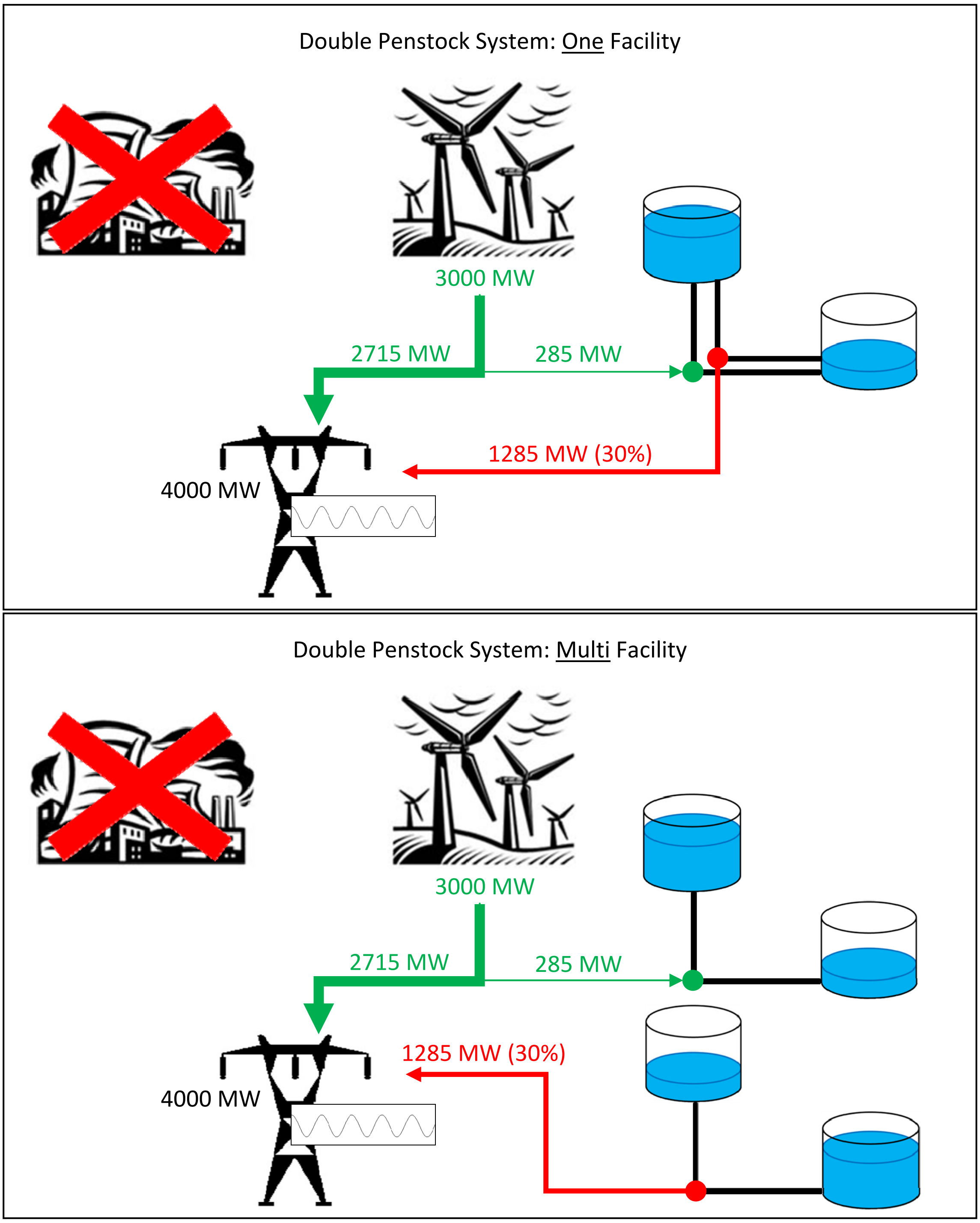


Figure 8-8: Instantaneous operation of a double penstock system (one & multi facility) when there is a demand of 4000 MW and a wind production of 3000 MW. Note: 30% of production must be generated from synchronous units at all times to maintain grid stability.

Finally, it is important to note that there is an underlying assumption in the modelling that only centralised power stations and hydro facilities can provide grid stabilisation. However, in future energy systems, grid stabilisation could be provided from wind turbines and decentralised units also [209], which could reduce the benefits of large-scale PHES. Due to the 40 year lifetime of PHES, this could be an important factor when constructing a new facility.

Furthermore, when a single PHES was simulated with no grid constraints on the 2020 Irish energy system, it achieved greater reductions in CEEP, PES, and CO_2 emissions than the double penstock simulated here, thus outlining the significant role of grid constraints.

To summarise, this section has illustrated that under traditional grid constraint assumptions, adding conventional PHES to the Irish energy system will reduce CEEP, PES, and CO_2 emissions. A double penstock operating strategy is more effective than a single penstock system, as it can accommodate these grid constraints by charging and discharging at the same time. However, this analysis was completed using one PHES capacity only and so the next section investigates how alternative PHES capacities would influence the results.

8.3.2. Size

A PHES facility has three capacities: pump, turbine, and storage. When analysing PHES, many national-scale studies have not assessed the optimum relationship between these capacities for the integration of wind power [141, 143, 144], particularly in relation to Ireland [91, 92]. Therefore, the objective in this section is to identify how different combinations of these three PHES capacities will affect the wind penetration feasible on the 2020 Irish energy system, for both a single and double PHES.

Firstly, a definition was created to determine the maximum feasible wind penetration (MFWP) for each scenario analysed, which was: the MFWP occurs when the CEEP exceeds 5% of the total wind energy produced. This is illustrated graphically in Figure 8-4, where it can be seen that the MFWP is 30%, 43%, and 55% for the REF2020, Single PHES, and Double PHES scenarios respectively. Using this definition, the MFWP was identified for a range of PHES storage capacities by simulating each one with an infinite pump and turbine capacity. As a recent study in Ireland [90] has suggested that PHES storage capacities in excess of 100 GWh are now technically and economically feasible, the results were evaluated up to a storage capacity of 500 GWh. In line with this, the nine energy storage capacities considered in this thesis were, in GWh, 1.8 (reference), 3, 6, 12, 25, 50, 100, 250, and 500. After the MFWP was identified for each of these storage capacities, the hourly values were examined in each simulation to identify the pump and turbine capacity required to achieve this MFWP, which revealed a number of interesting trends.

The results in Figure 8-9 indicate that as the storage capacity of a single PHES increases from the reference value of 1.8 GWh to 25 GWh, the MFWP increases rapidly from approximately 30% to 40%. Afterwards, it slows down, taking about 125 GWh more to increase a further 10%

to 50% and over 350 GWh more to reach a wind penetration of 60%. Interestingly, the pump and turbine capacities required are very similar for the first 25 GWh, but diverge away from one another after that. By 500 GWh, the pump capacity required to reach a 60% wind penetration is approximately 4500 MW, which is around 66% larger than the 2700 MW turbine required. Similarly for a double PHES, the results in Figure 8-10 indicate that it also increases the MFWP by 10% over the first 25 GWh. However, unlike a single PHES, the MFWP continues to increase at this rate up to a storage capacity of 100 GWh, when it reaches 80% of the total electricity demand. Subsequently, it takes an additional 150 GWh to rise a further 10% and finally, practically all of the electricity is provided using wind power with a storage capacity of 500 GWh. Once again, like the single PHES there is a clear divergence of capacities between the pump and turbine. However, this is even more severe for the double PHES facility because for each scenario considered the pump was approximately double the turbine capacity. After analysing the hourly operation of the systems simulated, it was clear that the pumping capacity is correlated to the excess electricity produced whereas the turbine is correlated to the power plant production it can replace (or in other words, the electricity demand that must be met). Therefore, as wind penetrations increase the pump size also increases so it can absorb more wind power which cannot be integrated onto the system. However, the turbine capacity doesn't increase this quickly, as the electricity demand required remains the same size even as more wind power is added. The relatively small increase in turbine capacity is thus due to the additional energy which is now stored in the PHES facility, as a result of the larger pump.

Furthermore, by comparing Figure 8-9 and Figure 8-10 (and as already discussed in section 8.3.1), it is evident that a double penstock PHES can enable much higher MFWPs than a single penstock PHES. However, the results also indicate that the pump and turbine capacities required by the double PHES to achieve its MFWPs are much larger than the capacities required by the single PHES. These findings created uncertainty in relation to the economics of a single and double PHES. On the one hand a double PHES can integrate a lot more wind energy, but on the other it requires larger pump and turbine capacities. Consequently, an economic assessment of a single and double PHES was also carried out, which will be discussed later in section 8.4.

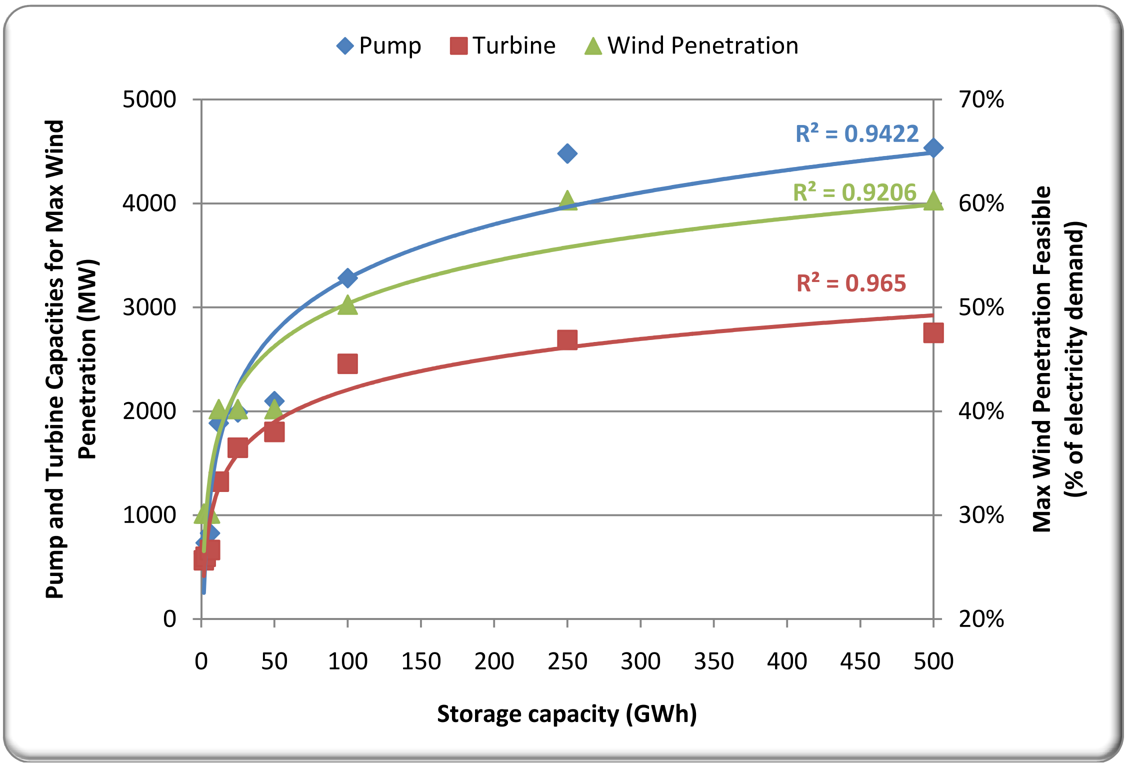


Figure 8-9: Maximum feasible wind penetration on the 2020 Irish energy system when various single PHES storage capacities are added to the system with infinite power capacities. Also outlined are the corresponding pump and turbine capacities required to achieve these maximum feasible wind penetrations identified at each storage capacity.

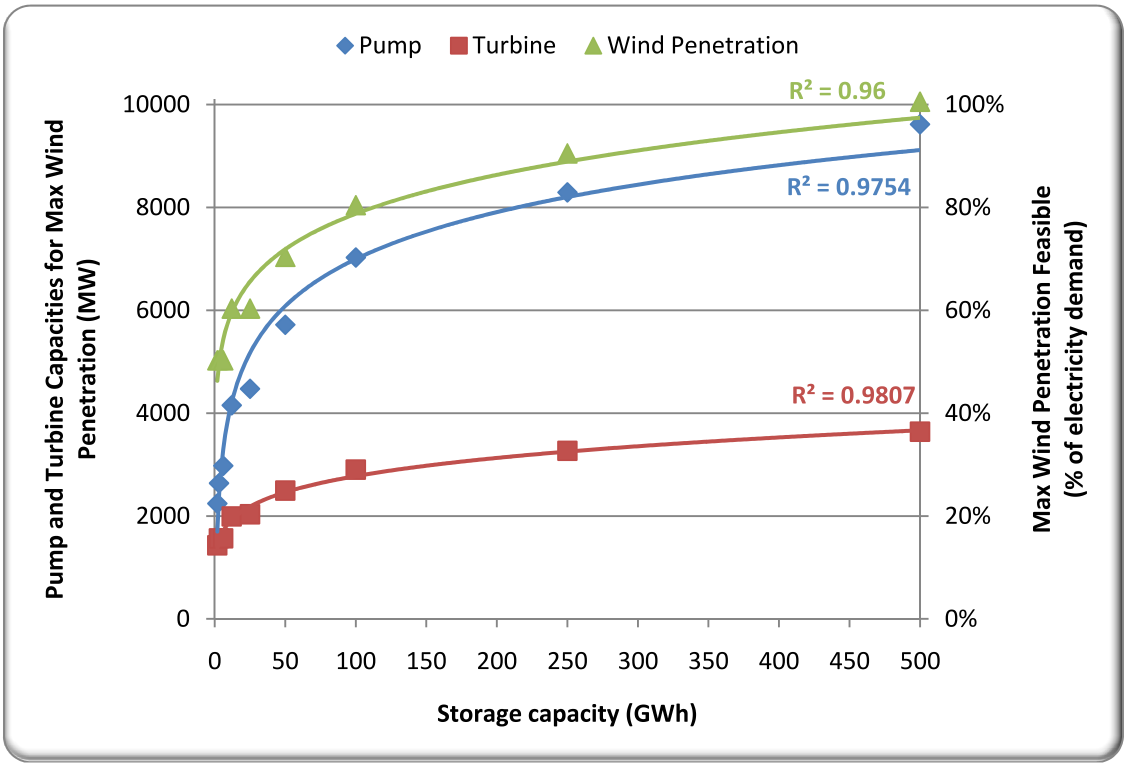


Figure 8-10: Maximum feasible wind penetration on the 2020 Irish energy system when various double PHES storage capacities are added to the system with infinite power capacities. Also outlined are the corresponding pump and turbine capacities required to achieve these maximum feasible wind penetrations identified at each storage capacity.

Finally, to ensure that the diverging trend between the pump and turbine capacities identified in Figure 8-9 and Figure 8-10 was not created due to the definition for a MFWP, this was recalculated based on a number of different criteria. As already outlined, the MFWP occurred when the total annual CEEP surpassed 5% of wind energy produced. Therefore, this was recalculated based on 10%, 15%, 20%, and 25% of wind power produced as well as 2%, 4%, 6%, 8%, and 10% of total electricity generated. As outlined in Figure 8-11 and Figure 8-12 for a single PHES as well as in Figure 8-13 and Figure 8-14 for a double PHES, all of these criteria produced a similar trend to that already observed in Figure 8-9 and Figure 8-10 of this study (although the magnitude of the MFWP did change depending on the CEEP which was deemed acceptable). In addition, the COMP coefficient, which was developed in Appendix F to define a MFWP based on a trade-off between increasing CEEP and decreasing PES, was also used to evaluate the MFWP for each storage capacity and once again a similar pattern was identified, which is evident in Figure 8-15 and Figure 8-16. Therefore, it was concluded that the definition of a MFWP may alter the magnitude of the pump and turbine required, but the diverging trend between pump and turbine capacities as the MFWP increases is consistent. Overall, the limiting factor used in this study, which was a maximum CEEP equivalent to 5% of wind, is a relatively conservative definition as many of the others would increase the savings associated with additional energy storage.

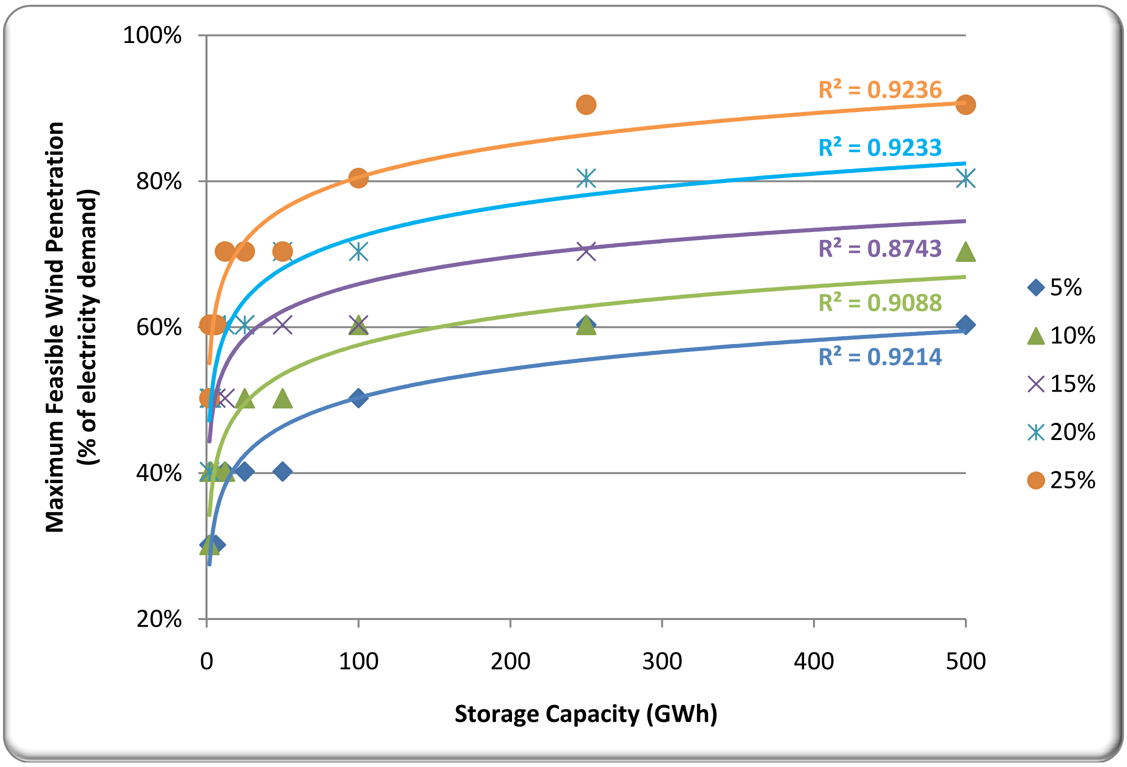


Figure 8-11: Maximum feasible wind penetration with various single PHES storage capacities on the 2020 Irish energy system based on different maximum allowable CEEP as a percentage of total wind power generated.

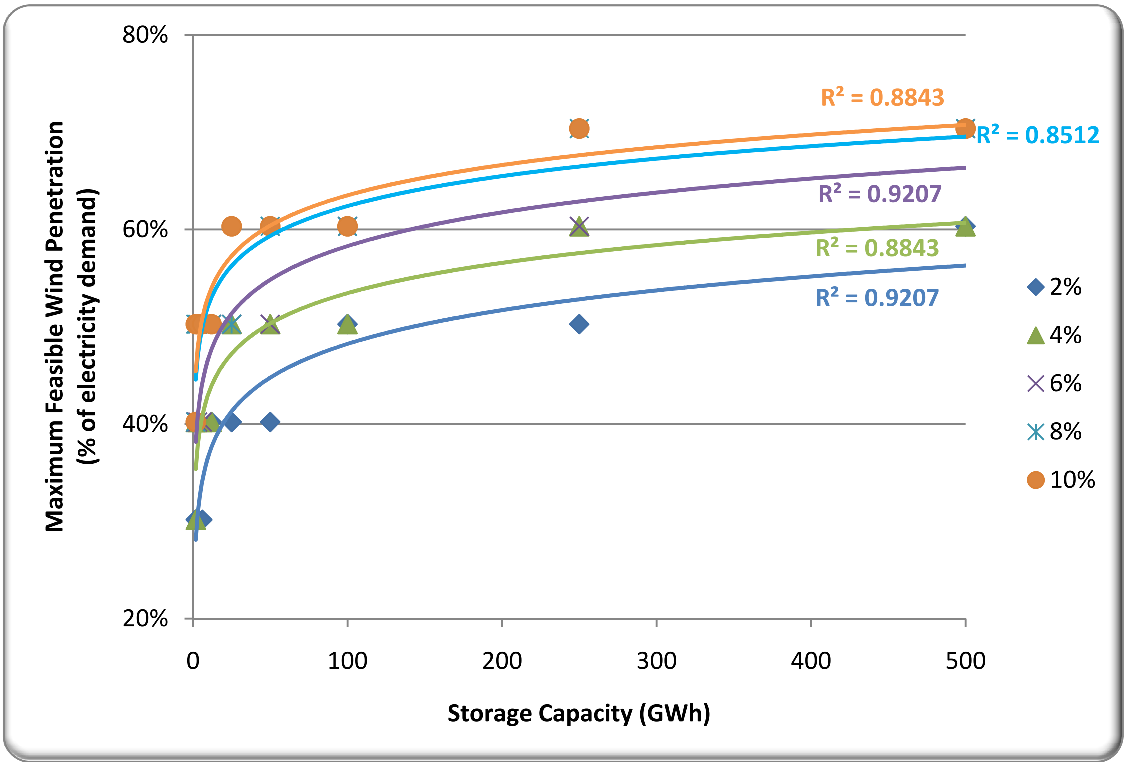


Figure 8-12: Maximum feasible wind penetration with various single PHES storage capacities on the 2020 Irish energy system based on different maximum allowable CEEP as a percentage of total electricity generated.

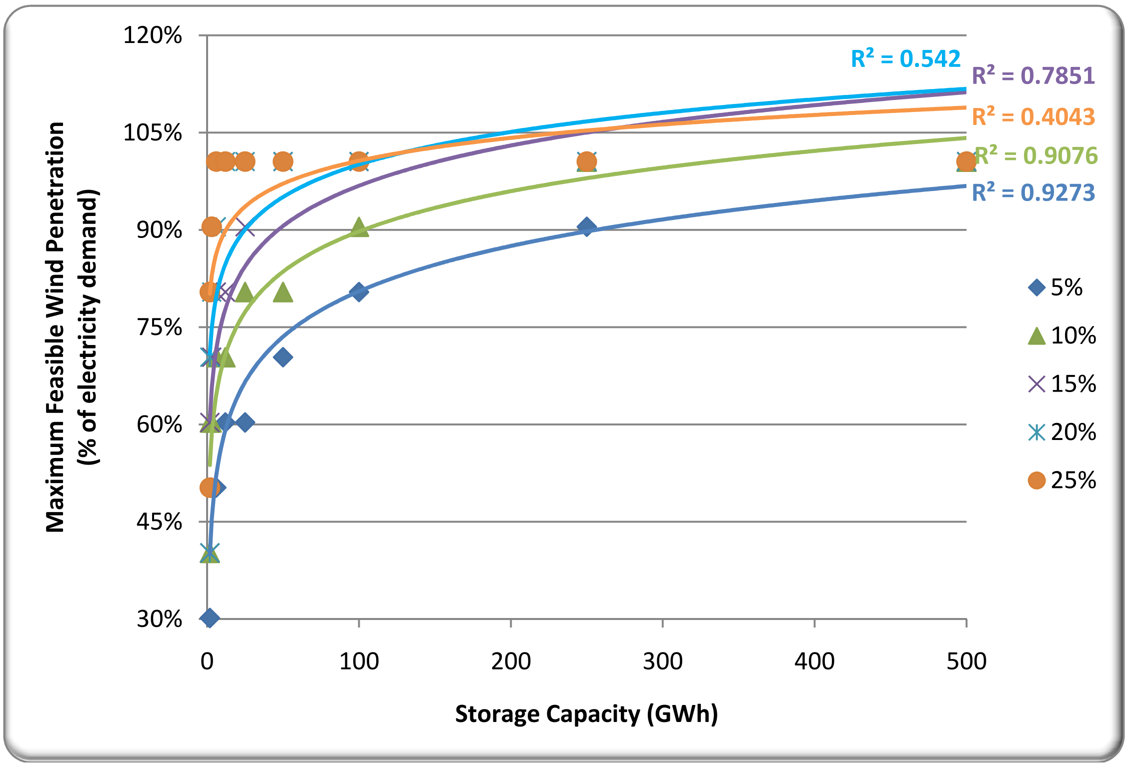


Figure 8-13: Maximum feasible wind penetration with various <u>double</u> PHES storage capacities on the 2020 Irish energy system based on different maximum allowable CEEP as a percentage of total wind power generated.

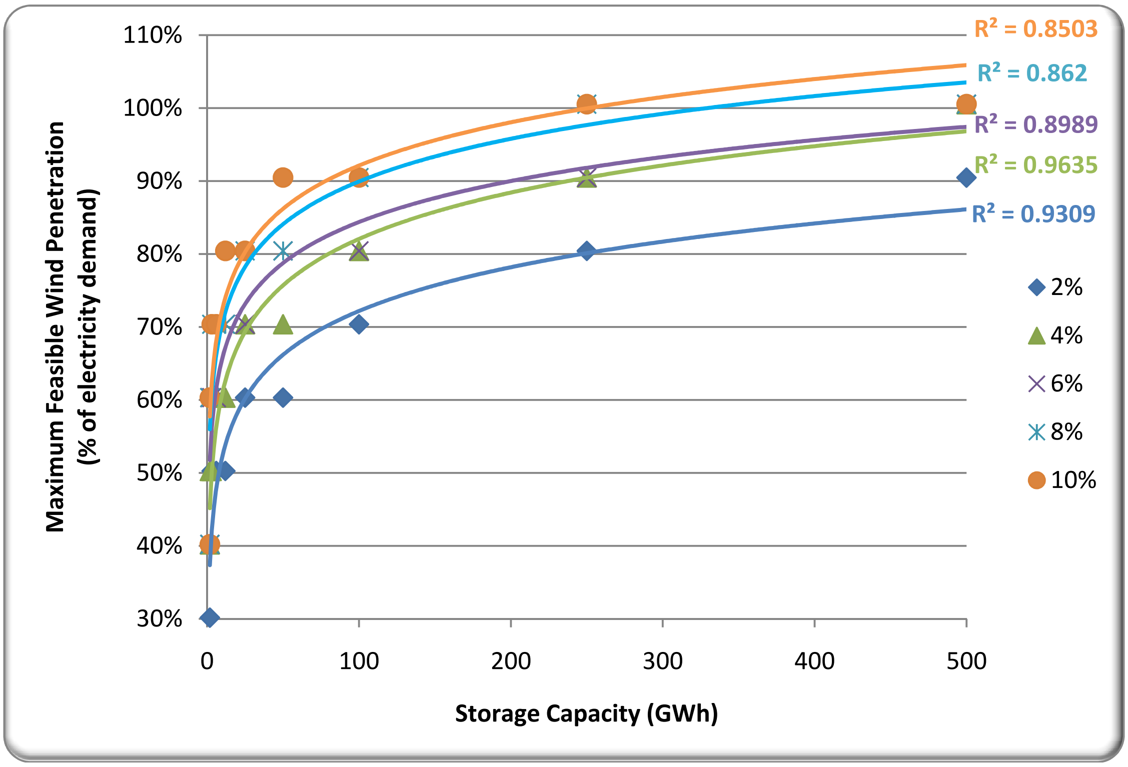


Figure 8-14: Maximum feasible wind penetration with various <u>double</u> PHES storage capacities on the 2020 Irish energy system based on different maximum allowable CEEP as a percentage of total electricity generated.

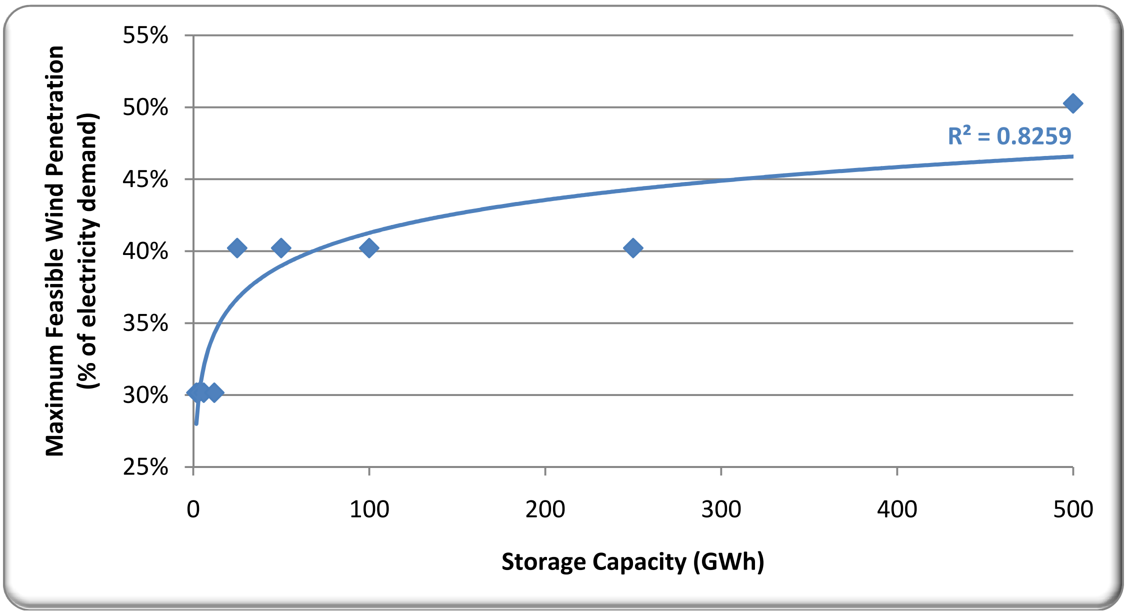


Figure 8-15: Maximum feasible wind penetration with various single PHES storage capacities on the 2020 Irish energy system based on the COMP coefficient developed in Appendix F.

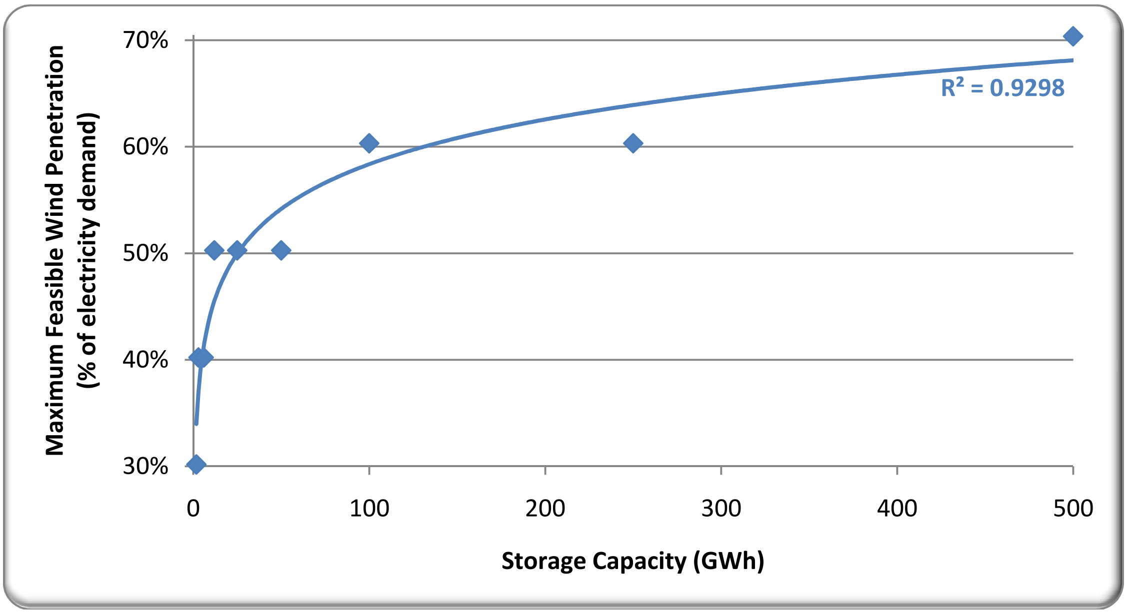


Figure 8-16: Maximum feasible wind penetration with various double PHES storage capacities on the 2020 Irish energy system based on the COMP coefficient developed in Appendix F.

8.3.3. Impact on Power Plant Operation

As almost 80% of the electricity generated in Ireland is from conventional power plants (see Table 8-13), it is important to consider the implications of large-scale wind and PHES on their operation. One of the most important implications to consider is the ramping requirement from the power plants caused by the addition of fluctuating renewable energy (i.e. wind). Therefore, to ensure that the results being produced by the EnergyPLAN model were realistic, the power plant fluctuations required were analysed on an hourly basis over a complete year (8784 hours) for different PHES scenarios and operating strategies. It was assumed for this analysis that the ramp-up demand on the power plants would be more important than the ramp-down demand and hence, it was the ramp-up demand which was analysed in detail, as displayed in Table 8-15 and graphed in Figure 8-17.

The results in Table 8-15 and Figure 8-17 were obtained using the power and storage capacities identified in section 8.3.2 previously (see Figure 8-9 and Figure 8-10), which provided the MFWPs for the different PHES operating strategies. It is evident in part 1.1 of Table 8-15 that for a single penstock PHES both the scale and frequency of the ramp-ups required from power plants increases as additional wind and PHES are added to the reference scenario. However, after analysing the operation of the system during the hours before the ramp-ups occurred, it became apparent that a number of these ramp-ups happened when the PHES facility finished emptying after discharging over a prolonged period of time. Therefore, these situations could be anticipated in advance and hence they could be avoided. To account for this, ramp-up demands were analysed once again while 'considering the PHES discharge'. It was assumed that if the PHES facility had energy available in the facility for each of the six hours prior to the hour where the ramping demand occurred, and the average energy in the PHES over this six hour period was greater than 500 MWh, then the ramping demand that occurred could have been avoided. Therefore, also displayed in Table 8-15 are the ramp-up demands for the single and double PHES for each scenario after this assumption was applied to the results.

Looking at the results in Table 8-15 and Figure 8-17 which did consider the discharge of PHES, it is clear that the ramping demands for power plants are larger when the MFWP is achieved on the REF2020 system, in comparison to those that occurred on 2009 energy system for both a single and double PHES. However, for all PHES operating strategies, wind capacities, and PHES capacities where the MFWP is achieved, the additional ramp-up demands placed on the power plants decreases with increasing storage capacities. Eventually at 500 GWh, the overall ramp-up demands on the power plants are larger in magnitude, but much less frequent than those that occurred during the operation of the 2009 Irish energy system (which had a wind penetration of only 10.5%). Therefore, it is assumed that adding large-scale wind and PHES to the existing Irish energy system will have a severe impact on the operation of existing power plants. However, if the discharge of the PHES facilities is controlled to prevent power plant fluctuations it will drastically reduce these implications, and as the storage capacities increase, it could eventually result in an energy system which is less challenging for power plants than the existing one.

Also, by comparing the single and double penstock operating strategies, it is evident from Table 8-15 and Figure 8-17 that for each storage capacity the double PHES requires similar ramping demands to the single PHES, even though the corresponding MFWPs are much larger for the double PHES. Consequently, not only can a double PHES accommodate the grid constraints specified, it can also integrate larger wind penetrations than a single penstock system while having similar implications on the power plant ramp-up demands. Finally, it is critical to recognise that EnergyPLAN is not designed for analysing the detailed operation of specific components such as power plants. Consequently, even though this analysis gives a realistic indication of the results, an energy tool designed for this specific issue is necessary for a more robust conclusion.

Table 8-15: Power plant ramping requirements for the MFWP identified at each storage capacity, using either a single or a double penstock system. Data is displayed graphically in Figure 8-17.

PHES Capacity		MFWP (% of electricity)	Average of Top 20 Power Plant Ramp-Ups (MW)	Number of Hours With PP Fluctuations*		
Pump-Turbine (MW)	Storage (GWh)			>1000 MW	<1000 MW & >500 MW	<500 MW & >250 MW
272: REF2009	1.8: REF2009	10.5%#	706#	1#	96#	717#
1. Single Penstock PHES						
1.1. Before Considering the PHES Discharge						
272: REF2020	1.8: REF2020	30%	946	7	266	812
600-500	1.8: REF2020	30%	951	6	322	824
700-600	3	30%	950	6	331	789
800-600	6	30%	934	5	307	792
1800-1300	12	40%	1344	93	413	707
1900-1600	25	40%	1470	75	332	683
2000-1800	50	40%	1594	51	291	657
3200-2400	100	50%	1889	129	286	599
4400-2600	250	60%	2194	168	276	493
4500-2700	500	60%	2186	128	246	489
1.2. After Considering the PHES Discharge						
272: REF2020	1.8: REF2020	30%	921	6	254	736
600-500	1.8	30%	918	5	267	758
700-600	3	30%	918	5	258	738
800-600	6	30%	918	5	255	730
1800-1300	12	40%	903	3	215	632
1900-1600	25	40%	904	3	210	612
2000-1800	50	40%	893	3	207	600
3200-2400	100	50%	952	3	158	491
4400-2600	250	60%	868	3	116	325
4500-2700	500	60%	862	3	108	314
2. Double Penstock PHES After Considering the PHES Discharge						
272: REF2020	1.8: REF2020	30%	922	5	260	759
2200-1400	1.8: REF2020	50%	980	7	248	724
2600-1500	3	50%	980	7	241	699
2900-1500	6	50%	960	5	229	681
4100-1900	12	60%	952	4	198	563
4400-2000	25	60%	952	4	193	547
5700-2400	50	70%	935	3	160	440
7000-2900	100	80%	898	2	131	349
8200-3200	250	90%	871	1	95	229
9600-3600	500	100%	848	1	50	143

***Total of 8784 hours.**
#Based on historical 2009 data [234, 235].

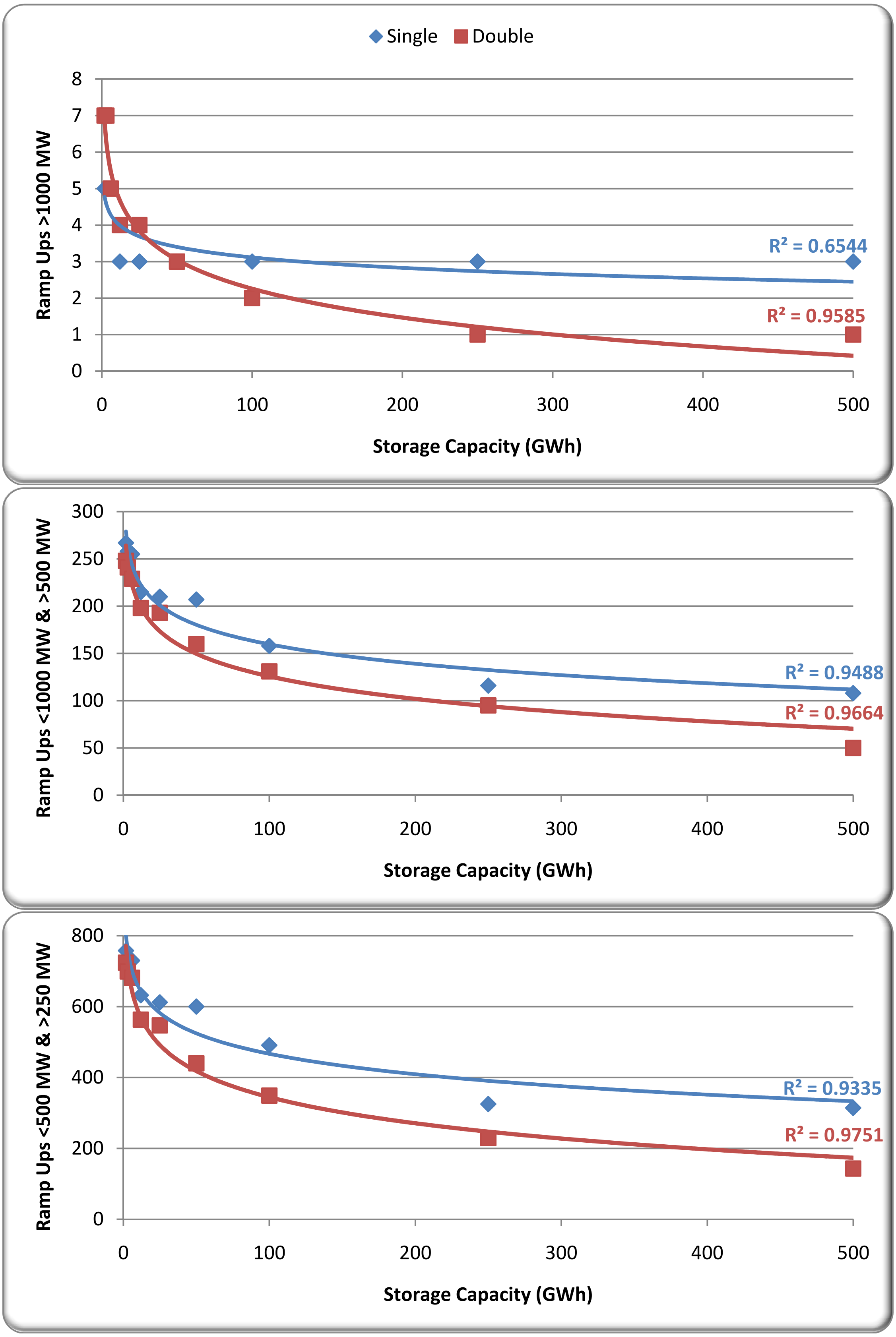


Figure 8-17: Scale and frequency of ramp-up demands placed on power plants for the MFWP identified at each storage capacity, when using either a single or a double penstock system: data provided in Table 8-15.

8.3.4. Summary

Overall, this section illustrates that large-scale PHES can enable higher wind penetrations on the Irish energy system, while also reducing the total energy required and the resulting CO_2 emissions. In addition, compared to their current operation, there are larger and more frequent ramping demands placed on power plants when the MFWP is achieved. However, as the storage capacity of PHES is increased, these ramping demands reduce and can even become less severe than those recorded for the year 2009. Finally, it was also evident in this section that the PHES pump and turbine capacities required to integrate wind power are not the same as each other. For both a single and double penstock operating strategy, it is evident that the pump capacity is related to the installed capacity of wind generation, while the turbine capacity is related to the installed power plant capacity. In addition, a double PHES system can integrate larger wind penetrations than a single PHES, even at much smaller storage capacities. However, to do so a double PHES requires much larger pump and turbine capacities. Due to the higher capital costs associated with a double PHES, it is difficult to conclude which operating strategy is the most effective at integrating wind power. Therefore, the following section investigates if the extra flexibility from a double penstock system is worth the additional investment required.

8.4. The Economic Implications of PHES

The technical assessment of PHES for the integration of wind energy has revealed a number of complex relationships between the capacities required and the corresponding MFWPs feasible for a single and double PHES. Therefore, this section estimates the cost of constructing and operating the scenarios proposed in section 8.3 under a variety of different economic assumptions. The results here were identified using version 8.3 of EnergyPLAN.

8.4.1. Costs for One PHES Capacity

The annual operating costs of the Irish energy system are made up of investment repayments, fuel costs, fixed O&M costs, variable O&M costs, as well as the exchange of electricity over the interconnector. A detailed description of the equations used within EnergyPLAN to calculate these costs are outlined on the EnergyPLAN website [181] and in Appendices E, F, and H. For these calculations, a range of assumptions have to be made in relation to investment costs, operation and maintenance costs, and lifetimes to analyse the costs of adding wind power and PHES to the 2020 Irish energy system. Those assumed for wind turbines and PHES are all displayed in Table 8-16, while the costs assumed for all the other components[11] on the Irish energy system are outlined in Appendices E and F. Although there are a wide range of costs reported for a single PHES [99, 170], no historical data was identified for the double PHES. Therefore, it was assumed that the double PHES would cost twice as much as a single PHES, considering the additional penstock, grid infrastructure, and components that would be required. This also accounts for a scenario where two single penstock PHES facilities need to be constructed to create a double penstock operating strategy. For the initial cost assessment, fuel prices corresponding to an oil price of $100/bbl for 2020 were assumed (see Table 8-17), along with an interest rate of 6% which has been used when assessing other energy infrastructure in Ireland [236]. Also, based on 2020 projections by the IEA, a CO_2 cost of $50/t was also incorporated into the calculations [4].

[11] All other investment costs remain the same in the analyses completed in this study and hence they are not essential to the PHES analysis.

Table 8-16: Costs assumed for PHES and wind turbines [99, 170, 237, 238].

Plant Type*	Pump-Turbine Investment (€M/MW)	Storage Investment (€M/GWh)	Fixed O&M (% of Investment)	Variable O&M (€/MWh)	Lifetime (Years)
Single PHES	0.50	7.5	1.5	1.5	40
Double PHES#	1.00	7.5	1.5	1.5	40
Wind turbines	1.14	0.0	1.8	0.0	20

***Transmission costs were not considered as the Irish TSO, EirGrid, has not specified which technologies are responsible for individual costs of transmission.**
#However, it was assumed that a double penstock would require more transmission than a single penstock, which is incorporated in the investment cost.

Table 8-17: Fuel prices assumed for 2020 in the analyses (€/GJ) [4, 239].

Crude Oil ($/bbl*)	Crude Oil	Fuel Oil	Gas Oil/ Diesel	Petrol/JP	Coal	Natural Gas	Biomass
100	13.60	9.60	17.00	18.00	3.19	8.16	7.00
150	20.40	14.40	25.50	27.00	4.23	12.49	7.00

***Assumed exchange rate of €1 = $1.282.**

Using these assumptions, the cost of a 2500 MW 25 GWh PHES on the 2020 Irish energy system while operating as both a single and a double penstock system was simulated for wind penetrations of 0% to 100% (0-30 TWh) of the electricity demand. As displayed in Figure 8-18, the results indicate that the PHES facility does not increase the wind penetration enough to warrant the initial investment required, with the reference scenario proving to be the most economical. In addition, the results suggest that the double penstock is not worth the additional investment required as it is more expensive than the single penstock operating strategy up to a wind penetration of 18 TWh (60%). However, this analysis was completed using only one PHES capacity and hence, the next section calculates the cost of integrating wind energy using the range of different PHES capacities identified earlier in section 8.3.2.

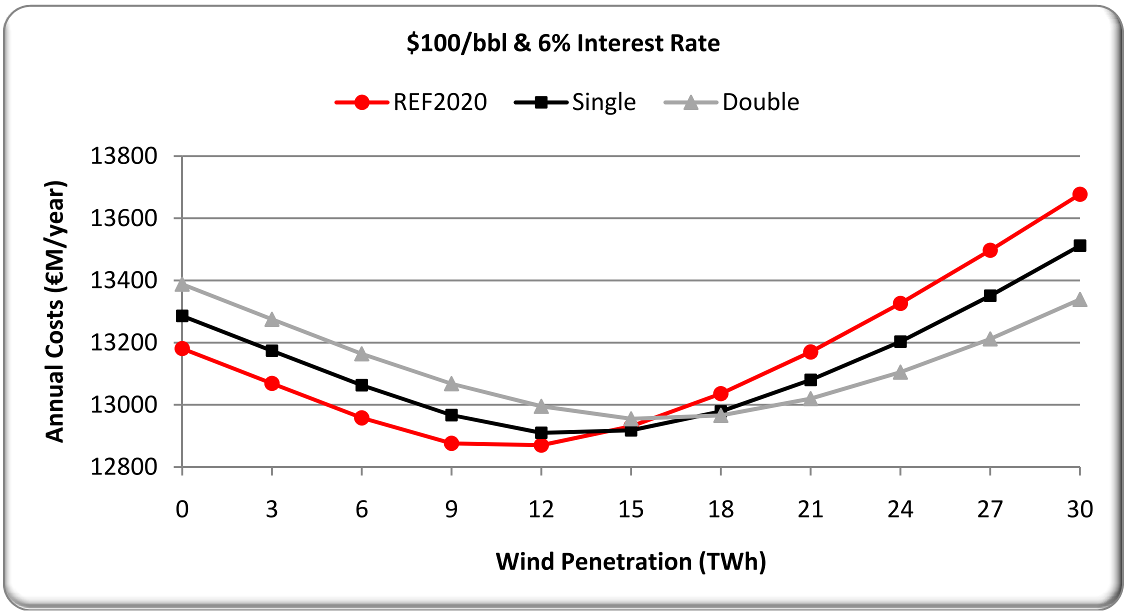


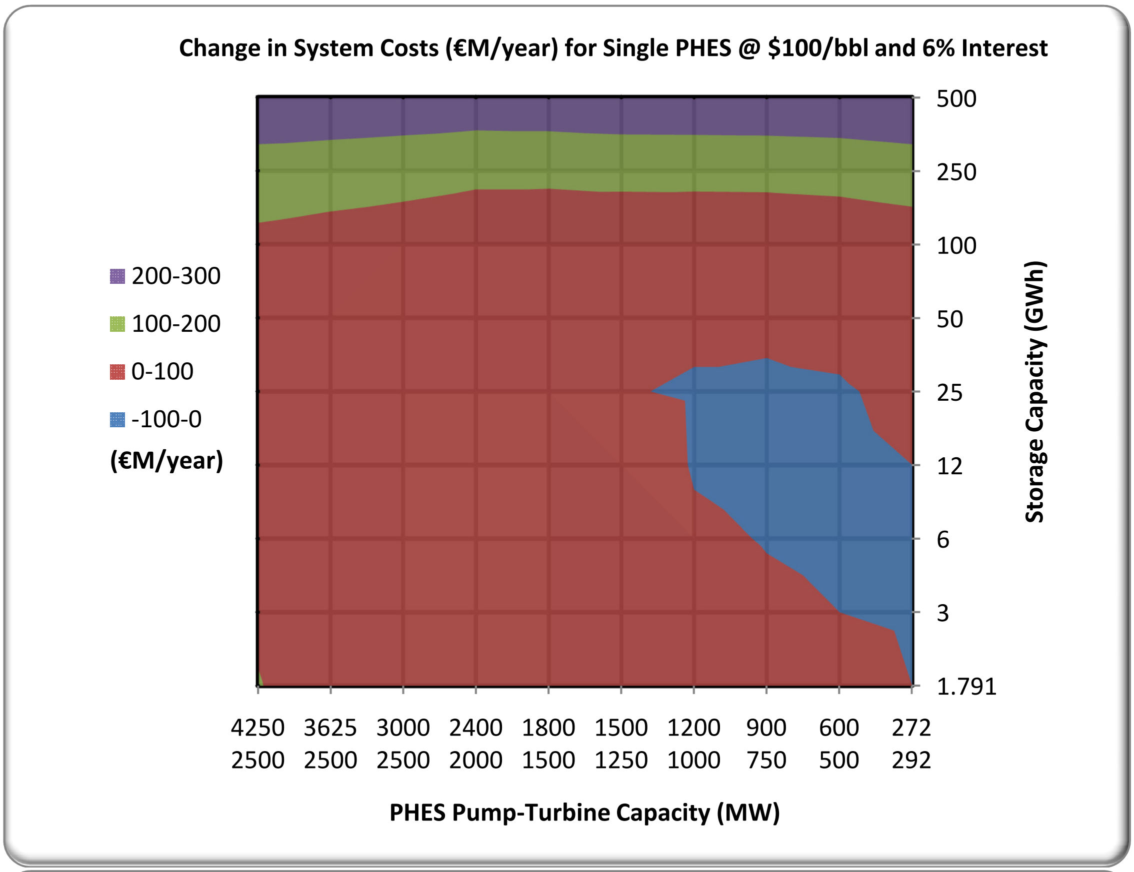
Figure 8-18: Cost of operating the Irish energy system in 2020 for the reference scenario, a 2500 MW / 25 GWh single PHES scenario, and a 2500 MW / 25 GWh double PHES scenario, for wind penetrations of 0% to 100% (0-30 TWh) of electricity demand, assuming fuel prices based on an oil price of $100/bbl and an interest rate of 6%.

8.4.2. Costs for Various PHES Capacities

Based on the ratios identified between the pump and turbine capacities in section 8.3.2, a selection of pump-turbine combinations (which are outlined in Table 8-18) were chosen to assess the operating costs over a range of different PHES storage capacities. These pump-turbine capacities were simulated for all 9 storage capacities considered and once again in each simulation the wind penetration was varied from 0-100% in steps of 10% on the 2020 Irish energy system. Subsequently, the cheapest wind penetration was identified for each combination of the PHES capacities, which is illustrated in Figure 8-19 for a single PHES and in Figure 8-20 for a double PHES.

Table 8-18: Pump and turbine capacities assumed when evaluating the economic viability of a single and double PHES system for various storage capacities.

Single PHES			Double PHES		
Pump	Turbine	Ratio ($C_{Pump}/C_{Turbine}$)	Pump	Turbine	Ratio ($C_{Pump}/C_{Turbine}$)
272	292	Reference	272	292	Reference
600	500	1.2	642	292	2.2
900	750	1.2	1650	750	2.2
1200	1000	1.2	2750	1250	2.2
1500	1250	1.2	3850	1750	2.2
1800	1500	1.2	4950	2250	2.2
2400	2000	1.2	6050	2750	2.2
3000	2500	1.2	7150	3250	2.2
3625	2500	1.45	8250	3750	2.2
4250	2500	1.7			



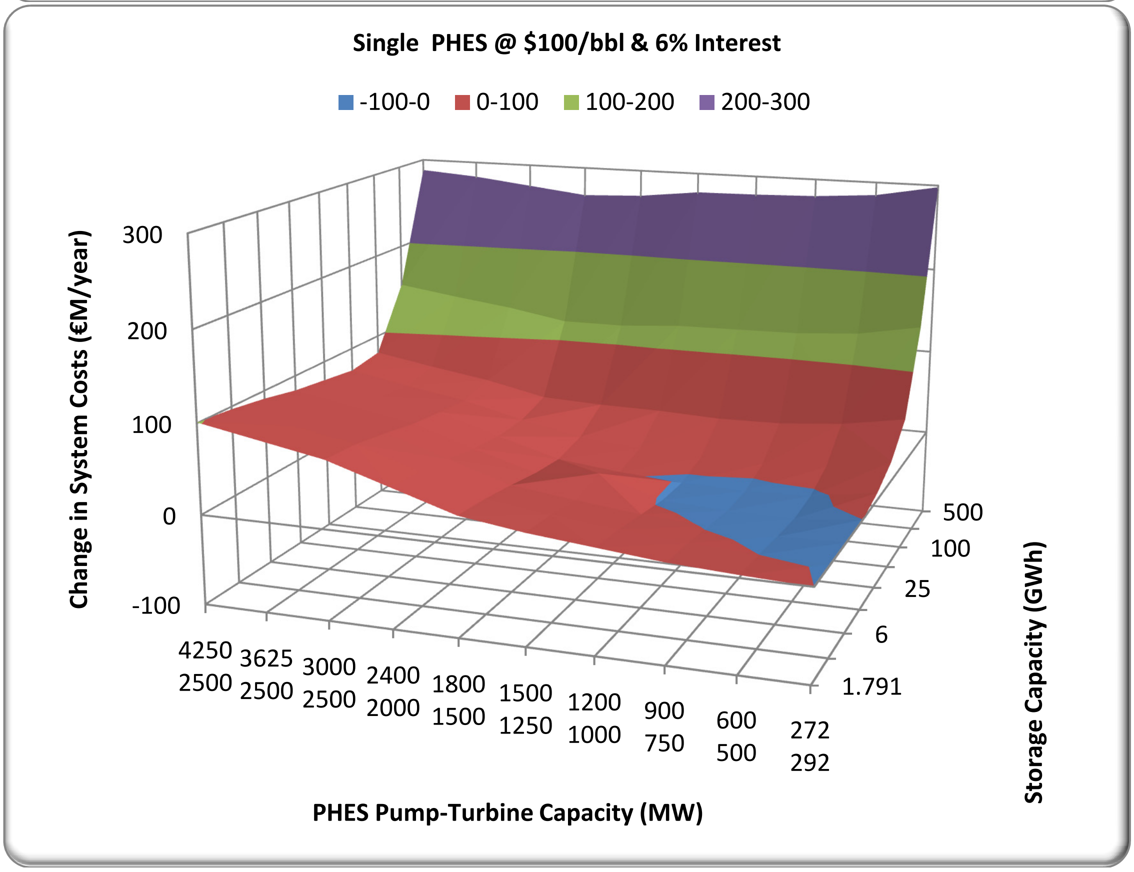
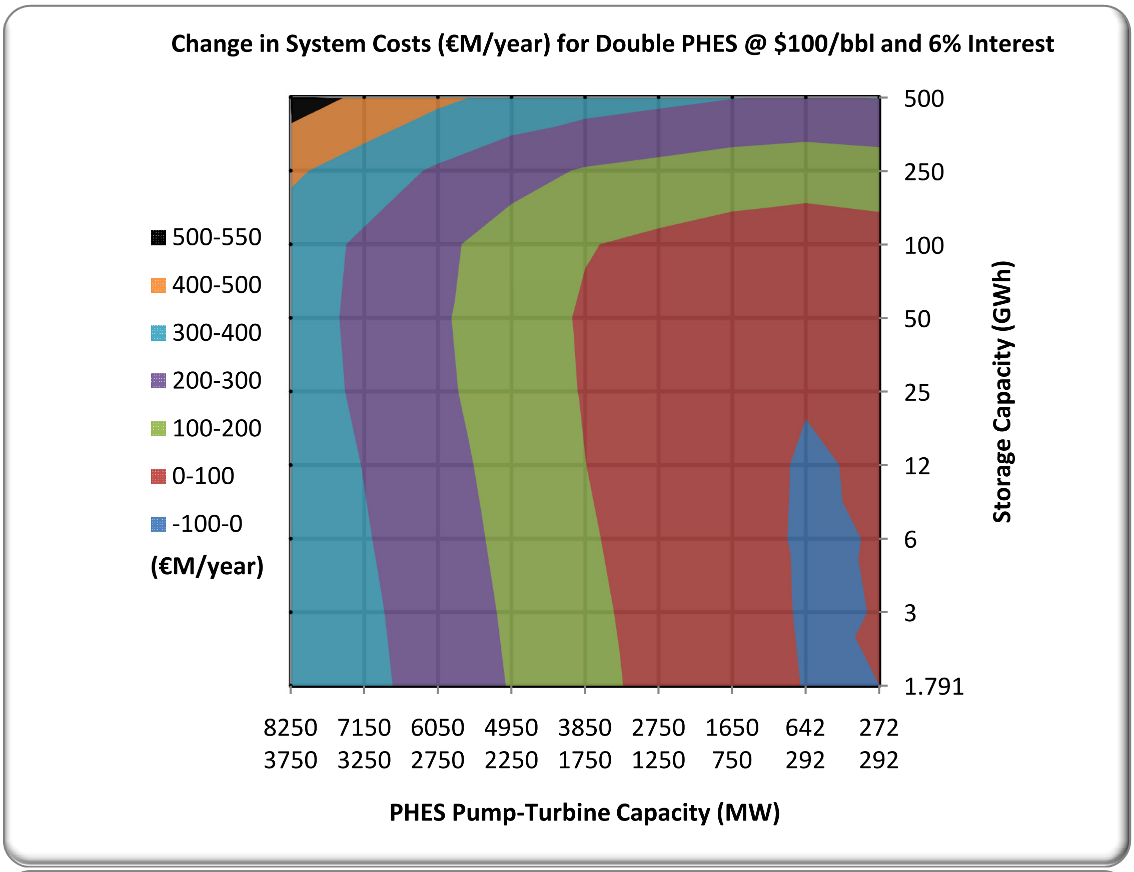


Figure 8-19: Change in energy system costs when various single PHES capacities from Table 8-18 are added to the 2020 Irish energy system compared to the reference, assuming fuel prices corresponding to $100/bbl and using an interest rate of 6%.



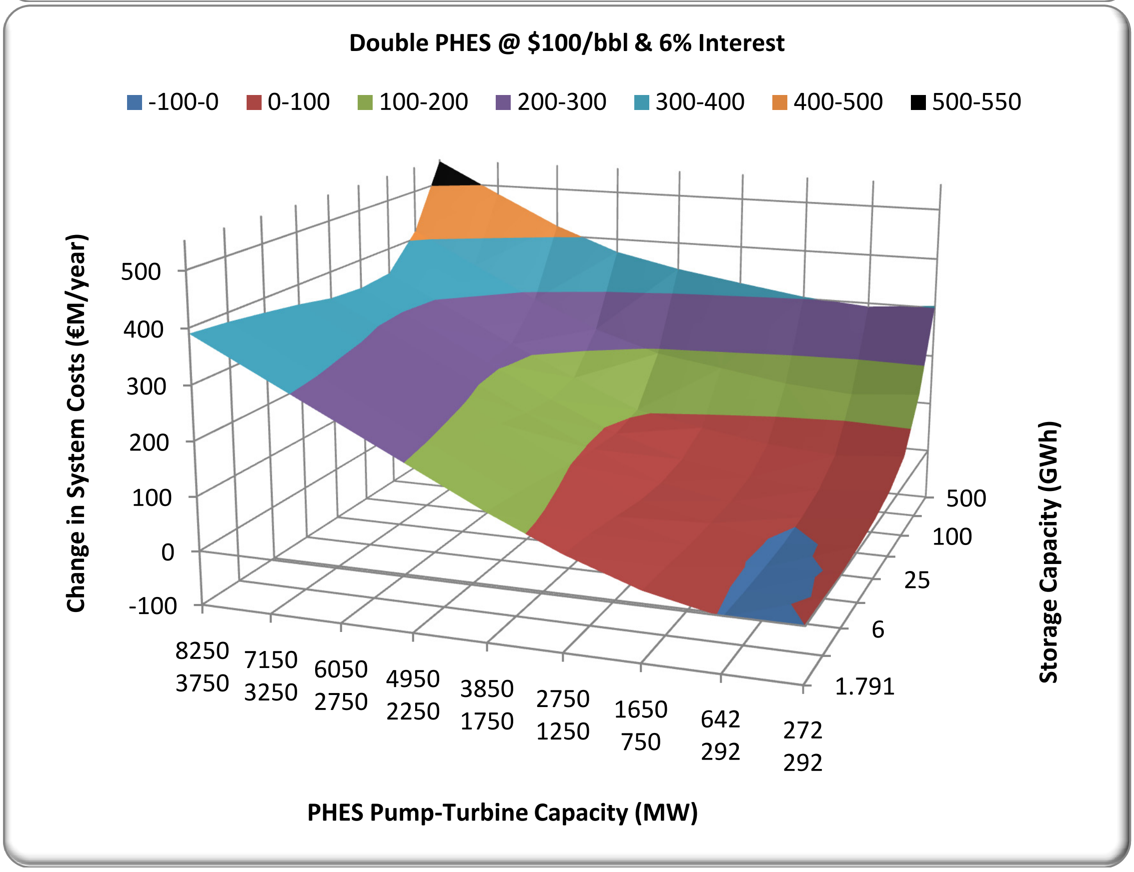


Figure 8-20: Change in energy system costs when various double PHES capacities from Table 8-18 are added to the 2020 Irish energy system compared to the reference, assuming fuel prices corresponding to $100/bbl and using an interest rate of 6%.

From the results, it is evident that the sizing of a PHES has dramatic implications on the overall operating costs of the system. Contrary to the results identified in Figure 8-18, the results in both Figure 8-19 and Figure 8-20 indicate that PHES could reduce the overall operating costs of the Irish energy system. However, the scale of these cost reductions are quite small and as such, Figure 8-21 indicates that the cheapest scenario for both a single and a double PHES only reduced the operating costs by approximately €9M/year and €3M/year respectively. Hence, there were no significant economical gains from the addition of PHES. Finally, it is also clear from Figure 8-19 and Figure 8-20 that the total operating costs of the system can be increased dramatically if the PHES capacities are not optimised for the system in question, especially for a double PHES. Therefore, it can be concluded that wind and PHES are capable of reducing the operating costs of the Irish energy system, but under 2020 cost predictions and considering the scale of these reductions along with the risk of increasing the operating costs, PHES is not yet an attractive alternative. Finally, to further investigate the validity of these conclusions, a sensitivity analysis was completed on a range of key parameters.

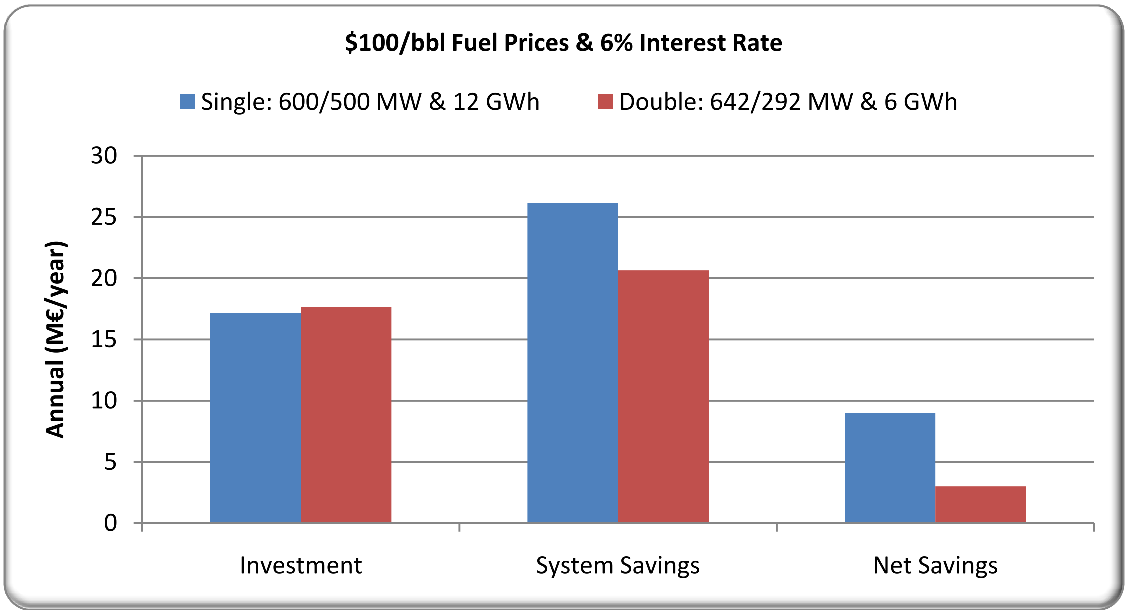


Figure 8-21: The investment and savings for the single and double PHES capacities which provided the largest reduction in system costs (40% wind penetration for both), when analysed using fuel prices corresponding to $100/bbl and an interest rate of 6%.

8.4.3. Sensitivity Analysis

The key parameters assessed in this sensitivity analysis include changes in the wind energy produced, a lower interest rate on investments, an increase in fuel prices, and a lower investment cost for the double PHES facility.

Wind Generation

There are two aspects to wind which were analysed in this sensitivity analysis: hourly distribution and total annual generation. The hourly wind distribution data in this study was based on historical data recorded in Ireland from the year 2009 [23]. To ensure that this particular wind distribution was not an artefact leading to erroneous conclusions in this study, the results were repeated based on hourly wind data recorded in Ireland from the year 2007. Using this data, there was no significant change in the trends identified in this study.

Also, changes in the total annual electricity generation from wind were assessed. As the installed wind capacity in Ireland has increased by an average of 35% each year between 1999 and 2009, it is difficult to conclude what variation occurs in total wind production from one year to the next using historical data. However, by analysing Danish wind data from 2003 to 2008[12] [240], it is evident that the total wind power produced from the same capacity of wind turbines can vary by up to +/-20% from one year to the next. Therefore, this has been used as a proxy in this study. The annual operating costs were recalculated based on an expected wind production which produced an actual wind production of +/-20% for three different scenarios: the REF2020 scenario with no additional PHES, the REF2020 system with a 2500 MW 25 GWh single PHES facility, and finally the reference REF2020 scenario with a 2500 MW 25 GWh double PHES facility. As expected, Figure 8-22 indicates that a 20% increase in the expected wind production will reduce the annual operating costs for each scenario while a 20% decrease in wind production will inflate costs. Due to the insignificant role of additional PHES below a wind penetration of 9 TWh (30%), the change in annual costs is the same for all three scenarios until this point. Afterwards, the reference scenario shows the least variation in costs, followed by the single PHES, and the double PHES shows the largest deviation in annual operating costs due to a change in annual wind production. However, for all three scenarios the increase in costs for a +20% wind production is very similar to the corresponding decrease in costs due to a -20% production. In fact, in all scenarios simulated the increase in annual operating costs was never greater than the corresponding reduction in annual operating costs. This indicates that over the 40 year lifetime of a PHES facility, the additional costs that occur during years of low annual wind production should be cancelled out by the savings in years of high annual wind production.

[12] The installed wind capacity in Denmark was practically the same from 2003 to 2008, as the maximum and minimum capacity recorded for each of these years were 3163 MW and 3116 MW respectively.

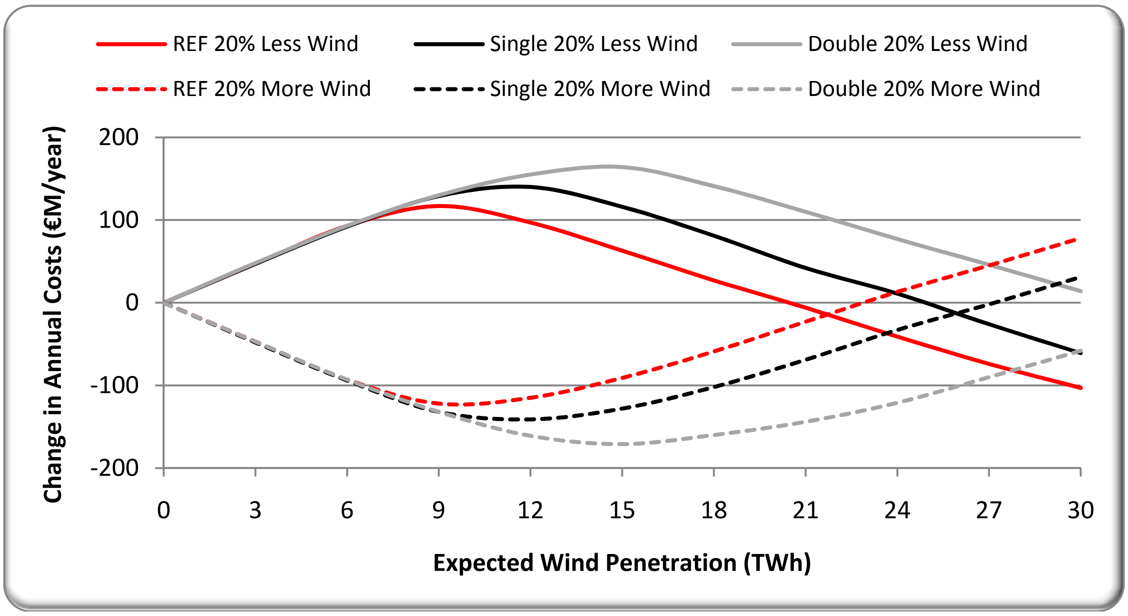


Figure 8-22: Change in annual costs (using a 6% interest rate and $100/bbl fuel prices) for an expected wind production of 0-30 TWh (0-100%) for the 2020 reference scenario on its own, with a single 2500 MW 25 GWh PHES, and with a double 2500 MW 25 GWh PHES.

3% Interest Rate

The economic calculations in this study were based on an interest rate of 6%, but it could be argued that a 3% interest rate is more applicable due to the 40 year lifetime of PHES and the societal gains from utilising more wind energy. Therefore, the costs were recalculated using a 3% interest rate instead, which are outlined in Figure 8-23 for the 2500 MW 25 GWh facility. As the initial investment costs for wind power and PHES are relatively high, a comparison between Figure 8-18 and Figure 8-23 indicates that a 3% interest would significantly improve the economical feasibility of a wind-PHES system in Ireland. This is even more apparent for the double penstock PHES, which could enable a wind penetration of approximately 60% using a 3% interest rate at a similar cost to the REF2020 scenario, which only has a wind penetration of 40%. Based on the trend identified here, the costs were also recalculated for the range of PHES capacities discussed in section 8.4.2 and displayed in Table 8-18. As outlined in Figure 8-24 to Figure 8-26, with an interest rate of 3% the optimum capacities for both a single and double penstock PHES could reduce the overall operating costs of the Irish energy system by approximately €25M/year and €35M/year respectively in 2020. In addition, the size of the PHES facility which provides the most economical scenario has increased significantly to 1800/1500 MW and 50 GWh for the single PHES and to 2750/1250 MW and 50 GWh for the double PHES.

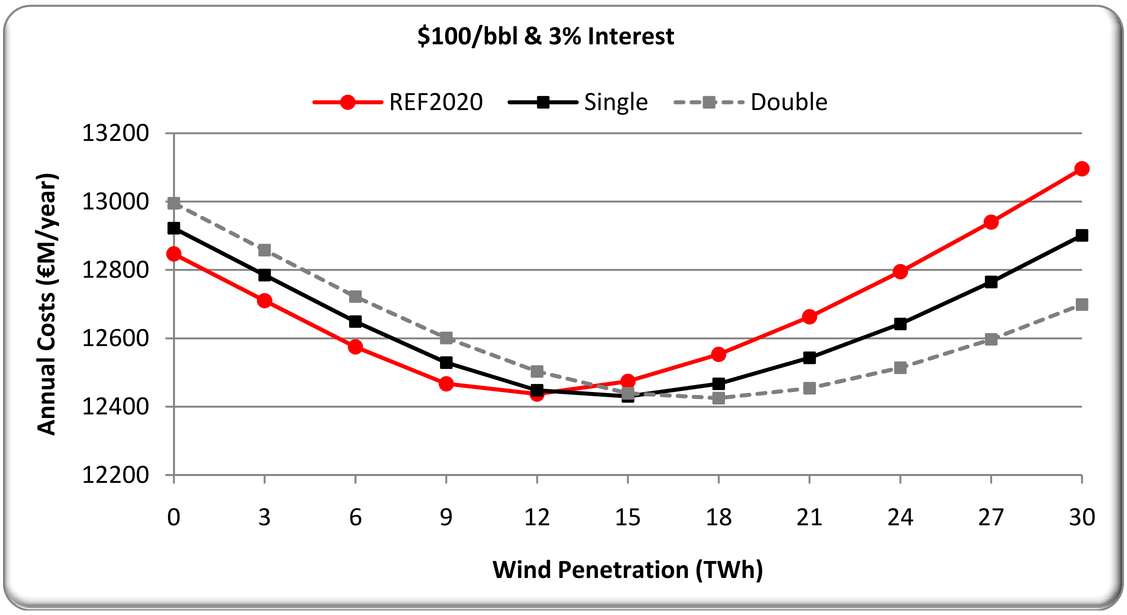
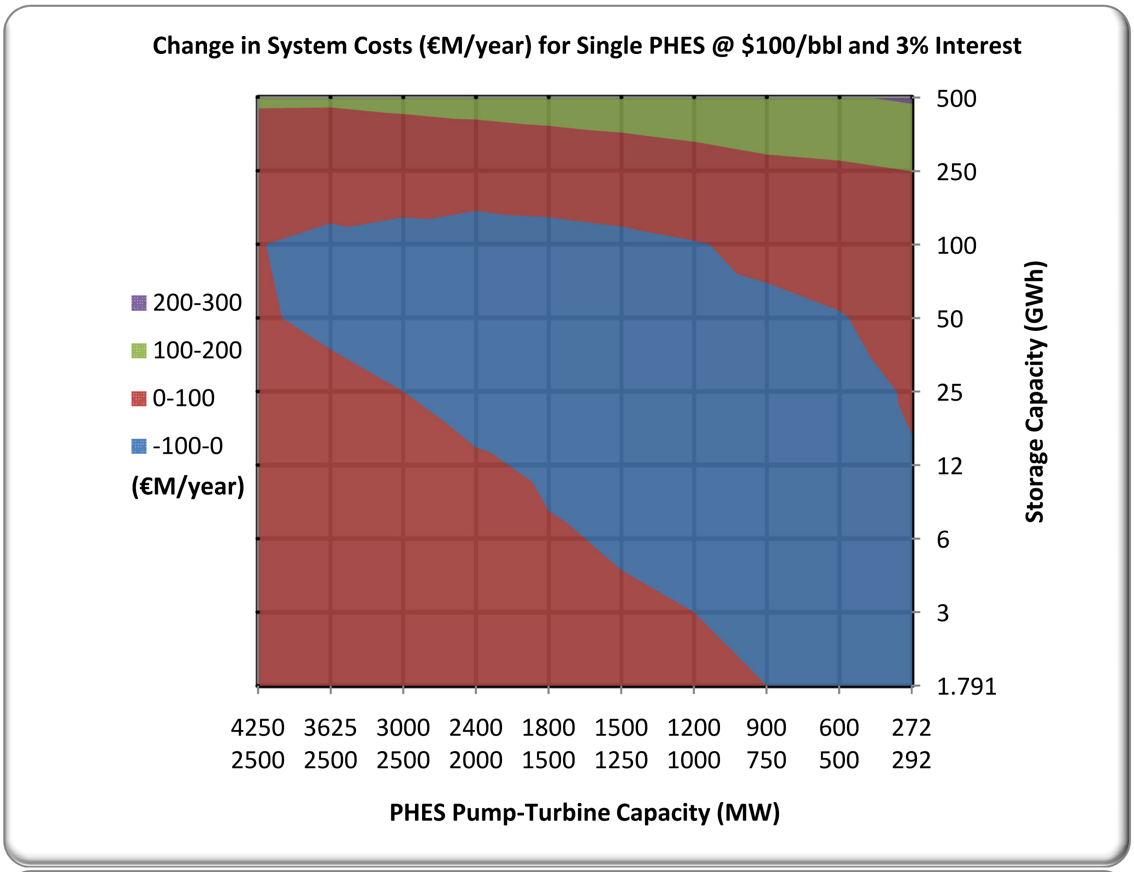


Figure 8-23: Cost of the Irish energy system in 2020 for the reference scenario, a 2500 MW / 25 GWh single PHES scenario, and a 2500 MW / 25 GWh double PHES scenario, for wind penetrations of 0% to 100% (0-30 TWh) of electricity demand assuming fuel prices based on an oil price of $100/bbl and an interest rate of 3%.



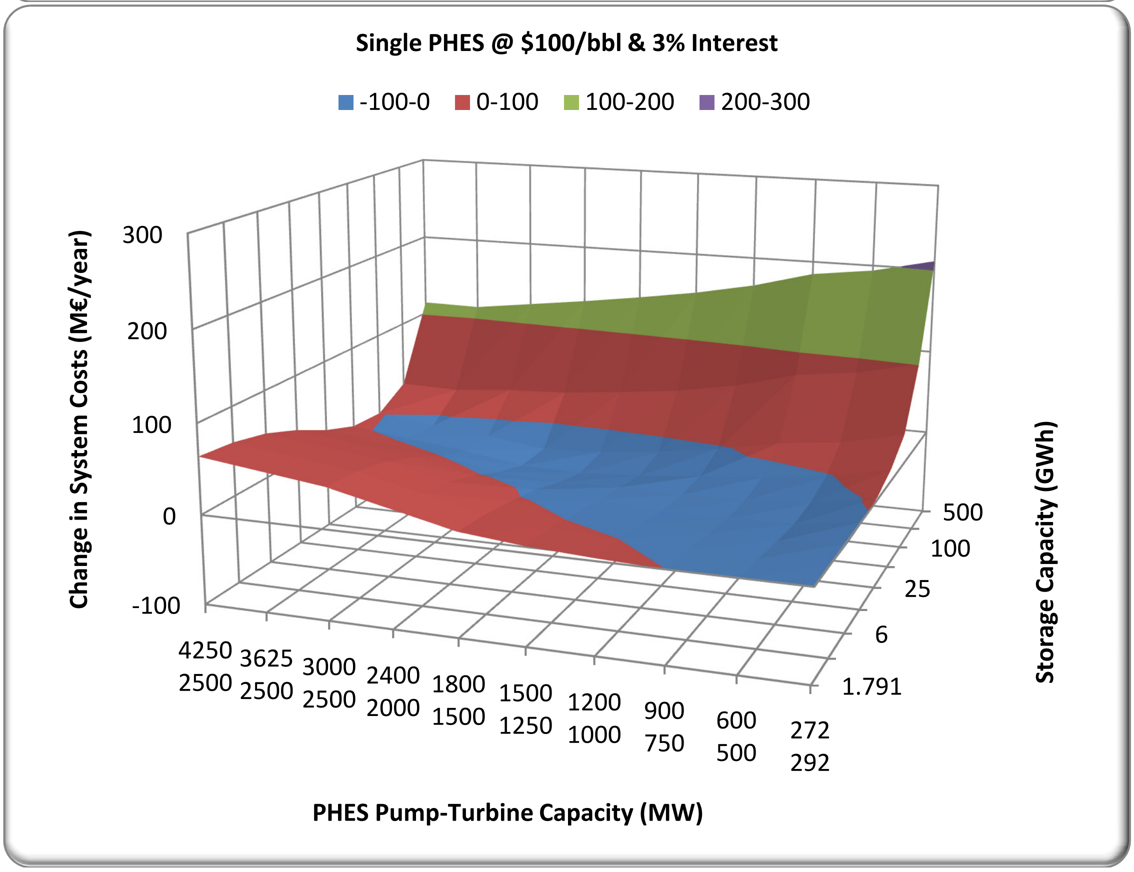
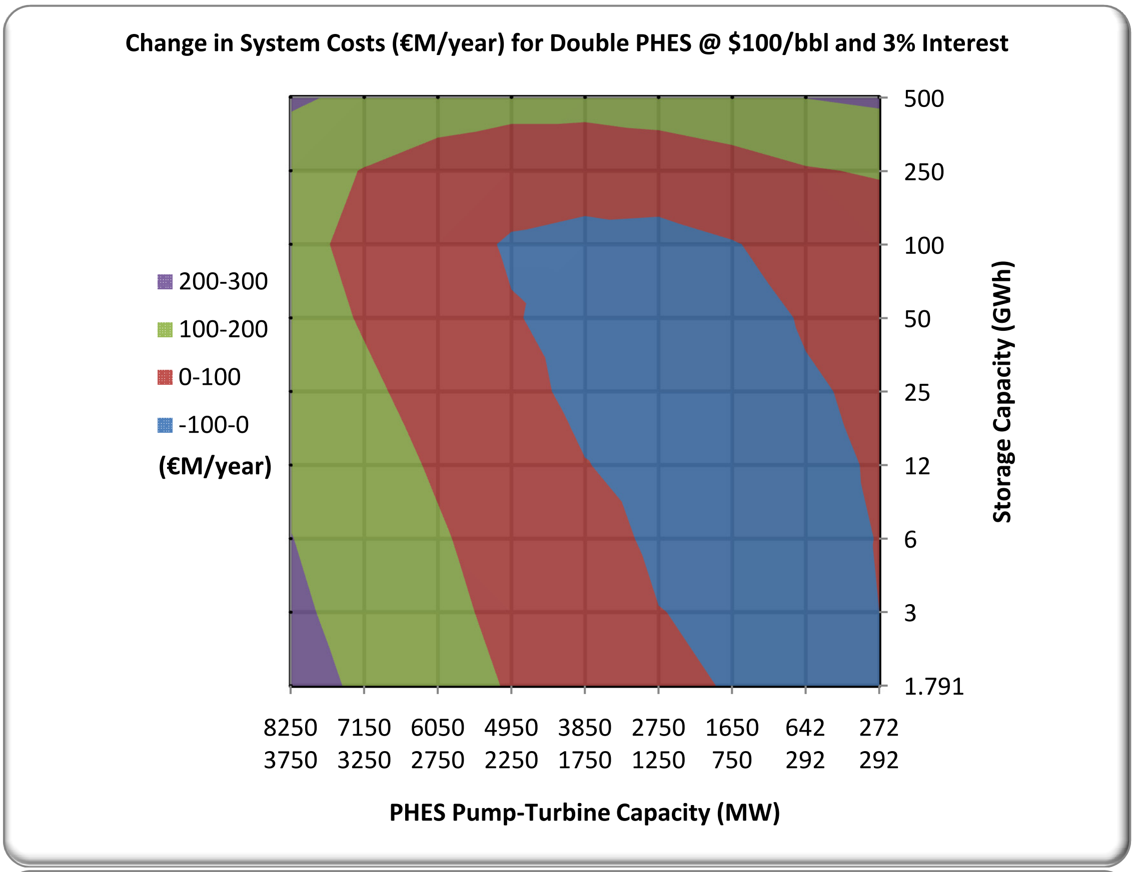


Figure 8-24: Change in energy system costs when various single PHES capacities from Table 8-18 are added to the 2020 Irish energy system compared to the reference, assuming fuel prices corresponding to $100/bbl and using an interest rate of 3%.



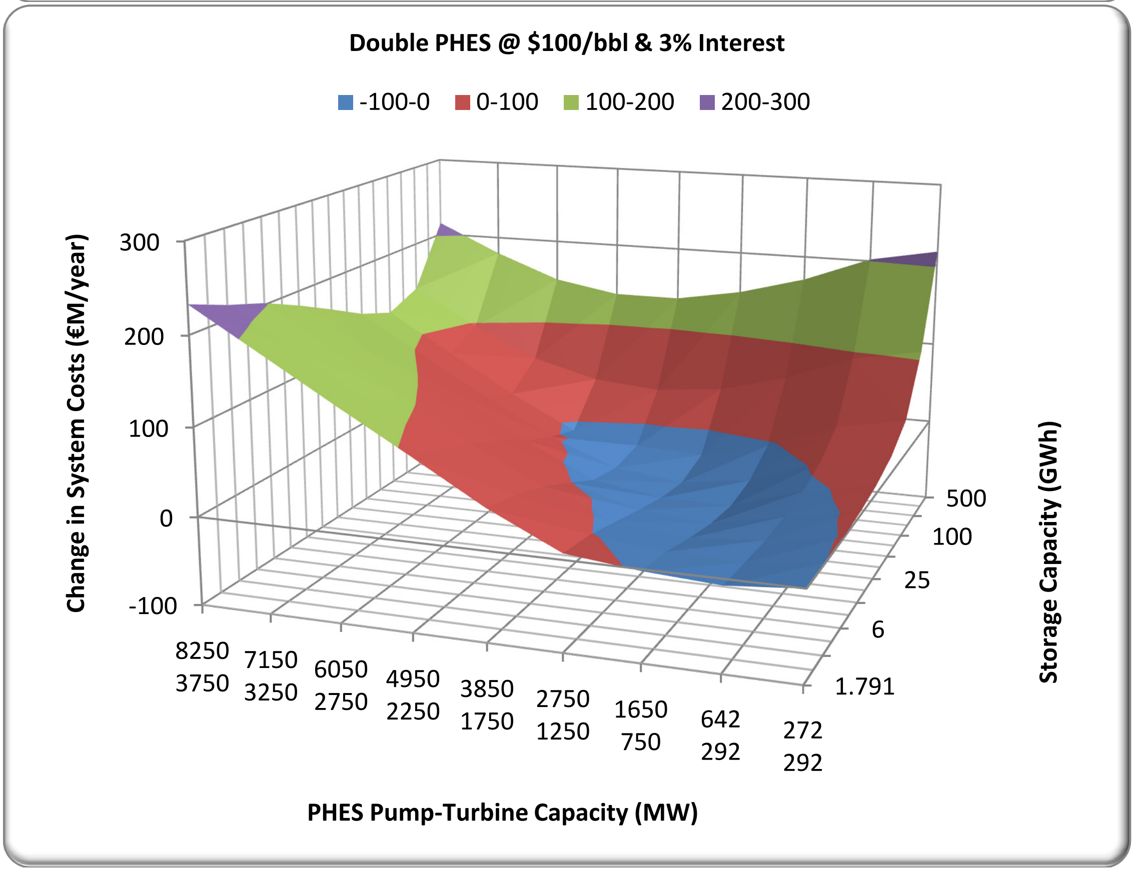


Figure 8-25: Change in energy system costs when various double PHES capacities from Table 8-18 are added to the 2020 Irish energy system compared to the reference, assuming fuel prices corresponding to $100/bbl and using an interest rate of 3%.

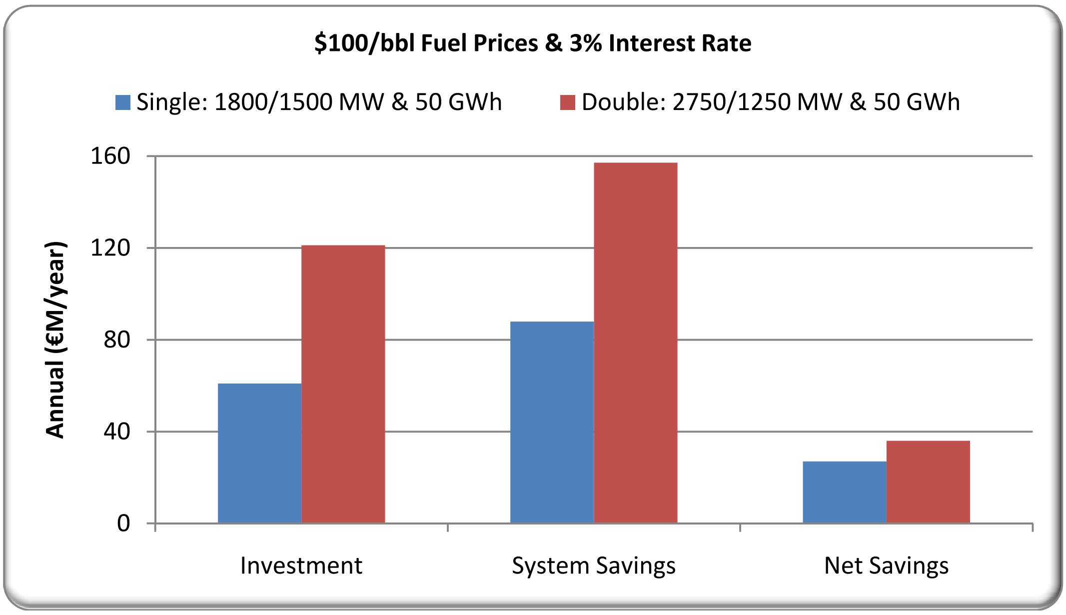


Figure 8-26: The investment and savings for the single and double PHES capacities which provided the largest reduction in system costs (50% wind penetration for single and 60% for double), when fuel prices correspond to $100/bbl and for an interest rate of 3%.

$150/bbl Fuel Prices

By 2020, global fuel prices are expected to reach an oil price equivalent of $100/bbl [4]. However, as already discussed in section 2.1 of this thesis, fuel prices can be extremely unpredictable due to many political and supply concerns [7]. To demonstrate the consequences of a fuel price increase, the results were recalculated based on an oil price of $150/bbl and an interest rate of 6%, with corresponding prices for other fuels outlined in Table 8-17. The results from the analysis were very similar to those observed for an interest rate of 3% and fuel prices corresponding to $100/bbl of oil. Once again a 2500 MW and 25 GWh double penstock PHES could enable a 60% wind penetration at a similar cost to a 40% wind penetration on the 2020 reference scenario, similar to the results presented for a fuel price of $100/bbl and a 3% interest, which is evident from Figure 8-27. Also, the optimum capacities for the single and double PHES were the same when using $150/bbl and 6% as those identified when using $100/bbl and 3%, which from Figure 8-28 was 1800/1500 MW and 50 GWh for the single PHES and from Figure 8-29 was 2750/1250 MW and 50 GWh for the double PHES. Once again, the reductions in operating costs in 2020 were €25M/year and €35M/year for the single and double respectively. The only key difference between the results was the scale of initial investments required. At a 3% interest rate and $100/bbl the initial investment costs for the single and double PHES were €60M/year and €120M/year respectively. As illustrated in Figure 8-30, at 6% and $150/bbl the investment costs were €85M/year and €170M/year, thus increasing the risk associated with constructing PHES.

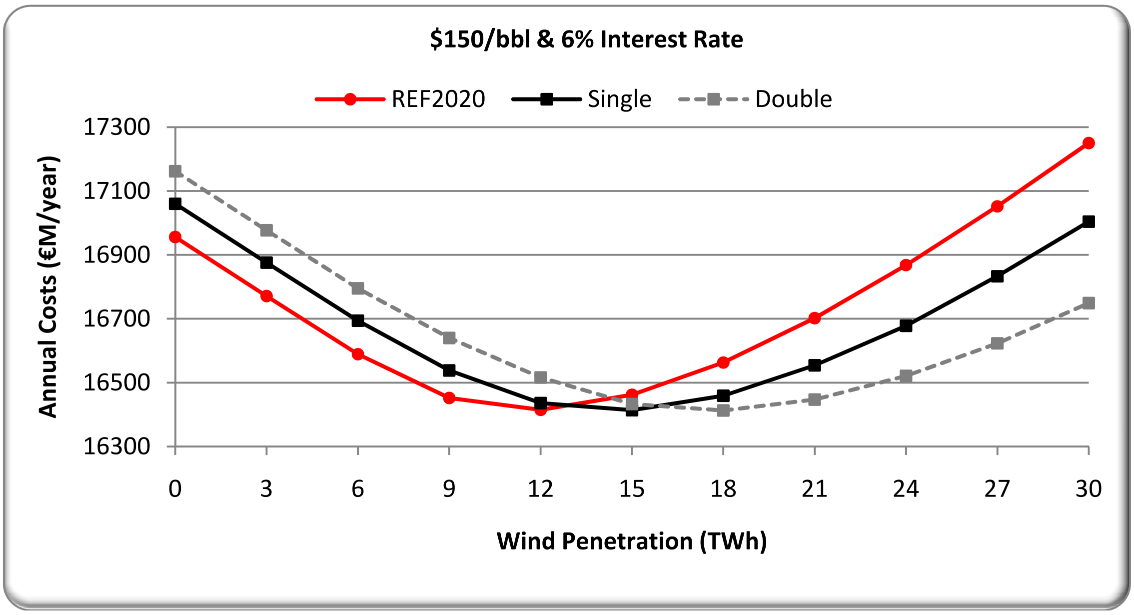
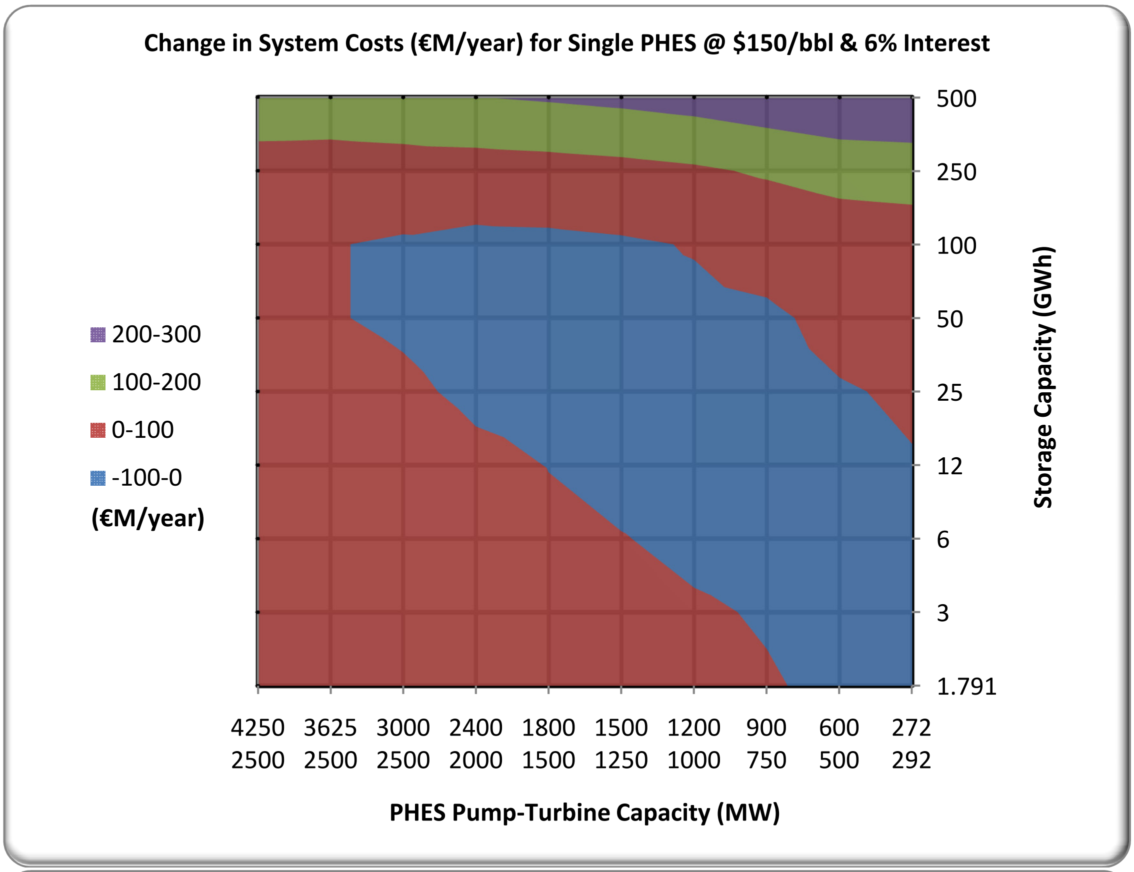


Figure 8-27: Cost of the Irish energy system in 2020 for the reference scenario, a 2500 MW 25 GWh single PHES scenario, and a 2500 MW 25 GWh double PHES scenario, for wind penetrations of 0% to 100% (0-30 TWh) of electricity demand assuming fuel prices based on an oil price of $150/bbl and an interest rate of 6%.



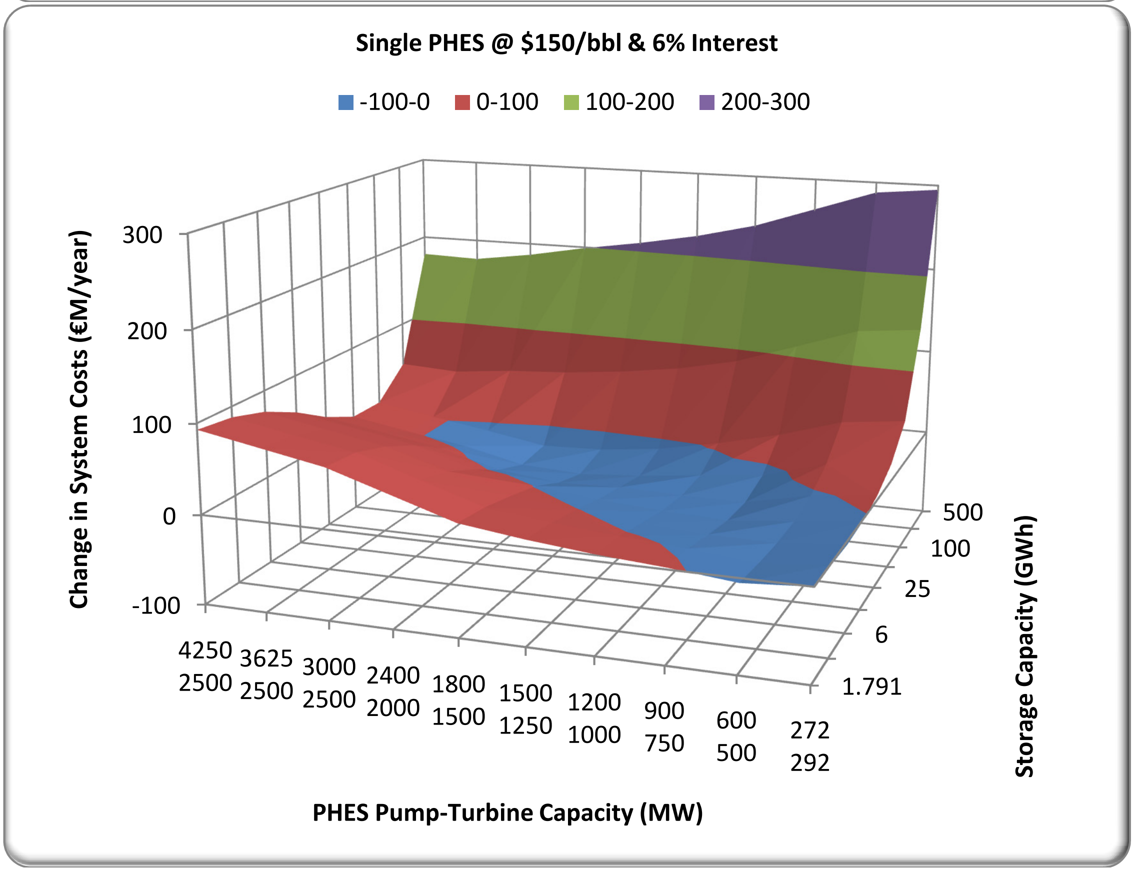
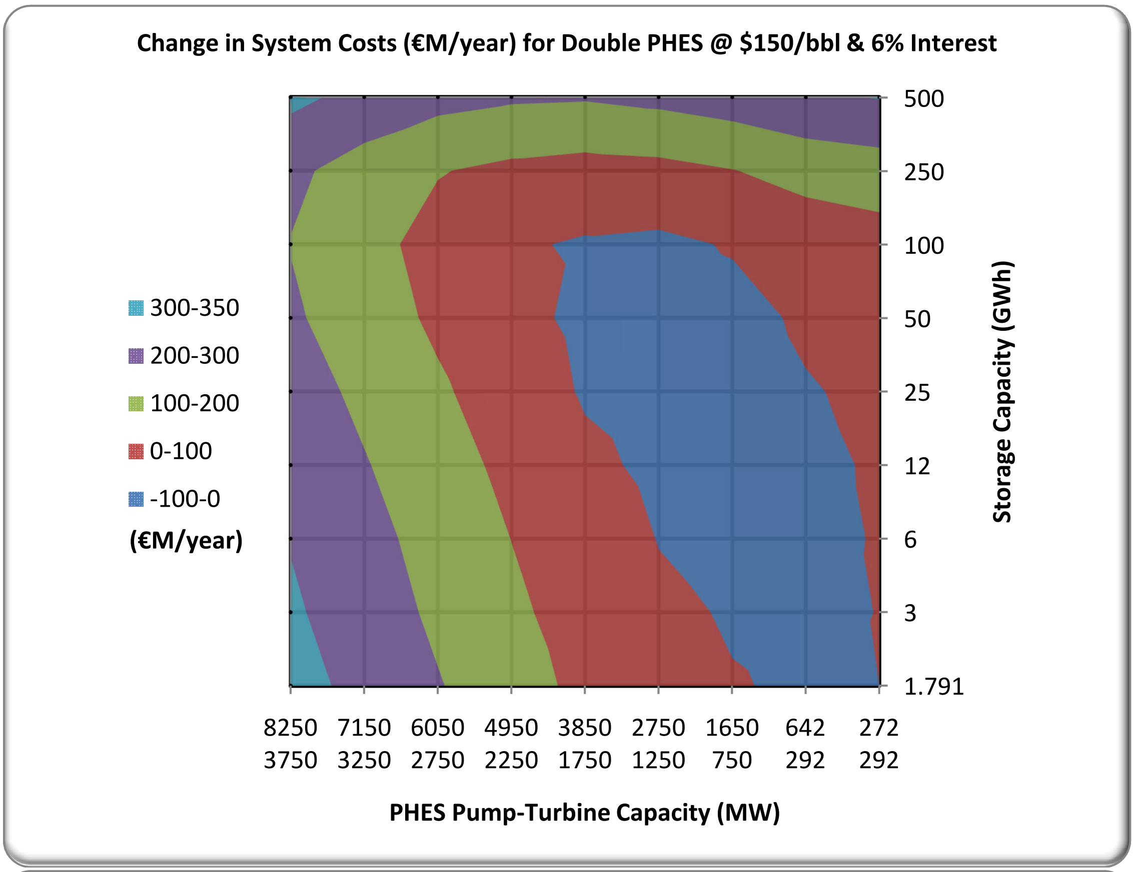


Figure 8-28: Change in energy system costs when various single PHES capacities from Table 8-18 are added to the 2020 Irish energy system compared to the reference, assuming fuel prices corresponding to $150/bbl and using an interest rate of 6%.



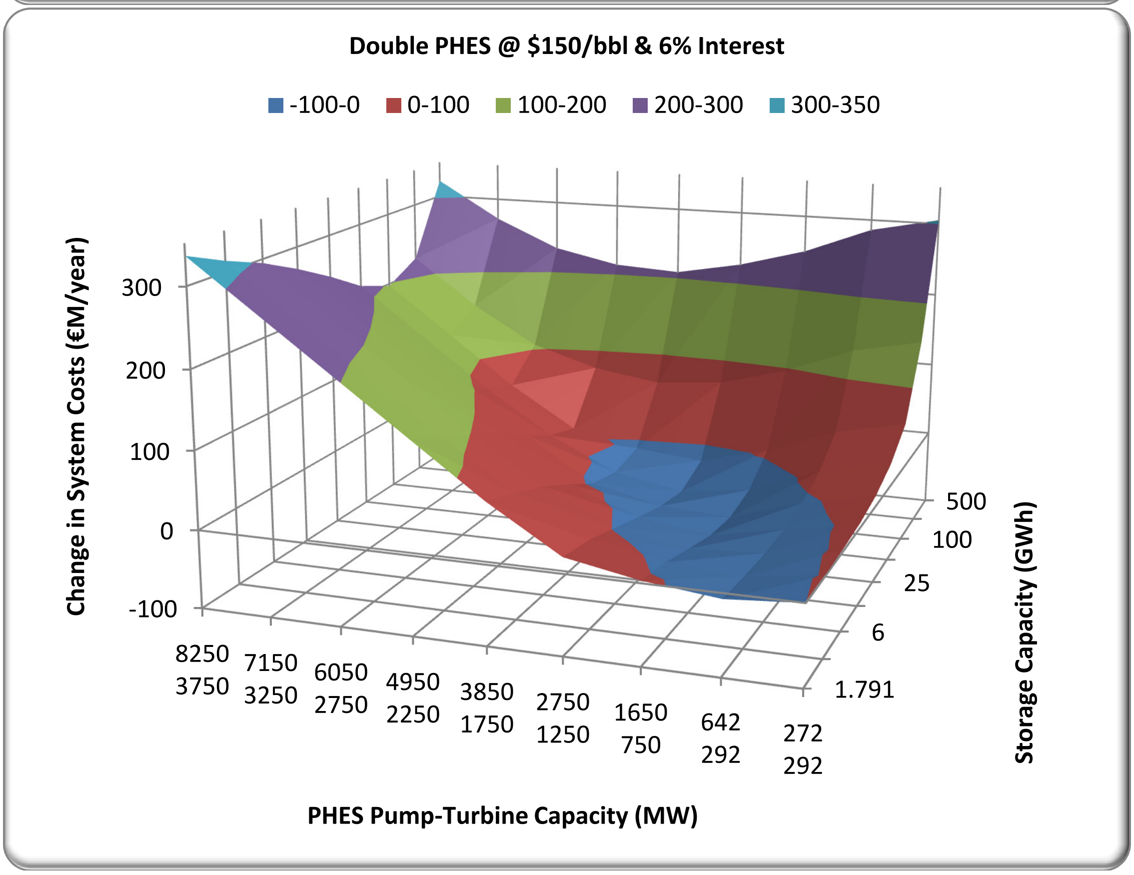


Figure 8-29: Change in energy system costs when various double PHES capacities from Table 8-18 are added to the 2020 Irish energy system compared to the reference, assuming fuel prices corresponding to $150/bbl and using an interest rate of 6%.

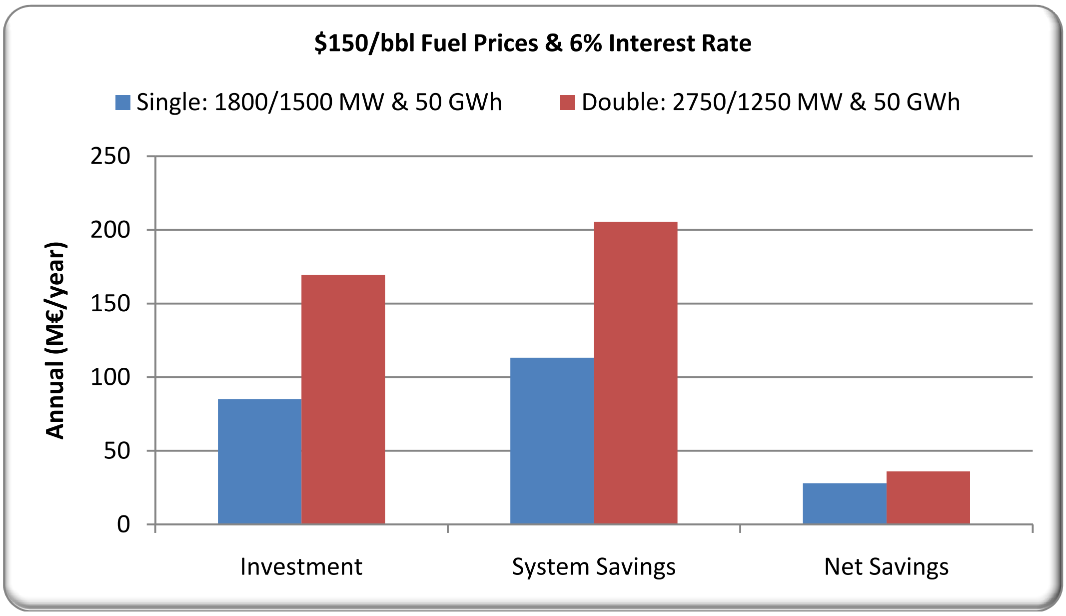


Figure 8-30: The investment and savings for the single and double PHES capacities which provided the largest reduction in system costs (50% wind penetration for single and 60% for double), when fuel prices correspond to $150/bbl and using an interest rate of 6%.

Double PHES Investment Costs

To complete this economic assessment, it was assumed that the double penstock PHES (€1M/MW) would cost twice as much to construct compared to the single PHES (€0.5M/MW). This assumption was based on the additional penstock, transmission, housing, and communication systems that would be necessary in a double PHES. However, no evidence was found to support this assumption and therefore the results were analysed for a double PHES investment cost of €0.75M/MW also. For the 2500 MW 25 GWh facility, the results in Figure 8-31 indicate that this lower investment cost for a double PHES does not alter the economic trend experienced for increasing penetrations of wind energy, but as expected it does improve the overall economic viability of a double PHES.

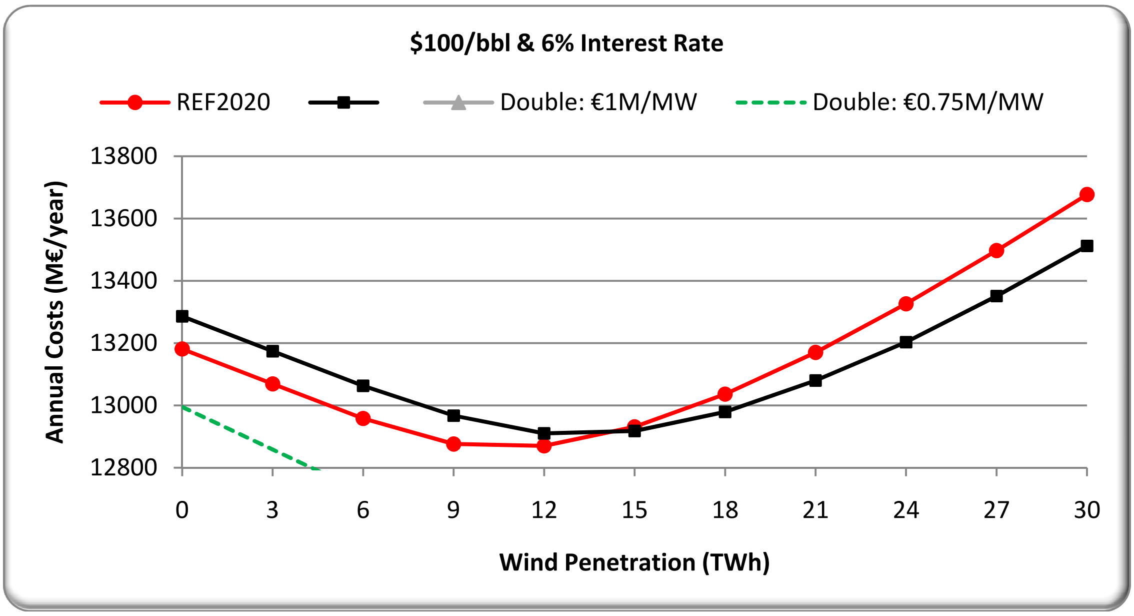
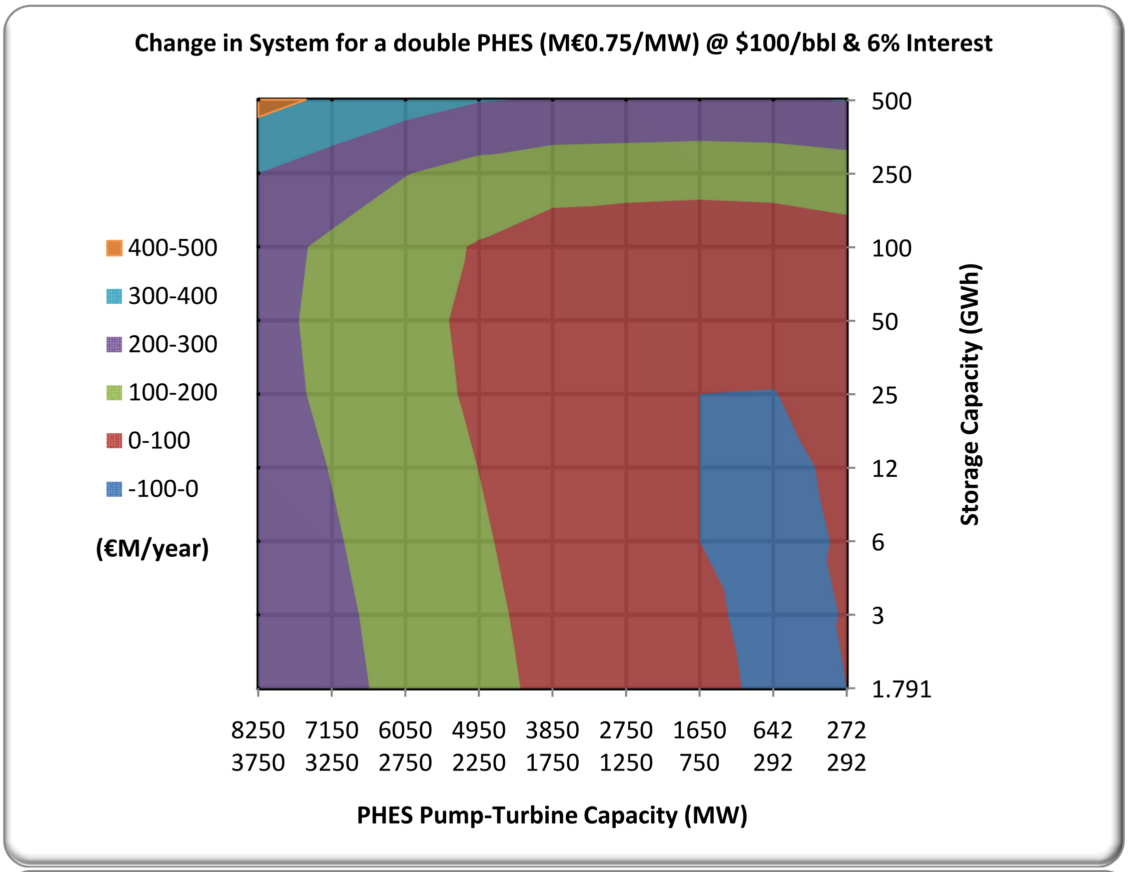


Figure 8-31: Annual costs for the Irish energy system in 2020 for the reference scenario, a 2500 MW 25 GWh single PHES scenario, and two 2500 MW 25 GWh double PHES scenarios (each with different investment costs), for wind penetrations of 0% to 100% (0-30 TWh) of electricity demand assuming fuel prices based on an oil price of $100/bbl and using an interest rate of 6%.

In line with this, Figure 8-32 indicates that if a double PHES can be constructed at €0.75M/MW, then it would become economically viable over a larger range of capacities than those reported in section 8.4.2. However, the results do not change as dramatically as those already displayed for a lower interest rate of 3% (Figure 8-25) and for higher fuel prices corresponding to $150/bbl (Figure 8-29). To conclude, it is important that the uncertainty surrounding the double PHES construction costs is considered when assessing the results in this study, but the implications of these seem less severe than those reported for the interest rate and the fuel prices.



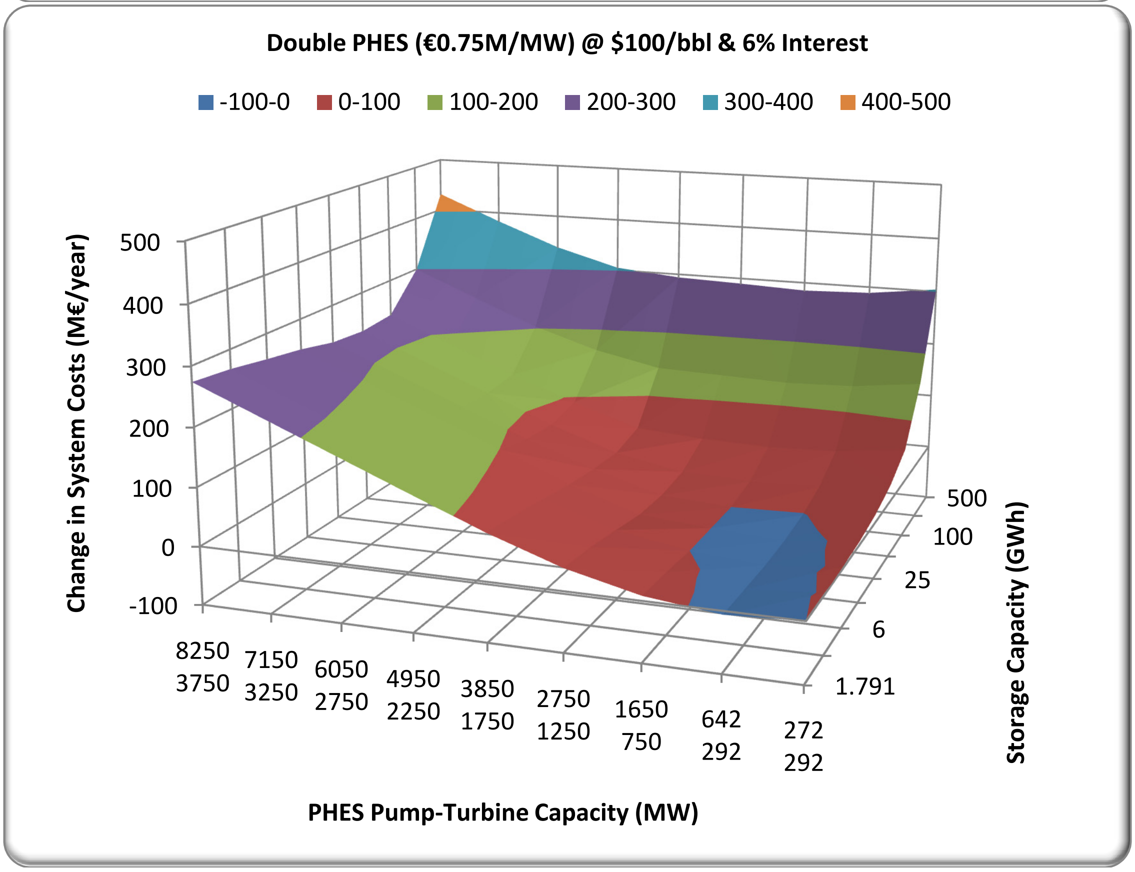


Figure 8-32: Change in energy system costs when various <u>€0.75M/MW double</u> PHES capacities from Table 8-18 are added to the 2020 Irish energy system compared to the reference, assuming fuel prices corresponding to $100/bbl and an interest rate of <u>6%</u>.

To recap briefly, this sensitivity analysis has verified that the wind distribution does not alter the results significantly and although any reduction in the total annual electricity generation from wind would increase the operating costs, this is equivalent to the savings identified due to a corresponding increase in annual wind generation. Also, the economic viability of PHES in conjunction with wind power is significantly enhanced by using a 3% interest rate to assess its economic viability or if global fuel prices reach $150/bbl. Under both of these scenarios and based on the costs assumed in Table 8-16, a double PHES system would enable a 60% wind penetration on the Irish energy system at the same cost as a 40% wind penetration on the reference scenario. In addition, the uncertainty surrounding the additional investment required for a double penstock PHES is important to consider when assessing the results in this section, although the sensitivity analysis indicates that the interest rate and fuel price assumptions have a greater impact on the results. Finally, before concluding that PHES is a suitable option for Ireland, it must also be compared to alternative technologies that could also be utilised.

8.4.4. Comparing PHES to Alternatives

As outlined in section 8.4.2, for $100/bbl and a 6% interest rate the cheapest single and double penstock capacities both corresponded to an investment of approximately €17M/year. Therefore, the results from the PHES analysis were compared to the same investment in two other technologies: domestic heat pumps (HP) and the creation of a district heating network utilising a new combined heat and power (CHP) plant. The capacities, costs, and investments required for these alternatives are outlined in Table 8-19.

Table 8-19: Capacity and cost assumptions for the alternative scenarios considered on the 2020 Irish energy system.

Alternative	Size	Unit	Costs Per Unit (€M)	Life-time (years)	Fixed O&M (% of investment)	Total Costs (€M/year)	Ref.
Heat Pumps	**135**	**MW_e**	**1.2**	**15**	**0.6**	**17.5**	**[241]**
CHP						**17.6**	
Convert PP	125	MW_e	0.80	30	2.00	9.3	[170, 241]
Thermal Storage	1	GWh	1.34	20	1.00	0.13	[228]
Peak Boilers	125	MW_{th}	0.15	20	3.00	2.2	[241]
Network	15	km	2.00	40	1.00	2.3	[242]
Central Heating	1500*	Conversions	0.0054	40	0.90	0.6	[241]
Heat Exchangers	15000	Customers	0.00275	40	0.90	3.11	[241]
Single PHES						**17.1**	
Pump	330	MW_e	0.25	40	1.5	6.7	[99, 170]
Turbine	210	MW_e	0.25	40	1.5	4.2	[99, 170]
Storage	10.2	GWh	7.50	40	1.5	6.2	[96]
Double PHES						**17.6**	
Pump	370	MW_e	0.50	40	1.5	15.07	[99, 170]
Turbine	0#	MW_e	0.50	40	1.5	0.00	[99, 170]
Storage	4.2	GWh	7.50	40	1.5	2.57	[96]

***Equates to 10% of total customers.**
#Capacity required is already installed in Ireland.

As displayed in Figure 8-33, under predicted 2020 fuel prices of $100/bbl and a 6% interest rate, an investment of €17M/year in domestic heat pumps provides the same savings for the Irish energy system as the optimum single PHES unit. The CHP alternative provided larger savings than the optimum double penstock PHES, but it was not as cost-effective as the optimum single PHES for 2020. However, it should be stressed that the PHES capacities have been optimised in this study, while the CHP capacities are just estimates based on the heating demands that had to be met and predicted costs [242]. Again, the sensitivity analysis discussed previously was repeated on these alternatives. As outlined in Figure 8-33, an increase in fuel prices to $150/bbl or a reduced interest rate of 3% will improve the savings associated with all four alternatives. Although the single PHES is the most economical alternative when this occurs, it is the double PHES which is the most sensitive to changes in fuel prices and interest rates, which is most likely due to the additional wind energy it enables. Finally, each of the scenarios were analysed for a 20% reduction and increase of total annual wind energy generation. As already outlined in section 8.4.3, PHES is very sensitive to changes in the total annual wind generation, which is evident once again in Figure 8-33. In contrast, the cost savings related to the HP and CHP scenarios are practically the same for the reference as those calculated for a +/-20% change of annual wind generation[13]. Consequently, the results indicate that even if optimum capacities of PHES are identified, there are alternatives that are as cost

[13] It should be noted that this sensitivity analysis did not assess fluctuations in the annual heat demand that occur due to hot and cold years, which could affect the results in the HP and CHP scenarios.

effective under predicted 2020 conditions and which are less sensitive to changes in fuel prices, interest rates, and annual wind production.

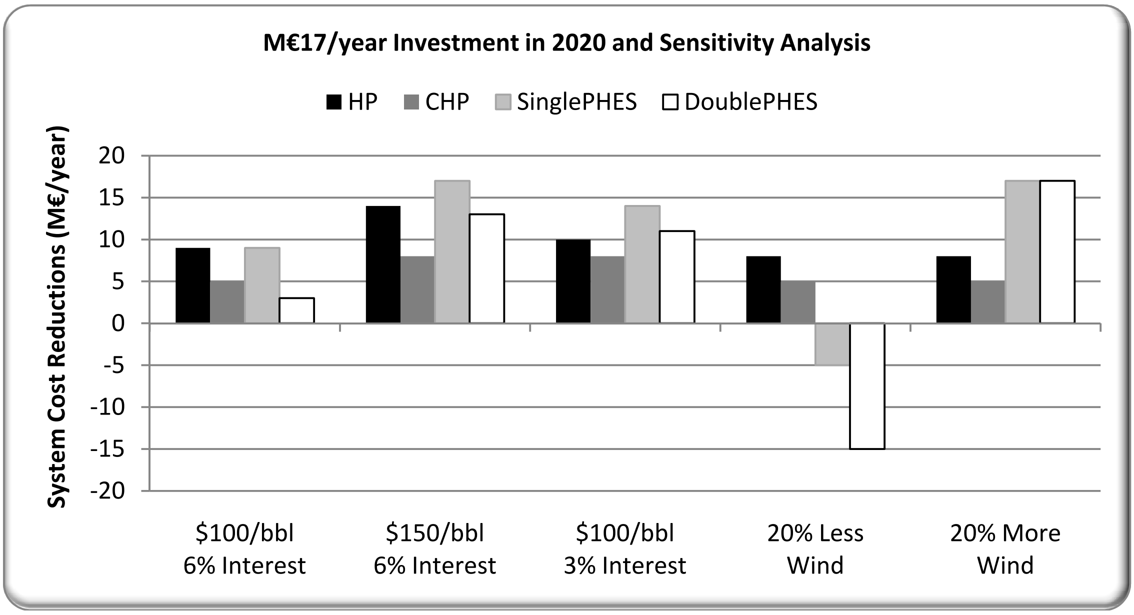


Figure 8-33: Annual system cost reductions compared to the reference when approximately €17M/year is invested in domestic heat pumps (HP), a CHP system with district heating (CHP), as well as the optimum single and double PHES facilities from section 8.4.2. All capacity and cost assumptions are outlined in Table 8-19 and a wind penetration of 40% was used as it was the most economical for each alternative.

Nonetheless, considering Ireland's significant dependence on imported fuel (see Figure 4-4), it is not only important to consider the economic implications of energy alternatives, but also the affect which they have on Ireland's energy consumption. Displayed in Figure 8-34 are the changes in a number of key energy parameters when each of the alternatives proposed are introduced to the 2020 Irish energy system. From these results it is evident that PHES improves Ireland's security of supply by more than the HP or CHP scenarios. To do this, PHES reduces CEEP by enabling the integration of more wind power and thus correspondingly reduces the PES, fossil fuel demand (FFD), and CO_2 emissions. Comparing the alternatives, it is clear that PHES reduces the FFD more than the HP or CHP scenarios. Therefore, it could be argued that the additional cost of PHES is worth these larger reductions in FFD, due to the socio-economic benefits for Ireland such as increased security of supply and less CO_2 emissions. These benefits were considered in this thesis by using a predicted CO_2 cost of $50/t, but since this is a global guideline [4] and Ireland is the 12th largest net importer of energy in the world (see Figure 4-7), this assumption may not be sufficient to reflect these benefits. In summary, PHES may not be the most economical alternative for 2020, but its additional socio-economic benefits could be worth the additional cost.

Finally, this analysis reflects two key broader concerns for Ireland: firstly, energy alternatives need to be evaluated in more detail while also considering the entire energy system and secondly, developing Irish specific energy planning costs and indices for evaluating these alternatives, especially in relation to socio-economic benefits, should be determined so optimum alternatives can be identified. In addition, it is essential that the initial HP and CHP analyses presented in this thesis are expanded based on the potential cost reductions identified as the optimum solution could in fact contain a mixture of all the technologies assessed here.

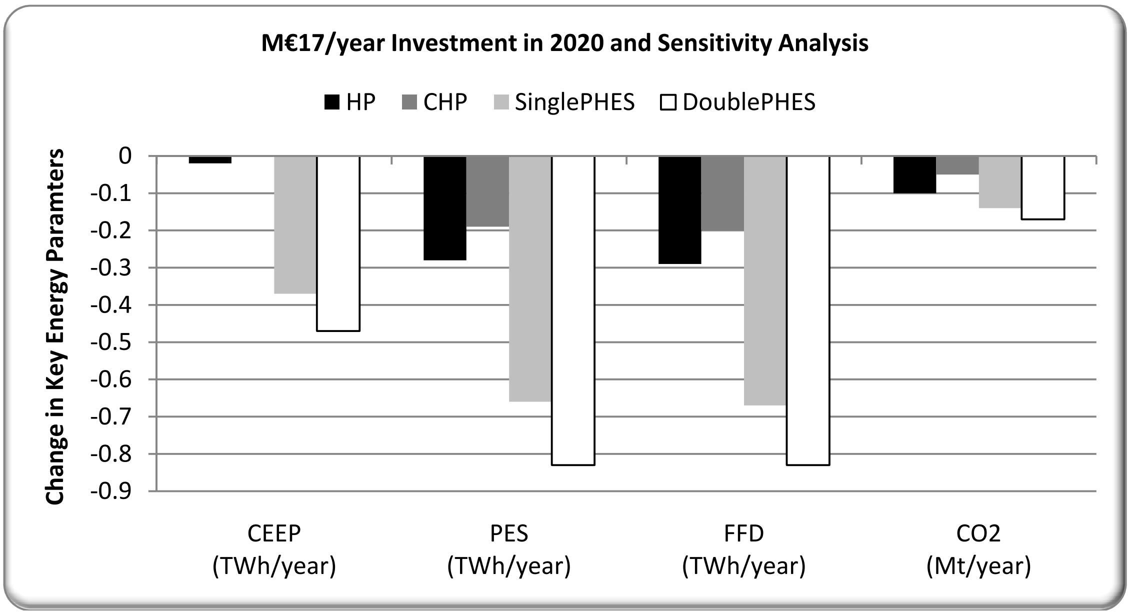


Figure 8-34: Change in key energy parameters compared to reference when approximately €17M/year is invested in domestic heat pumps (HP), a CHP system with district heating (CHP), as well as the optimum single and double PHES facilities from section 8.4.2. All capacity and cost assumptions are outlined in Table 8-19 and a wind penetration of 40% was used as it was the most economical for each alternative.

8.5. Conclusions

To conclude, this chapter has outlined that wind power and PHES can be used together to reduce the operating costs of the Irish energy system. However, under the conservative assumption that societal benefits (such as less pollution, improved health, increased job creation, and a better balance of payment) are accounted for with a predicted CO_2 price of $50/t, the savings calculated are too small based on a conventional 6% interest rate and the predicted fuel prices for 2020 to warrant the initial investment in PHES, especially as it could also increase the operating costs. However, if the interest rate for assessing PHES is reduced to 3% to reflect its lifetime of 40 years and the socio-economic benefits of additional wind, then PHES can enable up to 20% additional wind in Ireland without increasing the annual operating costs of the energy system. Equally, if global fuel prices increase to a level which reflects $150/bbl, then the same outcome will occur.

More specifically in relation to PHES, the analysis identified a divergence between the pump and turbine capacities required for a PHES when it is used to integrate increasing amounts of wind power. As wind penetrations increase, the pumping capacity required also increases so the PHES can soak up excessive wind production, but the turbine capacity doesn't increase as quickly because the power plant production which it is replacing remains the same. The slight increase in turbine capacity required is primarily related to the additional energy available in the PHES due to the increased pumping capacity. Finally, a single penstock and double penstock operating strategy have been analysed throughout this study to assess if the additional capacity required for a double penstock system is offset by the additional wind penetrations feasible. The results suggest that as wind penetrations increase, the double penstock system is a more economical alternative and it enables Ireland to utilise more indigenous wind energy. However, it is also more sensitive to changes in fuel prices, interest rates, and total annual wind production. The double penstock operating strategy also illustrated how ancillary services can be provided when integrating wind power onto modern electric grids. Although PHES was used in this study to create a flexible supply and demand portfolio in Ireland for the integration of wind, other alternatives could be used in a similar way such as electric vehicles, the electrification of heat, thermal storage, and many more. Hence, alternatives were briefly investigated towards the end of this research also.

The two alternative technologies to PHES which were assessed in this study were domestic heat pumps and a district heating network with CHP. After comparing the operating costs of the Irish energy system with these alternatives to those obtained with PHES, it was evident that domestic heat pumps are just as economical as an optimum PHES in Ireland based on projected fuel prices for 2020 and an interest rate of 6%. In addition, the savings associated with domestic HP are not as sensitive to changes in fuel prices, interest rates, or annual wind productions as PHES and thus, would be a more attractive investment (although this study did not investigate the consequences of variations in the annual heat demand). In addition, the PHES capacities proposed have been optimised over the course of this study, but the HP and CHP capacities proposed are only estimates based on the demands that have to be met. Conversely though, the single and double PHES systems can integrate more indigenous renewable energy as well as provide larger reductions in PES, FFD, and CO_2 than the HP and CHP scenarios. Therefore, these additional socio-economic benefits associated with PHES may be worth the additional cost. As a result, a more detailed analysis of these alternatives is necessary, Irish specific energy planning costs and indices which reflect the socio-economic benefits of indigenous renewable energy production need to be established, and it is essential that numerous alternatives across all sectors of an energy system are considered when evaluating solutions for the future.

Finally, there are a number of limitations which need to be considered when interpreting the results of this study. Firstly, it is clear that PHES is a key asset for wind energy as it enables the grid to operate securely while also incorporating high wind penetrations. However, in the future, wind turbines and decentralised plants could make a more significant contribution to grid stabilisation and hence the value of PHES could be diminished. Also, the EnergyPLAN tool used in this study is a scenario tool which simulates an energy system on an hourly basis, which does not account for the dispatch of individual power plants or the current flow on individual power lines. Therefore, a more detailed energy tool will be required to fully establish the implications of using different grid constraints on the Irish energy system. This type of study would also provide another essential comparison between the alternatives considered i.e. the role out of domestic heat pumps could require less transmission upgrades than the construction of large centralised PHES facilities. Overall, the ultimate necessity for the future which can be drawn from this study is the demand for more detailed analyses of a wide range of alternatives for an energy system, as significant savings can be realised using existing technologies especially by integrating the electricity, heat, and transport sectors.

9. The Dispatch of PHES on Electricity Markets

In a deregulated electricity market, an energy storage facility is typically defined as a merchant unit, which maximises its profits subject to technical constraints, or as a system asset, which is managed by the system operator to assist in maintaining system security and in reducing operational costs [92]. As a merchant unit, an energy storage facility will earn most of its revenue from the sale of electricity to the market [92, 146]. Hence, this chapter investigates how an energy storage facility can operate to maximise its revenue from the purchase of low-cost off-peak electricity and the sale of high-cost peak electricity on the market. In total, three practical operation strategies (24Optimal, 24Prognostic, and 24Historical) are compared to the optimum profit feasible for a PHES facility with a 360 MW pump, 300 MW turbine, and a 2 GWh storage utilising price arbitrage on 13 electricity spot markets. A more detailed discussion of this work is provided in Appendix H.

9.1. Electricity Markets

Electricity markets typically operate as a gross mandatory pool into which all electricity generated or imported must be sold, while all wholesale electricity for consumption or export must be purchased from this pool. Using this structure, the Single Electricity Market (SEM) was created for the island of Ireland in November 2007 and hence, it is a suitable case study for analysing the structure of existing electricity markets and how PHES can function on them.

In the SEM, each trade day comprises of 48 half hourly trading periods and participation in the pool is mandatory for all generators with a maximum export capacity greater than 10 MW [243]. Competitive bidding takes place one day ahead of delivery during which all dispatchable generators provide price and quantity information for each trading period. The spot market demand is cleared for each trading period and dispatch schedules are determined [244]. The clearing price is the price per MWh declared by the highest price generator required to meet demand. This determines the system marginal price (SMP) which will be awarded to all scheduled generators in a given trading period. Wind is Ireland's largest renewable energy resource with an installed capacity of approximately 1260 MW [234] compared to a maximum demand of approximately 5000 MW [23]. Like the majority of the EU-27 member states, Ireland exercises explicit priority dispatch of renewables [245]. Therefore, during dispatch scheduling wind generated electricity is treated as a negative load, which results in all available wind power being accepted onto the grid. Consequently the availability of wind during each trade period determines the net load to be supplied by conventional generation plant to maintain grid equilibrium. A graphical illustration of the scheduling process is illustrated in Figure 9-1. Using this procedure, a schedule of Ex-Ante (EA) prices is published at 16:00 one day ahead of the trade date in question. Four days after the trade date, final Ex-Post (EP) prices are published which includes the price of imbalances, constraints, and imperfections that could not have been predicted during the EA calculations [243].

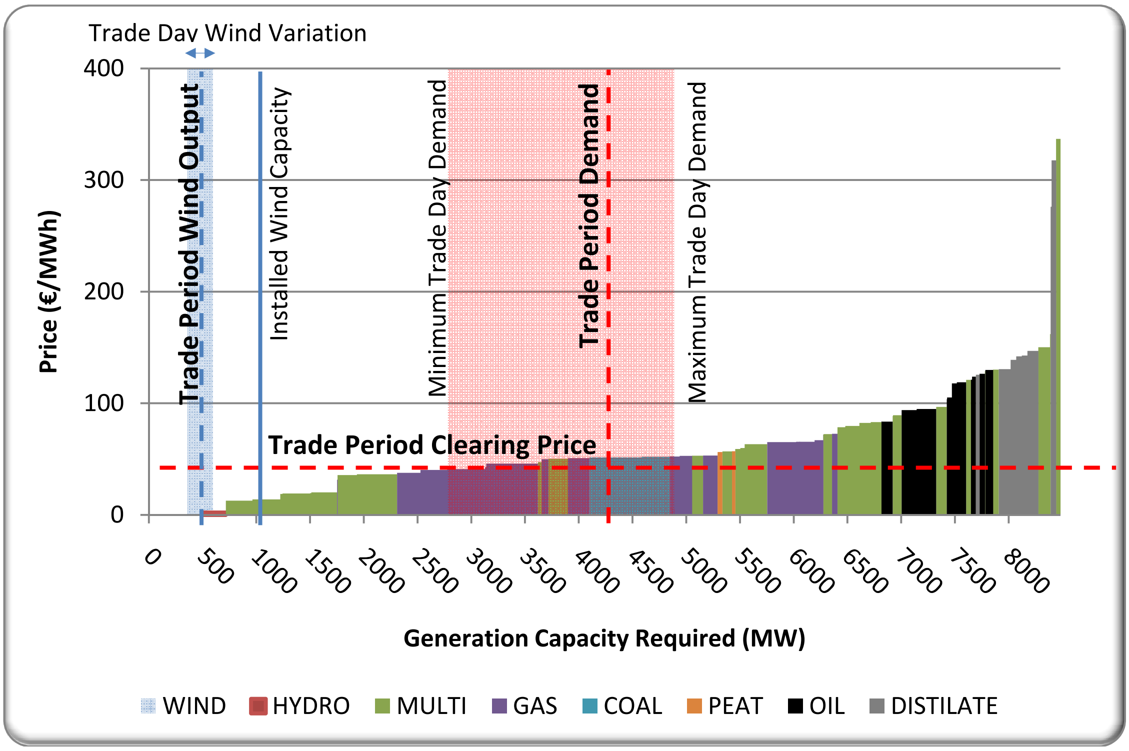


Figure 9-1: Generator bidding process on the Irish electricity market divided by fuel. It illustrates the clearing price and the priority dispatch of wind [246]: prices are based on generator submissions to the SEM on the 1st of January 2008 [235].

As the demand for electricity, the production from wind turbines, and the availability of conventional generation varies for each trading period, the SMP varies also. In 2008 for example, the lowest SMP price in Ireland was €2.54/MWh, the maximum SMP was €696.85/MWh, and the average SMP was €80.53/MWh, as displayed in Figure 9-2.

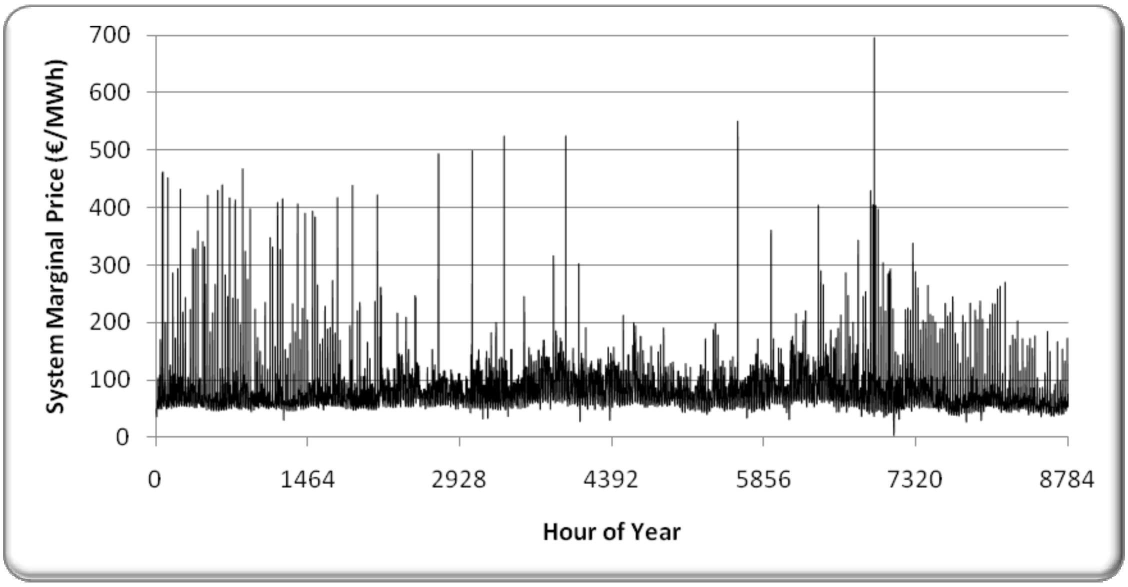


Figure 9-2: System marginal price for each trading period on Irish electricity market in 2008 [235].

This price differential usually occurs on a daily basis also, primarily due to the daily fluctuation in electricity demand on the grid, as displayed in Figure 9-3. Although some PHES facilities can take advantage of seasonal variations in electricity prices, most PHES facilities have been designed to utilise this daily price difference [163]. Various studies (which have been discussed in section 6.2.2) investigated new methods for dispatching PHES to maximise the profit available based on this price differential. However, none of the operation strategies identified could be utilised by a single PHES unit on a wholesale electricity market. Hence, using the Irish electricity market as a case study, the objective in this chapter was to develop a new dispatch strategy for PHES on wholesale electricity markets, which would enable it to maximise its profits based on electricity price arbitrage[14]. This is done by identifying the maximum feasible profit that a PHES facility can achieve on an electricity market with perfect pricing foresight for one year, then comparing this to a range of realistic operating strategies which could be put into practice, and subsequently investigating the economic viability of a PHES facility utilising price arbitrage on various electricity markets.

[14] As well as the electricity market, there is also an ancillary services and capacity payments market in Ireland. However, due to the limited capacities of PHES, it can only be optimised on one market each day. Hence, to analyse the profits on these markets, a separate analysis would be required.

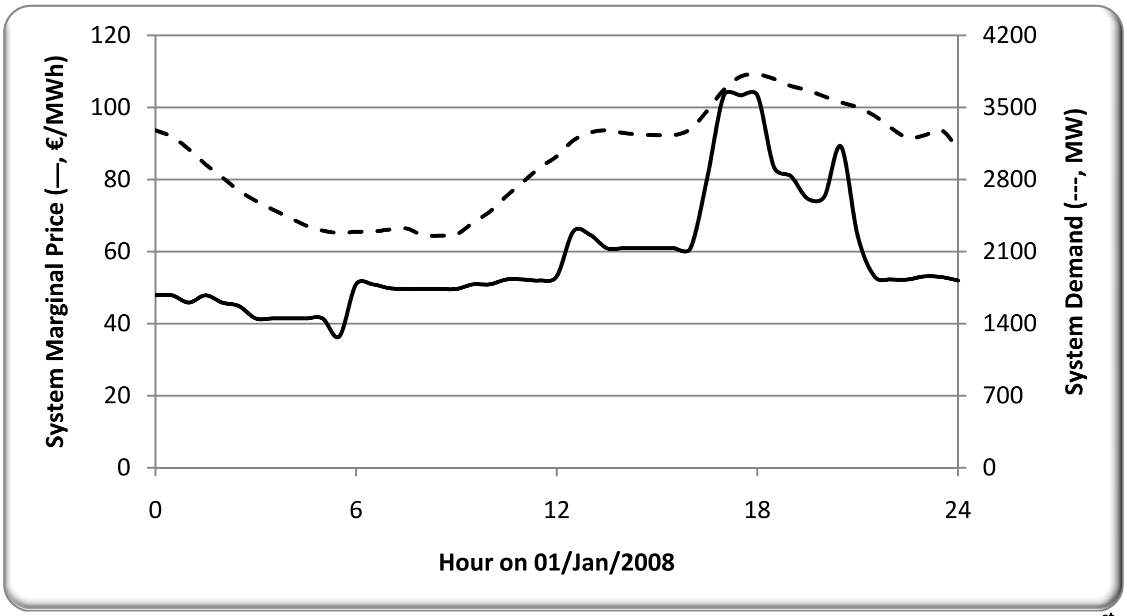


Figure 9-3: System marginal price and electricity demand for each trading period in Ireland on the 1st January 2008 [235].

9.2. Methodology

In total four different operation strategies were created for energy storage on a liberalised electricity market, which are called 'Optimal', '24Historical', '24Prognostic', and '24Optimal'. The Optimal operation strategy identifies the maximum theoretical operational income given an hourly time series of electricity prices over a one year period. Hence, it assumes perfect foresight of electricity prices for the year. The Optimal algorithm is described, formulated, and illustrated in Appendix H. In practice, energy storage plants could not implement the Optimal operation strategy since the fluctuations of spot market prices in the coming hours and days are not known for a whole year. Therefore, three additional strategies were created, which could utilised by an energy storage operator:

1. 24Historical strategy: decisions on buying and selling electricity are solely based on the knowledge of the average price over 12 historical and 12 future prices.
2. 24Prognostic strategy: decisions on buying and selling electricity are based on the average price of the upcoming 24 hours. Such a strategy requires the presence of good price prognoses.
3. 24Optimal strategy: operation of the energy storage facility is optimised using the same procedure as the optimal strategy, but it optimises the energy storage for the next day only. After optimising the first day, the procedure then repeats itself until the entire year is complete. Once again, such a strategy requires the presence of good price prognoses.

The concept behind the historical and prognostic strategies is to take the average price of a user-specified period and bid on the market correspondingly. The bid on the market occurs so that the price difference between the buying and bidding prices is equally distributed around the average price. The price is updated on an hourly basis, as opposed to a fixed average over a specified period. This implicitly assumes that the system operator can update market bids on an hourly basis, which distinguishes the 24Prognostic and the 24Optimal strategies, as the latter uses a fixed 24 hour time period i.e. the next day. The equations derived for the prognostic and historical strategies are outlined in Appendix H, while Figure 9-4 demonstrates their concept for a 24-hour period. Here, the centre line represents the average price for the upcoming 24 hour-period (i.e. 24Prognostic strategy), which is updated every hour for the next 24 hours. Based on that, the buying and selling prices are defined.

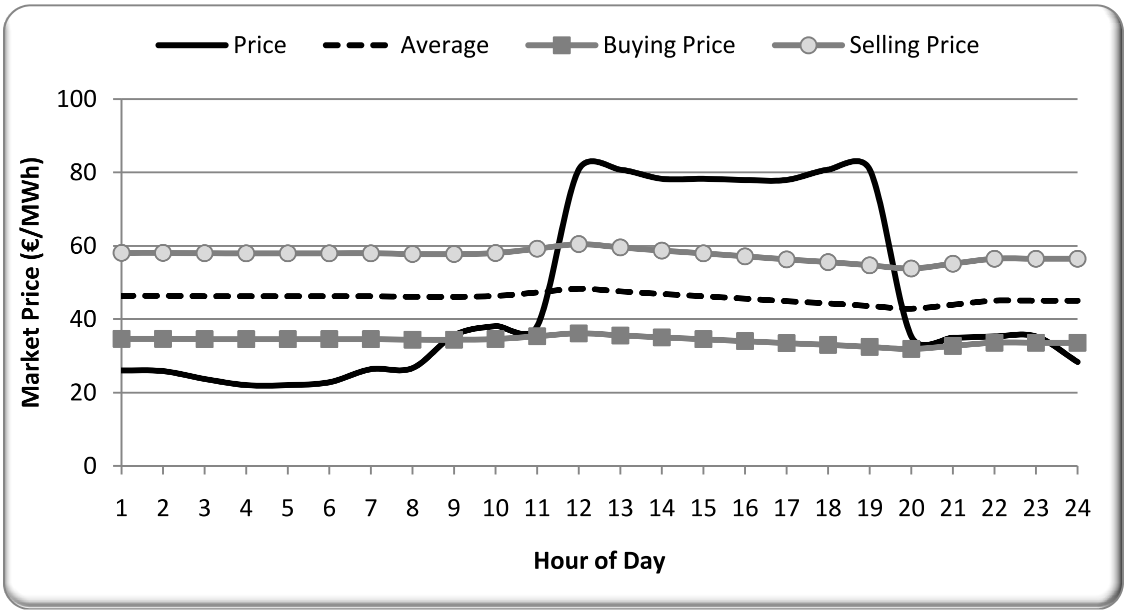


Figure 9-4: This graph illustrates the average, buying, and selling prices for the 24Prognostic strategy, which is updated every hour for the next 24 hours. The same concept is used for the 24Historical strategy, but 12 historical hours and 12 future hours are used to define the average, buying, and selling price.

Two deterministic modelling tools have been used to analyse the operation of a PHES facility on an hourly basis over one year. The first tool is contained within EnergyPLAN [181] and it was developed by Lund and Salgi [210] to evaluate two practical operation strategies for CAES, which were called '24Historical' and '24Prognostic'. Here, the EnergyPLAN tool is used to model these two strategies when applied to PHES. In addition, the new operating strategy called '24Optimal' has been developed in MATLAB [247]. Finally, the 'Optimal' strategy which was also developed in [210], was simulated in both tools to model PHES and subsequently, their results were compared to ensure they were both operating in the same way.

Using each of the strategies defined previously, the profit feasible using electricity price arbitrage for a PHES facility with the parameters outlined in Table 9-1 was identified, for each of the electricity markets displayed in Table 9-2. Previous studies have indicated that these are the typical capacities of existing PHES facilities [99, 163], while chapter 7 concluded that these capacities could be constructed in Ireland in the future. Also, using a pumping capacity of 360 MW and a turbine capacity of 300 MW enables the PHES facility to both charge and discharge for approximately 6 hours and hence, the facility can take advantage of daily low and high prices which typically occur on an electricity market.

Table 9-1: Capacity assumptions for the PHES facility used to test the various operating strategies.

PHES Parameter [source]	Value	Unit
Pumping capacity	360	MW
Turbine capacity	300	MW
Storage capacity	2000	MWh
Pumping efficiency [163]	92	%
Generating efficiency [163]	92	%

Table 9-2: Electricity market data used for analysing the profit feasible from the PHES facility described in Table 9-1.

Electricity Market Operator	Region	Symbol	Link
Australian Energy Market Operator	New South Wales, Australia	AU	http://www.aemo.com.au
Energy Exchange Austria	Austria	AA	http://en.exaa.at
Elexon*	Britain	GB	http://www.elexon.co.uk
Alberta Electric System Operator	Alberta, Canada	CAA	http://ets.aeso.ca
Independent Electricity System Operator	Ontario, Canada	CAO	http://www.ieso.ca
Single Electricity Market Operator	Island of Ireland**	IE	http://www.sem-o.com
Gestore Mercati Energetici	Italy	IY	http://www.mercatoelettrico.org
Electricity Authority	New Zealand, North Island	NZN	http://www.ea.govt.nz
Nordpool Spot	Nordic region***	NP	http://www.nordpoolspot.com
Operador do Mercado Ibérico de Energia	Portugal	PL	http://www.omip.pt
Operador del Mercado de Electricidad	Spain	SP	http://www.omel.es
ISO New England	New Hampshire, New England, USA	USANE	http://www.iso-ne.com
New York ISO	Capital–F, New York, USA	USANY	http://www.nyiso.com

***Based on the market index price.**

****Based on final EP2 prices.**

*****Includes Denmark, Finland, Norway, and Sweden.**

9.3. Results and Discussion

Firstly, the profit for the energy storage facility was identified using all four operating strategies for each of the electricity markets, as displayed in Figure 9-5. It is clear that the profit feasible varies dramatically from one market to the next due to the varying degrees of electricity price arbitrage on each market. This is caused by a range of issues which affect the market price such as the varying market structures, regulations, demands, and plant portfolios. Analysing the implications of these on the market price is beyond the scope of this study and hence, it could be examined in future research. Regardless of the profit obtained however, it is evident from the results that the 24Optimal strategy can obtain almost all of the profit that is feasible from each market: on average the 24Optimal strategy obtained 97% of the profit which was identified using the Optimal strategy. In comparison, the 24Prognostic and 24Historical strategies achieved 81% and 83% respectively of the Optimal strategy profits. However, it is likely that this large proportion of maximum profits achieved by the 24Optimal strategy is related to the 6 hour charge/discharge cycle of the PHES facility considered (see Table 9-1). To illustrate this, the results were recalculated for a storage capacity of 8 GWh instead of 2 GWh. As displayed in Figure 9-6, the profits achieved for an 8 GWh PHES facility using the 24Optimal strategy are only 82% of those achieved when the Optimal strategy is used. In addition, the 24Prognostic and 24Historical returned higher profits for the 8 GWh by achieving an average of 87% and 83% of the Optimal profits respectively. However, as PHES facilities are typically constructed with a charge/discharge cycle of approximately 6-8 hours [163], the 24Optimal strategy is very applicable to most existing PHES facilities. This is significant as the 24Optimal strategy shows that PHES units with charge/discharge cycles of approximately 6 hours do not need an intra-day market to maximise their profits from electricity arbitrage, but instead they need accurate electricity prices one day in advance.

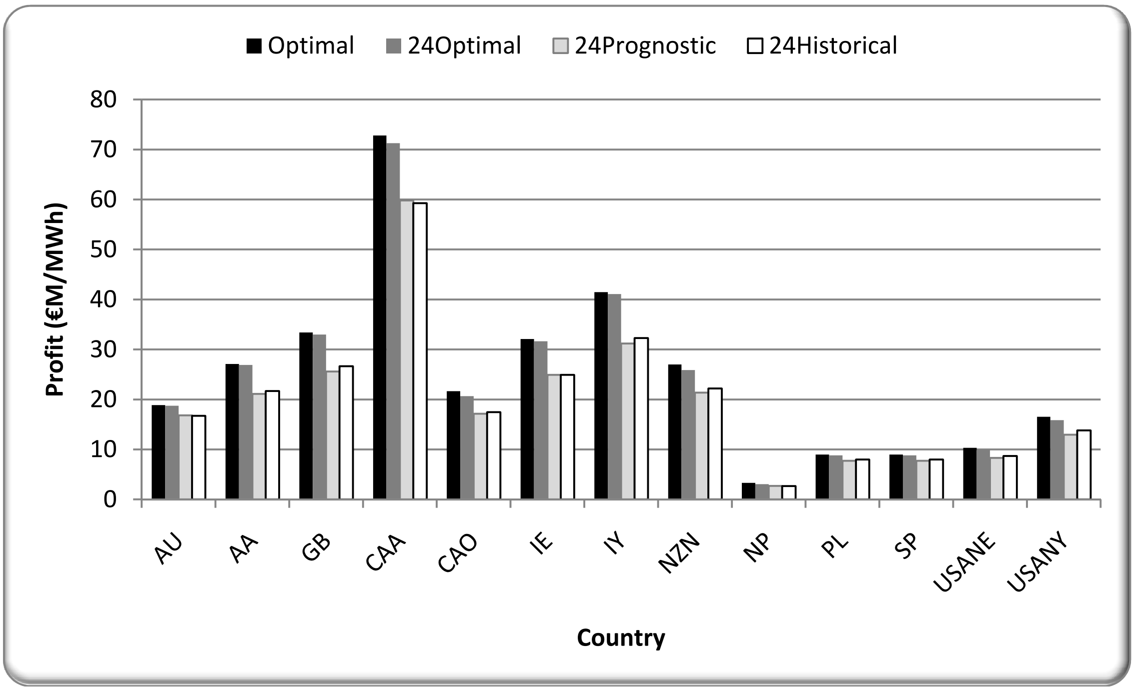


Figure 9-5: Profit for 2008 on each of the electricity markets (see Table 9-2) considered for all four optimisation strategies with a 2 GWh storage capacity.

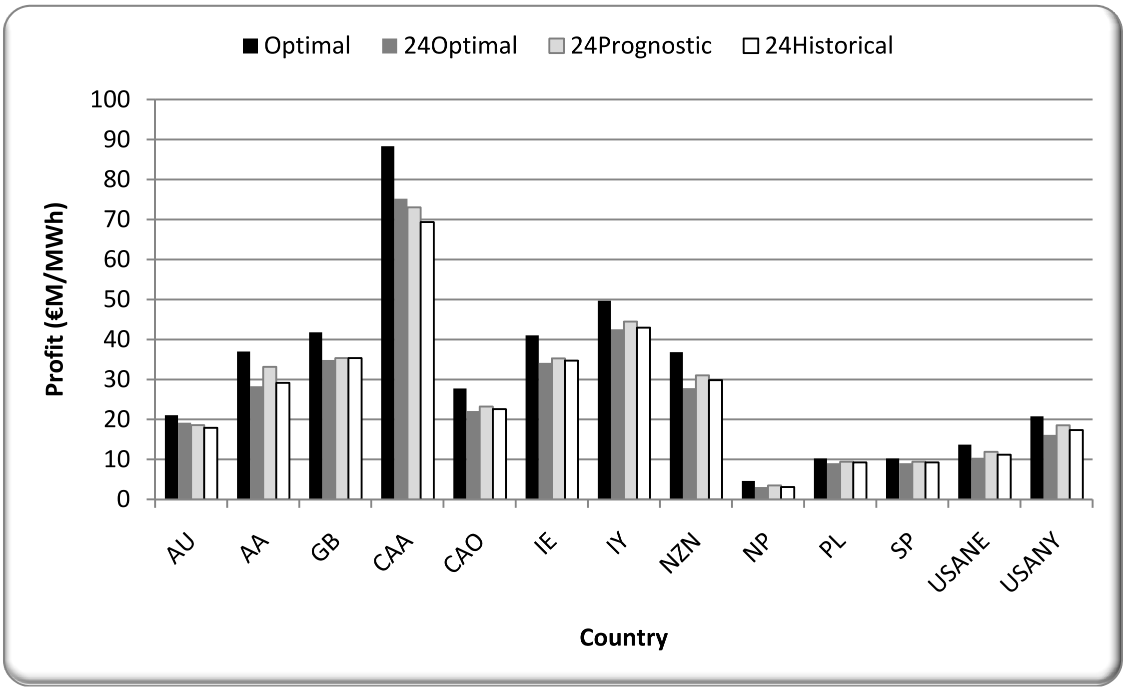


Figure 9-6: Profit for 2008 on each electricity market (see Table 9-2) considered for all four optimisation strategies with an 8 GWh storage capacity.

Although some markets already provide exact electricity prices one day in advance[15], the Irish electricity market does not. Instead, the day-ahead market in Ireland only provides indicative prices called that Ex-Ante (EA) prices. Four days after the day of trading, final prices, called Ex-

[15] The Nordpool market provides exact electricity prices one day in advance and uses a regulating market to account for changes that occur on the following day.

Post2 (EP2) prices, are produced which include the cost of balancing the system. Therefore, if the 24Optimal strategy was utilised on the Irish market, the energy storage facility would be optimised using indicative EA prices, but charged the final EP2 prices. As outlined in Figure 9-7, when the 24Optimal strategy is optimised and charged based on the final EP2 prices, it makes the most profit. Also, although the profits from the PHES facility are reduced when the facility is optimised and charged based on predicted EA prices, the least profit occurs when the energy storage facility is optimised based on predicted EA prices, but charged the final EP2 prices (i.e. the current situation).

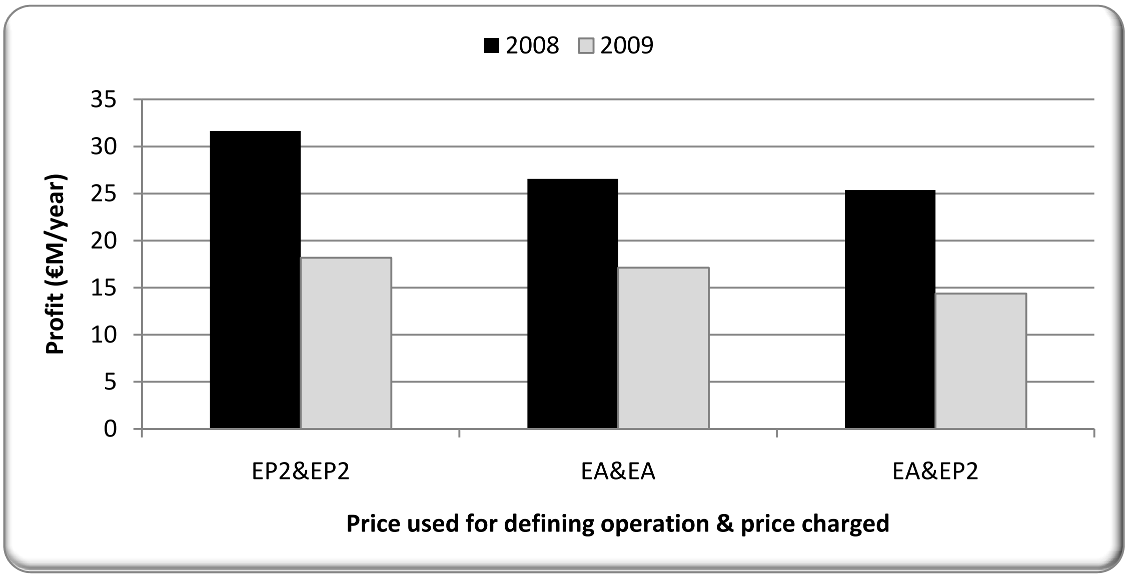


Figure 9-7: PHES facility profit using the 24Optimal strategy on the Irish electricity market when it is optimised and charged different prices in 2008 and 2009.

After closer inspection of the price distributions, two primary reasons were identified for this profit reduction. Firstly, some extreme events can occur during the year where the predicted prices can change dramatically during the operation of the PHES. As outlined in Figure 9-8, between hours 2060 and 2168 in 2008, the electricity price was predicted to be relatively low at approximately €60/MWh and hence, the PHES facility decided to operate the pump. However, the actual price was very high at approximately €260/MWh and as a result, instead of making a predicted profit that day of ~€25,000, the facility made a loss of ~€200,000.

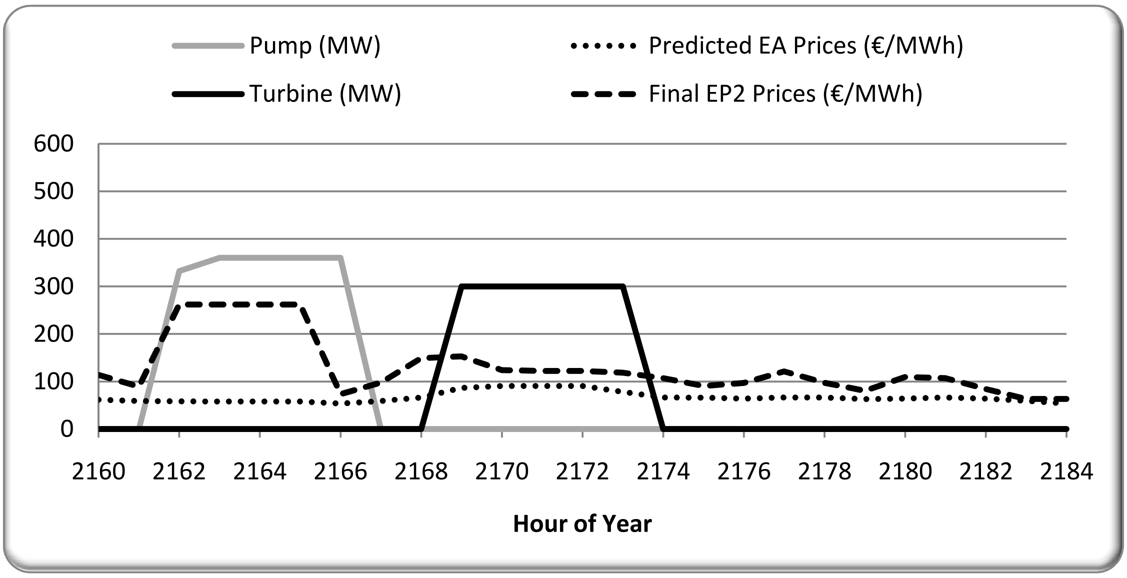


Figure 9-8: Pump and turbine operation based on predicted Irish market prices in 2008.

Secondly, less extreme reductions in the daily profit are also experienced due to the relationship between predicted EA prices and final EP2 prices. As displayed in Figure 9-9, prices which are predicted to be low are more likely to increase, while prices which are predicted to be large are more likely to decrease [83]. Therefore, the hours when the PHES is pumping are more likely to increase and thus increase costs, while the hours when the PHES is generating are more likely to decrease and thus decrease income. In conclusion, for a PHES to maximise its profits, the operator needs to obtain the final electricity price in advance or else have very accurate price predictions.

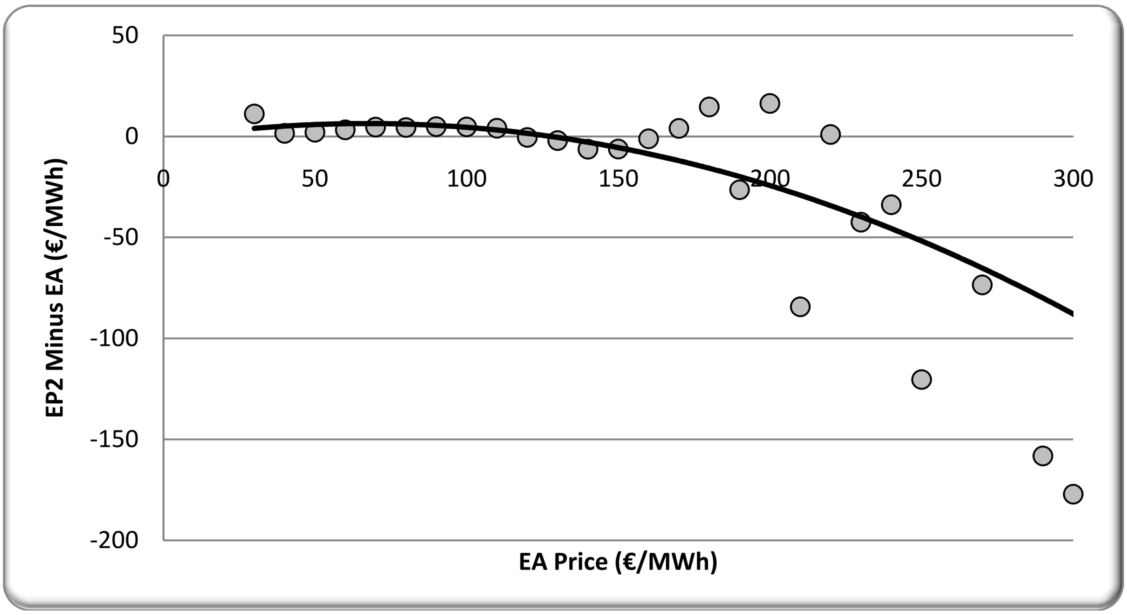


Figure 9-9: Average price difference between predicted EA prices and final EP2 prices on the Irish electricity market in 2008.

Next, the profits identified for the PHES facility using the 24Optimal strategy were compared with the annual investment costs required using the assumptions outlined in Table 9-3 along with Equation 4 in section 7.2, which consists of the total investment costs *I*, the installed capacities *C*, lifetimes *n*, an interest rate *i*, and the annual fixed O&M costs as a percentage of the total investment. As Deane *et al.* [99] outlined in a review of existing and proposed PHES facilities around the world, there is no 'general' cost for a PHES facility as it is very site dependent: the authors concluded that the investment costs could vary from 0.47 to 2.17 €M/MW. Therefore, to account for this variability, a low and high investment scenario was investigated based on this data. In addition, this analysis was carried out over a five year period and hence, it was only completed for the electricity markets which provided the price data necessary. Finally, as the lifetime of PHES is approximately 40 years (and up to 100 years for some components), the annual investment cost will be sensitive to the interest rate. Therefore, an interest rate of 3% and 6% was also used for both the high and low investment costs.

Table 9-3: Low and high cost assumptions for the PHES facility.

PHES Parameter	Cost [source]	Unit
	Common economic assumptions	
Variable O&M costs	1.5 [96]	€/MWh
Fixed O&M costs	1.5 [170]	% of investment
Lifetime	40 [96, 170]	Years
Interest Rate	6 [236]	%
	Low Investment Assumptions	
Pump investment*	0.235 [96, 99]	€M/MW
Turbine investment*	0.235 [96, 99]	€M/MW
Storage investment	7.884 [96]	€M/GWh
	High Investment Assumptions	
Pump investment*	1.085 [99]	€M/MW
Turbine investment*	1.085 [99]	€M/MW
Storage investment	15.77 [96]	€M/GWh

***This is 50% of the pump-turbine costs reported, which has been halved to reflect the pump and turbine capacity separately.**

As displayed in Figure 9-5 previously and Figure 9-10, the profit feasible from the PHES varies considerably from one electricity market to the next. However, Figure 9-10 also indicates that the profit on the same market can vary substantially from year to year. For five of the six markets analysed, the total profit varied by over 50% over the five year period analysed, which makes PHES a risky investment. In addition, Figure 9-10 emphasises the importance of locating a suitable site for constructing the PHES facility. If the initial investment costs are low and the PHES facility is constructed in a suitable market, then the profit fluctuations will not result in significant losses. However, as a PHES facility has a typical lifetime of approximately 40 years, it is likely that any potential investor would need some additional profit stability. A low interest rate is one policy which could improve the long-term feasibility of PHES. When the interest rate is increased from 3% to 6% on the initial investment, the annual repayments correspondingly increase by approximately 40%. If the initial investment costs are high at 2.17 €M/MW, then this equates to approximately €17M extra investment each year. However, even though a low interest rate would improve the economics of PHES, the results indicate that a suitable electricity market and low investment costs are still the most significant factors.

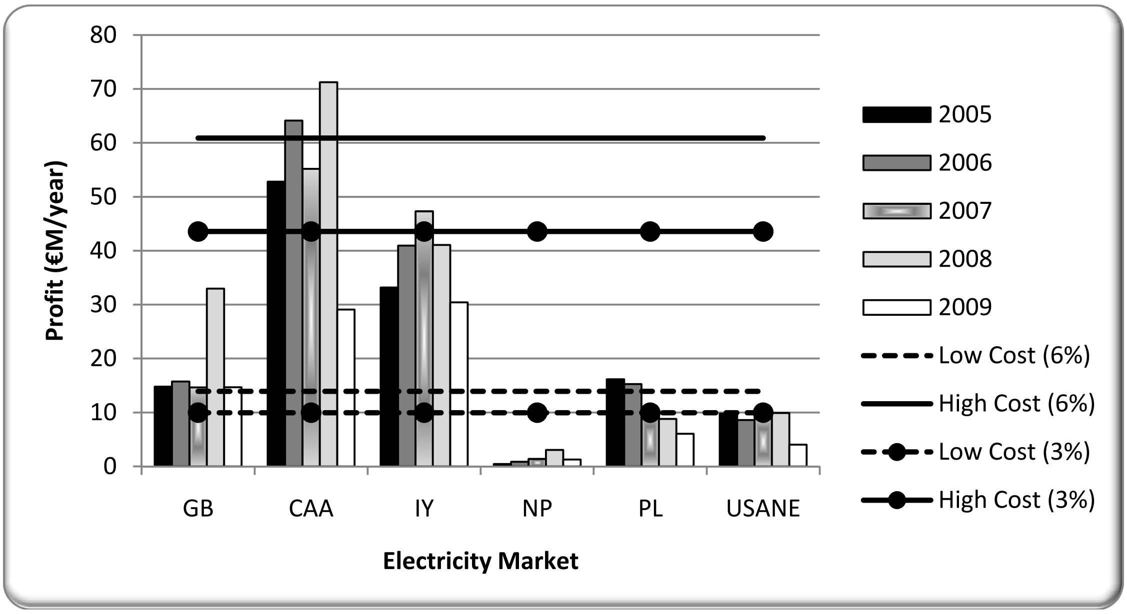


Figure 9-10: PHES profit using 24Optimal strategy on the electricity markets with data available for 2005 to 2009, along with high (€2.17M/MW) and low (€0.47M/MW) annual investment costs based on a 3% and 6% interest rate.

Finally, there are a number of limitations that should be considered when assessing the results discussed in this chapter. Firstly, the implications of the PHES facility on the historical markets prices used was not accounted for. If a PHES was installed, it is likely that low electricity prices would increase due to an increased demand from the PHES pump, and high electricity prices would decrease due to the generation provided from the PHES pump. However, due to the complexity of modelling the implications of a PHES unit on historical market prices as well as the relatively small scale of the PHES unit considered (compared to the size of the markets), the results in this study are still indicative of the expected profit from a PHES unit using price arbitrage. In addition, although a fixed O&M cost was considered in the economic calculations, the simulations here assumed that the PHES site was available for the entire year when maximising its profit on the electricity market. There could be a reduction in the profits feasible from electricity arbitrage, depending on the downtime of the PHES in the year. Lastly, the profit calculations in this study only considered the energy market. The PHES facility could make additional profit on the regulating, capacity, and ancillary services markets, if they exist and depending on the regulations specified in each market.

9.4. Conclusions

The results indicate that the 24Optimal operation strategy is the most profitable practical method of dispatching a typical PHES facility. Under this strategy the PHES is optimised based on the day-ahead electricity prices and by doing so, almost all (~97%) of the profits feasible can be obtained when the charge and discharge cycles are each approximately 6 hours, which is typical for an existing PHES plant. This indicates that long-term foresight of electricity prices is not essential for most PHES facilities to maximise their profits using electricity price arbitrage. However, a further analysis based on the Irish electricity market indicated that for the 24Optimal strategy to be effective, the day-ahead electricity prices must be the actual prices which the PHES facility is charged or the PHES operator must have very accurate price predictions. Otherwise, the predicted profit could be significantly reduced and even become a loss. Finally, using the 24Optimal strategy, the PHES profit from energy arbitrage on some electricity markets can surpass the annual investment repayments required. However, the annual profit from the PHES facility varied by more than 50% on five out of six electricity markets considered over the five year period analysed: 2005 to 2009. Therefore, even with low investment costs, a low interest rate, and a suitable electricity market, a PHES facility is still a risky investment in most markets without a more predictable profit or some additional revenue, which could come from ancillary services, capacity payments, or a balancing market.

10. Conclusions

The Irish energy system, wind energy, and pumped hydroelectric energy storage (PHES) were used to assess the role of large-scale energy storage and the integration of fluctuating renewable energy in this study. The Irish energy system was deemed suitable for three key reasons: it has a significant wind resource which could supply over 200% of Ireland's electricity demands with existing technologies, its ambitious wind energy targets which includes 34-37% of electricity from wind by 2020, and its isolated structure due to limited interconnection (chapter 4). Hence, utilising large-scale energy storage offers unique benefits for the Irish energy system. After an extensive review of all the energy storage technologies available, PHES was chosen as the most suitable for Ireland since it is the most mature, largest, and cheapest form of energy storage currently available (chapter 5). However, three key issues were often reported in the literature in relation to PHES: firstly there were very few suitable sites remaining for the construction of PHES, secondly it is unclear how much additional wind energy could be integrated onto the Irish energy system with PHES and thirdly, the role of energy storage on existing electricity markets was ambiguous (chapter 6). Hence, creating solutions for these issues defined the structure of this research.

To identify suitable PHES locations (chapter 7), a new software tool was developed which can search a user-specified terrain with user-specified parameters and recognise a suitable site for constructing PHES. The results from this software can be used in the Energy Capacity and Cost Calculator also developed in this study, which will estimate the size and cost of the facility found. After using these tools to search County Clare in Ireland, which is approximately 3150 km^2, at least 8 locations suitable for the construction of PHES were identified with capacities as large as 570 MW and 22.5 GWh. Therefore, this research has illustrated that Ireland has a significant freshwater PHES resource, so the next step was to quantify the implications of constructing it.

The implications of PHES were defined under two distinct objectives in this study: firstly, what is the maximum technical wind penetration feasible with PHES and secondly, what is the most economical wind penetration that can be achieved with PHES on the Irish energy system (chapter 8). Based on previous literature in this area, it was clear that a model of the Irish energy system would be necessary to answer these questions (section 6.2.1). Hence, a review of existing energy tools was carried out to identify a tool which could not only model the technical and economical implications of wind energy and PHES, but could also be applied to the Irish energy system (section 8.1.1). After assessing approximately 68 energy tools, EnergyPLAN was deemed the most suitable tool available for this study as it could model an entire national energy system, it could be applied to Ireland, it could be downloaded and assessed, online training was available, and previous studies completed using EnergyPLAN were very applicable to this study (section 8.1.2). Using EnergyPLAN, a model of the Irish energy system was created based on the year 2007 to ensure it could simulate Ireland accurately, and based on the year 2020 so the implications of PHES could be assessed (section 8.2).

With the 2020 model, the maximum feasible wind penetration was identified on the Irish energy system for various capacities and operating strategies of PHES, plus the implications of these wind penetrations on existing power plants was also examined (section 8.3). Here it was concluded that the grid constraints required to maintain grid stabilisation are closely linked to the benefits of PHES. Using a double penstock PHES operating strategy, it is possible to accommodate these grid constraints while also supplying up to 100% of Ireland's electricity using wind power. In contrast a single penstock operating strategy could only enable up to 60% of Ireland's electricity from wind power. However, the capacity analysis indicated that a double PHES would require much larger pump and turbine capacities than a single PHES. Therefore, the economic assessment was essential to identify whether the additional wind penetrations feasible from a double PHES were worth the additional pump and turbine capacities required.

Based on predicted 2020 fuel prices which reflect an oil price of \$100/bbl, a CO_2 cost of \$50/t, and an interest rate of 6%, results indicate that PHES is not a viable alternative for Ireland (section 8.4.2). However, if an interest rate of 3% was used to assess PHES and wind energy, due to their lengthy lifetimes and socio-economic benefits, then PHES would be an economical alternative in Ireland for 2020 (section 8.4.3). Similarly, if fuel prices increased to reflect an oil price of \$150/bbl, this would also be the case. Nonetheless, a comparison between PHES and two other alternatives, which were domestic heat pumps and a district heating network with CHP, indicated that these alternatives can provide similar savings to PHES while also being more robust against fuel prices, interest rates, and annual variations in wind generated electricity (section 8.4.4). In addition, as the benefits of PHES are dependent on grid constraints, the value of PHES could depreciate as distributed forms of energy generation begin to contribute to grid stabilisation. Conversely though, PHES does enable Ireland to utilise more indigenous wind power and obtain larger reductions in energy consumption, fossil fuels, and CO_2 than both the HP or CHP alternatives. Hence, depending on the socio-economic value which Ireland places on these issues, PHES could indeed be worth the additional economic cost. Therefore, PHES could be a viable alternative for Ireland under certain circumstances, but initial results indicate that heat pumps and district heating could offer more significant long-term economic savings at lower risk and hence, further work is necessary in these areas to ensure the optimum solution.

Separate to the results obtained in chapter 8, a number of conclusions can be made in relation to the methodology developed for evaluating energy storage on the Irish energy system. Firstly, it is crucial to consider the structure of an energy system when evaluating energy storage. Typically, most energy alternatives are assessed to identify how fuel consumption can be minimised by replacing fossil fuel technologies with renewable alternatives. Energy storage is only considered here because it is an additional source of flexibility in an energy system and hence, more renewable energy can be utilised. Therefore, energy storage is only useful if the energy system being evaluated requires additional flexibility. Considering this, energy storage should be assessed in the context of a future long-term system. In other words, the existing Irish energy system may need flexibility, but will the technologies available in 2020, 2030, or 2050 also need it? Secondly, when evaluating energy storage, it is vital that it is compared to a range of alternatives. Evaluating technologies as a solitary solution will not produce the optimum result for Ireland, as benefits and drawbacks are all relative. In line with this, the third key conclusion about the methodology utilised in chapter 8 concerns the sectors considered. When evaluating alternatives to energy storage, it is essential that all sectors of the energy system are considered, especially due to the potential flexibility that can be created by merging the supply and demand across the electricity, heat, and transport sectors. In other words, the electricity sector is no longer an independent entity within a national energy system, as the construction of technologies such as energy storage will have to be compared with technologies such as heat pumps and thermal storage in the heating sector, as well as electric vehicles in the transport sector. To summarise, when evaluating energy storage in the future, it is important to consider a long-term horizon, if flexibility is necessary, alternative investments, and the entire energy system.

Finally, if PHES is required on the Irish energy system in the future, it will need to be accommodated on the electricity market and hence this was also investigated (chapter 9). At present, there are three electricity markets in Ireland: ancillary services, capacity payments, and energy. As PHES must create the energy it needs before the time of delivery, it can only be optimised for one market at a time and hence the focus in this study was the energy market. Therefore, the objective was to maximise the profits of a PHES facility utilising electricity price arbitrage. For this analysis a PHES with a 360 MW pump, 300 MW turbine, and a 2 GWh storage capacity was used as case study, which chapter 7 indicated could be constructed in Ireland. During the investigation a new 24Optimal operating strategy was created for PHES on electricity markets, which enables them to achieve approximately 97% of the profits that could ever be obtained. Utilising this operating strategy in Ireland, the PHES facility could have earned approximately €18M in 2008 and €32M in 2009. The annual repayment costs for the same facility would be between €10M/year and €60M/year, depending on the initial capital costs and the interest rate required. Hence, if one of the PHES sites identified in chapter 7 can be constructed at a cost of approximately €0.5M/MW, then this facility could make a profit on the Irish electricity market by utilising electricity price arbitrage. However, chapter 9 also indicates that to do so the market should offer the PHES facility a fixed price one day in advance or else the operator will require very accurate price predictions. Otherwise, its income could be cut by approximately 20%. To build on this study, the profits feasible on the ancillary services and capacity payments markets should also be assessed in the future.

Overall, the results in this study have verified that Ireland can build large-scale PHES, it can provide all of its electricity using PHES and wind energy, and it can accommodate PHES on its electricity market. However, it is also important to recognise the limitations in these results. The sites identified in chapter 7 will require a more detailed assessment to determine their exact size, cost, and environmental impact. EnergyPLAN is a planning tool and hence a more detailed model of the grid would be necessary to fully evaluate the consequences of large-scale PHES and wind energy. Also, the PHES profits feasible from the ancillary services and capacity payments markets should also be assessed before altering the market to accommodate it. Therefore, even though the results portrayed throughout this thesis provide a good indication of the final results, their specific limitations need to be appreciated also. All of these issues could form the basis for more research in the future, but this research will continue by focusing on the most significant conclusion reported: Ireland needs to develop a long-term energy plan that utilises its significant fluctuating renewable energy resources such as wind, wave, tidal, and solar, by assessing alternatives which generate flexibility by integrating the electricity, heat, and transport sectors. As Paul Cunningham concluded after discussing Ireland's Green Economy with numerous researchers, entrepreneurs, and politicians [248]:

Chapter 10

"Ireland has immense natural resources, its people innovative skills; what we need now is a measureable and verifiable green action plan, co-ordinated thinking, and the determination to push it through. If we get this right, the green economy and green technologies can benefit every single one of us."

11. Future Work

Throughout this study a number of new methodologies, software tools, and definitions have been developed. Most significantly for Ireland though is the new model of the Irish energy system created in EnergyPLAN, which can be used to analyse a broad range of different technologies in the future, primarily as it considers the electricity, heat, and transport sectors. The benefits of this have already been illustrated in section 8.4.4, when PHES was compared to domestic heat pumps and a district heating system with CHP. Therefore, the primary focus for the future will be to investigate the feasibility of alternative energy technologies for Ireland which will ultimately lead to a 100% renewable energy system. This process has already begun by carrying out a technical assessment of a biomass, hydrogen, and electricity based 100% renewable scenarios for Ireland.

11.1. 100% Renewable Alternatives

Once the 2007 model of the Irish energy system was created and validated against historical data, an initial draft of a 100% RES for Ireland was developed. In total, four 100% renewable energy scenarios were made for Ireland including a:

1. Biomass Energy System (BES): a 100% renewable energy system based on biomass.
2. Hydrogen Energy System (HES): a 100% renewable energy system using hydrogen.
3. Electricity Energy System (EES): a 100% renewable energy system maximising the use of renewable generated electricity.
4. A combination of each (COMBO): a 100% renewable energy system based on the results from the BES, HES, and EES scenarios.

For each scenario a number of assumptions were made about the future energy demands and production units required. Although these assumptions would have to be validated further before an accurate solution is proposed, they do provide an indication of the trends that can be expected if various technologies are used as an integral part of a 100% renewable energy system for Ireland. Listed here are the assumptions used in three of the 100% renewable energy systems investigated for Ireland:

Assumptions for the biomass energy system (BES)

1. All electricity, heat, and transport demands were maintained at 2007 levels.
2. Energy storage is increased to 3000 MW and 15 GWh.
3. Eliminate existing electric heating.

4. Supply 10% of individual heating with solar thermal.
5. Supply 35% of individual heating with biomass boilers: accounts for all homes in rural areas.
6. Supply 55% of individual heating using district heating: accounts for heating demand in all towns and cities with more than 1500 people.
7. Introduce 251 MW (0.92 TWh) of tidal power.
8. The entire fuel demand in industry is supplied using biomass.
9. All transportation fuel is supplied by biofuels, including jet fuel. Biomass is converted to bio-ethanol at a ratio of 1:1.35 (for private cars and jet fuel) and to biodiesel at a ratio of 1:1 (for road freight).

Assumptions for the hydrogen energy system (HES)

1. All electricity, heat, and transport demands were maintained at 2007 levels.
2. An electrolyser of 10,000 MW and storage of 240 GWh is added to produce, store, and provide hydrogen to the power plant, transport, and heating sectors.
3. Supply 10% of individual heating with hydrogen micro CHP.
4. Supply 10% of individual heating with solar thermal.
5. Supply 10% of individual heating with heat pumps.
6. Supply 15% of individual heating with biomass boilers.
7. Supply 55% of individual heating using district heating: accounts for heating demand in all towns and cities with more than 1500 people.
8. Introduce 251 MW (0.92 TWh) of tidal power.
9. Introduce 3000 MW (3.33 TWh) of wave power.
10. The entire fuel demand in industry is supplied using biomass.
11. Transportation fuel is primarily supplied by hydrogen: all private cars and jet fuel is replaced by hydrogen, while 50% of road freight is fuelled by hydrogen and 50% biodiesel.

Assumptions for the electricity energy system (EES)

1. All electricity, heat, and transport demands were maintained at 2007 levels.
2. Energy storage is increased to 3000 MW and 15 GWh.
3. Supply 10% of individual heating with solar thermal.
4. Supply 35% of individual heating with heat pumps: accounts for all homes in rural areas.

5. Supply 55% of individual heating using electric heating: accounts for heating demand in all towns and cities with more than 1500 people.
6. Introduce 251 MW (0.92 TWh) of tidal power.
7. Introduce 1000 MW (1.11 TWh) of wave power.
8. The entire fuel demand in industry is supplied using biomass.
9. All road transportation is fuelled by electricity and biomass: The private car fleet is fuelled by 80% electricity and 20% bio-ethanol (which can include electric, hybrid, or bio-ethanol cars). All road freight is fuelled using biodiesel and all jet fuel is supplied using bio-ethanol.

Once these assumptions were reflected in the model of the Irish energy system, the capacity of wind power was increased incrementally to identify the maximum wind penetration that could be achieved, as this is the most economical renewable energy resource available in Ireland (see section 4.2). The process used to define the maximum wind penetration feasible is described in more detail in Appendix I.

Using the scenarios described and the methodology defined in Appendix I, the PES and the energy generated from all of the different technologies were calculated for all three scenarios, as displayed in Figure 11-1. From the outset it is evident that all three scenarios (BES, HES, and EES) have a lower primary energy supply than the 2007 reference. This is primarily due to the introduction of more efficient systems such as CHP and district heating in the BES and HES, as well as fuel cell transportation in the HES, and electric vehicles in the EES. Of the three alternatives, the EES has the lowest primary energy supply at 590 PJ, while the BES has the highest at 660 PJ. This is due to the large amount of biomass required to replace fossil fuels in the transport sector. In addition, unlike hydrogen and electric vehicles, bio-ethanol vehicles do not aid the integration of higher wind penetrations. The PES of the HES was also very similar to the BES at 629 PJ. This illustrates that a hydrogen economy is also very demanding on resources, especially in comparison to the EES. The main reason for this decrease in PES in the EES is the efficient use of electricity. In the HES, electricity is transformed to hydrogen and then typically transformed back to electricity at a later stage, which results in a very inefficient system. In contrast, the EES uses electricity directly so the losses are reduced, primarily in the transport sector.

The biomass consumption varies considerably within each scenario also, in terms of total consumption and also in terms of its specific uses. As expected, the BES uses the most biomass at 611 PJ, which is 92.5% of the PES. In the HES and the EES the biomass consumption is much less than the BES at 513 PJ and 472 PJ respectively. However, the use of biomass in both the HES and the EES is very different. The HES uses a large amount of biomass in the power plants, to create electricity to produce hydrogen for heating and transportation. In contrast, the EES uses a lot of biomass directly in the transport sector.

Also from these results, it is evident that the biomass energy system can utilise very little wind energy compared to the HES and the EES. In total, the BES was only able to integrate 10.4 TWh of renewable generated electricity, while the HES was able to integrate 29 TWh and the EES 29.7 TWh. This is due to the much larger electricity demands and energy storage capacities available in the HES and the EES. The HES uses a lot of electricity to generate hydrogen which can then be stored for use in power plants, hydrogen micro-CHP, and transport. The EES uses a large amount of electricity for electric heating and transportation, while electric vehicles can also act as a large sink for excess renewable energy.

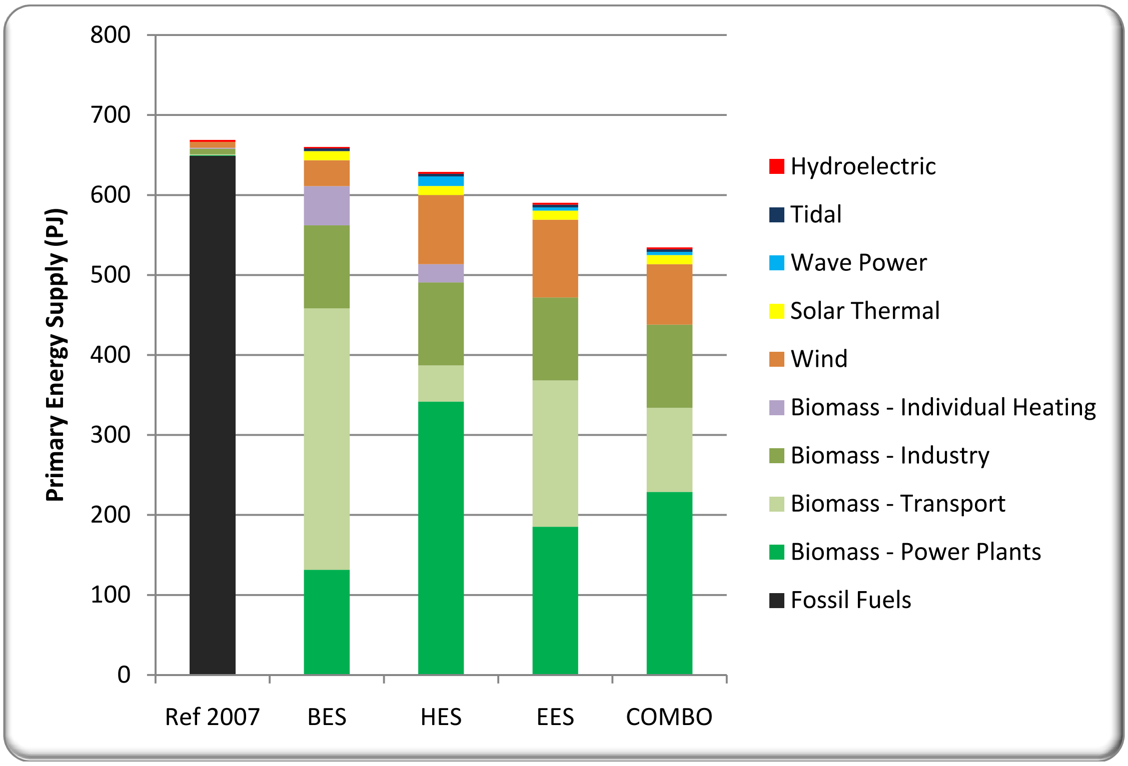


Figure 11-1: Primary energy supply in reference, BES, HES, EES, and COMBO scenarios.

Based on the results from the BES, HES, and ESS, a COMBO scenario was created with the following characteristics:

1. All electricity, heat, and transport demands were maintained at 2007 levels.

2. No energy storage is added: enough is provided by the electric vehicles in the transport sector.
3. Supply 10% of individual heating with solar thermal.
4. Supply 35% of individual heating with heat pumps: accounts for all homes in rural areas.
5. Supply 55% of individual heating using district heating: accounts for heating demand in all towns and cities with more than 1500 people.
6. Introduce 251 MW (0.92 TWh) of tidal power.
7. Introduce 1000 MW (3.33 TWh) of wave power.
8. The entire fuel demand in industry is supplied using biomass.
9. Transportation is fuelled by electricity, hydrogen, and biomass. The private car fleet is fuelled by 80% electricity and 20% bio-ethanol, road freight is supplied by 50% bio-ethanol and 50% hydrogen, and jet fuel is supplied using 50% hydrogen and 50% bio-ethanol.

The objective was to combine the efficient use of biomass in the BES scenario with the efficiency of rural heating in the EES. Therefore, CHP and district heating was used instead of electric heating in the EES, while heat pumps were maintained as the primary heat technology in rural areas. For the transport sector, the efficiency of electric vehicles was maintained for private transport, and a mix of hydrogen and biomass was used for road freight and aviation fuel. From Figure 11-1, it is evident that this results in the most efficient energy system of all. The PES is reduced by 20% to 534.5 PJ and 23.7 TWh of renewable generated electricity is used. Finally, the biomass required in the COMBO scenario is reduced to 438 PJ, which is 71% of the biomass demand in the BES. This is also 59.6% of the potential biomass resource in Ireland, although this is a total potential and not a residual potential i.e. it does not account for land that may be unavailable to avoid affecting food production or other industries [44]. Therefore, even though the biomass requirement in the COMBO scenario is low, it still might be too much depending on the residual biomass that is available in Ireland.

In addition to the issues already discussed, it is also worth noting that energy savings were not considered in detail in this analysis. It was assumed that energy demands would remain the same as 2007: this may be too low as energy demands are likely to increase in the future, or it may be too high as it may be possible to reduce demands below 2007 levels depending on the energy savings feasible. In the future, energy conservation will need to be considered in more detail, when identifying the least-cost 100% renewable energy system for Ireland.

11.2. Conclusions

In summary, this work illustrates that an Irish energy system with district heating, heat pumps, and a transportation mix of electricity, hydrogen, and biomass, is the most efficient and resource-friendly method of converting Ireland to a 100% renewable energy system. However, this analysis was carried out from a technical and resource perspective and not an economic perspective, which may alter the results. Also, the assumptions used to create the alternatives in this study are crude and the combinations of technologies used to supply the demands are not at optimum capacities. However, although the results obtained in this study are not ideal, they do illustrate the options available to Ireland in achieving a 100% renewable energy system.

Overall, this research focused primarily on the benefits of large-scale energy storage, but the most significant finding in this work is the need for a more detailed analysis of energy system alternatives for Ireland. Therefore, it is hoped that this work can motivate a larger interest in identifying accurate predictions and costs (especially socio-economic) for the future of the Irish energy system, specifically among experts within each of the relevant areas and hence improve the overall accuracy of the models created. It is imperative that Ireland quantifies the benefits of existing technologies such as CHP, district heating, heat pumps, biomass boilers, and electric rail more accurately, as well as the potential of future technologies such as electric vehicles and the hydrogen economy. Future studies will focus on these technologies with the overall objective of defining a realistic pathway towards a 100% RES for Ireland. This will contribute to an increasing body of 100% RE research that has already been carried out for regions such as Australia [249], New Zealand [250, 251], Japan [203], America [250, 252], Denmark [228-232], Portugal [145], and Europe [189, 253, 254].

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Appendices

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   Version 3 of same published as: Leahy MJ, Connolly D, Buckley DN, Chapter 21: Wind Energy storage Technologies, in: W Tong (Ed.) Wind Power Generation and Wind Turbine Design, WIT Press, 2010, pp. 661-714.

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Appendix A

Connolly D, Leahy M. A Review of Energy Storage Technologies: For the integration of fluctuating renewable energy, Version 4. University of Limerick, 2010. Available from: http://www.dconnolly.net/publications.html.

Version 3 of same published as: Leahy MJ, Connolly D, Buckley DN, Chapter 21: Wind Energy storage Technologies, in: W Tong (Ed.) Wind Power Generation and Wind Turbine Design, WIT Press, 2010, pp. 661-714.

A Review of Energy Storage Technologies

For the integration of fluctuating renewable energy

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10 December 2010
Version 4.1

This review was carried out as part of David Connolly's Ph.D. project, which was supervised by Prof. Martin Leahy (University of Limerick), Prof. Henrik Lund (Aalborg University), and Dr. Brian Vad Mathiesen (Aalborg University). It was funded by the Irish Research Council for Science, Engineering, and Technology (IRCSET).

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Abstract

A brief examination into the energy storage techniques currently available for the integration of fluctuating renewable energy was carried out. These included Pumped Hydroelectric Energy Storage (PHES), Underground Pumped Hydroelectric Energy Storage (UPHES), Compressed Air Energy Storage (CAES), Battery Energy Storage (BES), Flow Battery Energy Storage (FBES), Flywheel Energy Storage (FES), Supercapacitor Energy Storage (SCES), Superconducting Magnetic Energy Storage (SMES), Hydrogen Energy Storage System (HESS), Thermal Energy Storage (TES), and Electric Vehicles (EVs). The objective was to identify the following for each:

1. How it works
2. Advantages
3. Applications
4. Cost
5. Disadvantages
6. Future

A brief comparison was then completed to indicate the broad range of operating characteristics available for energy storage technologies. It was concluded that PHES is the most likely stand-alone technology that will be utilised in Ireland for the integration of fluctuating renewable energy. However, the HESS, TESS, and EVs are the also very promising, but require more research to remove uncertainty surrounding their benefits and costs.

For some countries, CAES could be a more suitable technology than PHES depending on the availability of suitable sites. FBES could also be utilised in the future for the integration of wind, but it may not have the scale required to exist along with electric vehicles. The remaining technologies will most likely be used for their current applications in the future, but further developments are unlikely.

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Nomenclature

Symbol	Description	Unit
A	Area of parallel plates on capacitor	m^2
C	Capacitance	F
E_{CAP}	Energy stored in capacitor	J
E_{COIL}	Energy stored in coil (of SMES device)	J
$E_{KINETIC}$	Total kinetic energy in flywheel	J
F	Force	N (kgm/s^2)
I	Current	A
L	Inductance of coil (in SMES device)	H
P_C	Power Capacity	W (J/s)
S_C	Storage Capacity	Wh
T	Temperature in Kelvin / degrees Celsius	K / °C
V	Voltage	V
d	Distance between parallel plated on capacitor	m
t	Time	h, s
m_f	Mass of flywheel	kg
g	Acceleration due to gravity	m/s^2
$v_{CIRCULAR}$	Circular velocity of flywheel	m/s
ε_0	Permittivity of free space	F/m
ε_r	Relative permittivity/dielectric constant	F/m
η	Efficiency of PHES when pumping or generating	-
η_G	Efficiency of PHES when generating	-
ρ	Density	kg/m^3
σ	Specific strength of flywheel material	Nm/kg

Acronyms and Abbreviations

Symbol	Description
AC	Alternating Current
ACTES	Air-Conditioning Thermal Energy Storage
ATS	Aquifer Thermal Storage
BES	Battery Energy Storage
BOP	Balance-of-Plant
CAES	Compressed Air Energy Storage
DC	Direct Current
DoD	Depth-of-Discharge
DOE	Department of Energy (US)
DTS	Duct Thermal Storage
DSM	Demand Side Management
DSO	Distribution System Operator
EU	European Union
FBES	Flow Battery Energy Storage
FC	Fuel Cell
FES	Flywheel Energy Storage
GW	Gigawatt
GWh	Gigawatt-hour
HESS	Hydrogen Energy Storage System
ICE	Internal Combustion Engine
kW	kilowatt
kWh	kilowatt-hour
LA	Lead-Acid
MJ	Mega joule (1 MJ = 0.28 kWh)
MW	Megawatt
MWh	Megawatt-hour
NaS	Sodium-Sulphur

Symbol	Description
NiCd	Nickel-Cadmium
PCS	Power Conversion System
PHES	Pumped Hydroelectric Energy Storage
PSB	Polysulphide-Bromide
SCES	Supercapacitor Energy Storage
SMES	Superconducting Magnetic Energy Storage
T&D	Transmission and Distribution
TES	Thermal Energy Storage
TESS	Thermal Energy Storage System
TSO	Transmission System Operator
UK	United Kingdom
UPS	Uninterruptable Power Supply
US	United States (of America)
VR	Vanadium-Redox
VRLA	Valve Regulated Lead-Acid
ZnBr	Zinc-Bromine

1 Introduction

Energy storage is a well established concept yet still relatively unexplored. Storage systems such as pumped hydroelectric energy storage (PHES) have been in use since 1929 [1], primarily to level the daily load on the electricity network between night and day. However, as the electricity sector is currently undergoing a lot of change, energy storage is starting to become a realistic option for [2]:

1. Restructuring the electricity market.
2. Integrating renewable resources.
3. Improving power quality.
4. Aiding the increase in distributed energy production.
5. Helping the network operate under more stringent environmental requirements.

Energy storage can optimise the existing generation and transmission infrastructures whilst also preventing expensive upgrades. Power fluctuations from renewable resources can their penetration onto electricity networks. However energy storage devices can manage these irregularities and thus aid the implementation of renewable technologies. In relation to conventional power production, energy storage devices can improve overall power quality and reliability, which is becoming more important for modern commercial applications. Finally, energy storage devices can reduce emissions by aiding the transition to newer, cleaner technologies such as renewable resources and the hydrogen economy. Therefore, Kyoto obligations can be met and penalties avoided.

Historically, a number of obstacles have hampered the commercialisation of energy storage devices. Firstly, there are inconclusive benefits from energy storage. Consumers do not understand what exactly the benefits of energy storage are in terms of savings, additional renewables, and power quality. This issue is enhanced by the high capital costs typically associated with energy storage technologies and the lack of experience for many participants involved including investors, transmissions system operators (TSOs), and market designers. Consequently, it is even uncertain who should pay for energy storage? Some participants view storage as 'grid infrastructure', especially in markets where energy storage is primarily dispatched as a grid asset. However, other participants view it as another generator which should be built and operated by individual investors. If this is the case, then electricity markets need to be structured to accommodate energy storage: for example regulating markets need to be liberalised and energy storage should be able to bid for both demand and generation on the electricity market.

Even with these concerns, it is still envisaged that as renewable resources and power quality become increasingly important, energy storage costs are expected to decline and concerns in relation to their deployment should be resolved. Therefore, this report was carried out to identify the numerous different types of energy storage devices currently available. The parameters used to describe an energy storage device are defined in section 0, followed by a description its components in section 0. Subsequently, some typical energy storage applications are described in section 4 and in section 0, each energy storage technique currently available is analysed under the following key headings: operation; advantages; applications; cost; disadvantages; and future potential. Finally, in section 6 a brief comparison of the various technologies is provided which creates the conclusions outlined in 7.

1.1 Energy Storage for Ireland

In order to reduce greenhouse gases, Ireland's primary objective is to produce at least 40% of its electricity from renewable resources by 2020 [3]. In line with this, Ireland's wind capacity reached approximately 1000 MW in 2008, which Table 1-1 indicates is approximately 13% of the total Irish generating capacity. However, not only did this only provided 8.1% on Ireland's total electricity demand [4], but previous research has indicated that grid stability can be affected once wind capacity passes 800 MW [5]. As a result, Ireland will need to address the effects of wind intermittency in the immediate future as it progresses towards its 2020 targets.

Table 1-1: Conventional and wind generation capacity for Ireland and Northern Ireland in 2008[#].

Item	Republic of Ireland (MW)	Northern Ireland (MW)	All-Island (MW)
Total Conventional Capacity (MW)	6245	1968	8213
Total Wind Capacity (MW)	1000[♦]	182*	1182[♦]
Total	7245	2150	9395

[#]Data is correct as of 18th January 2008.
[♦]Numbers have been rounded for convenience.
***Will increase to 408 MW by August 2009.**

Energy storage on an electric grid provides all the benefits of conventional generation such as enhanced grid stability, optimised transmission infrastructure, high power quality, increased renewable energy penetration, and increased wind farm capacity. However, almost all energy storage technologies produce no carbon emissions during generation and do not rely on imported fossil fuels. As a result, energy storage is a very attractive option for increasing wind penetration onto the electric grid when it is needed.

Currently Ireland's solution to the intermittency of wind generation is primarily based on increased grid interconnection [6]. Hence, the Irish TSO (EirGrid) is in the process of constructing a 500 MW interconnector from Ireland to Wales that will allow for importing and exporting of electricity to and from Britain. Effectively, Britain will be Ireland's 'storage' device: excess electricity can be sold when the wind is blowing and electricity can be imported when it is not. However, unlike an energy storage device, the availability of an interconnector will not only depend on the Irish energy system, but on the British one as well.

Denmark which not only has the largest penetration of wind energy in the world, but is also a very similar country to Ireland in terms of population, energy demand, and renewable resources, also built large interconnectors to neighbouring countries Germany, Norway and Sweden (see Table 1-2). However, the Danish experience has indicated that interconnection is not an ideal solution for the integration of wind power, as they often export their wind power cheaper than the electricity that is imported. When excess wind power is available Denmark needs to get export it, so its neighbouring counties can buy wind power from Denmark at a cheap price. However, when wind production is low, the neighbouring countries can then sell power back to Denmark at a higher rate, as the Danish system must meet demand. Although Denmark often makes a profit under these circumstances, the value of its wind energy is reduced. As a result, Danish studies indicate that the financial benefit associated with their large interconnection is small compared to the implementation of other technologies which would create flexibility within the Danish energy system [7]. Similarly, if Ireland uses Britain as a power sink/source to accommodate wind power, Ireland too could reduce the value of its wind power, by exporting cheap and importing expensive electricity.

To conclude, energy storage technologies may provide a source of flexibility that enables Ireland to utilise its wind power at lower socio-economic costs than solutions such as interconnection. By using energy storage with or instead of interconnection, Ireland could potentially develop an independent, stable, and green electric grid. Based on this possibility alone, it is worth assessing the various types of storage technologies that exist so an assessment of large-scale energy storage in Ireland can be completed.

Table 1-2: Grid interconnection in and out of Denmark.

Country	Interconnection From Denmark (MW)	Interconnection To Denmark (MW)
Germany	1200	800
Norway	950	1000
Sweden	610	580
Total	2760	2380

2 Energy Storage Parameters

Throughout this report, various parameters of the different energy storage technologies that exist will be discussed. These parameters are defined below for clarity:

- Power Capacity: is the maximum instantaneous output that an energy storage device can provide, usually measured in kilowatts (kW) or megawatts (MW).
- Energy Storage Capacity: is the amount of electrical energy the device can store usually measured in kilowatt-hours (kWh) or megawatt-hours (MWh).
- Efficiency: indicates the quantity of electricity which can be recovered as a percentage of the electricity used to charge the device.
- Response Time: is the length of time it takes the storage device to start releasing power.
- Round-Trip Efficiency: indicates the quantity of electricity which can be recovered as a percentage of the electricity used to charge and discharge the device.

2.1 Battery/Flow Battery Only

For electrochemical based storage technologies such as advanced batteries and flow batteries, there is specific terminology, which is:

- Charge-to-Discharge Ratio: is the ratio of the time it takes to charge the device relative to the time it takes to discharge the device i.e. if a device takes 5 times longer to charge than to discharge, it has a charge-to-discharge ratio of 5:1.
- Depth-of-Discharge (DoD): is the percentage of the battery capacity that is discharged during a cycle.
- Memory Effect: If certain batteries are never fully discharged they ‘remember’ this and lose some of their capacity.

3 Energy Storage Components

Before discussing the technologies, a brief explanation of the components within an energy storage device are discussed. Every energy storage facility is comprised of three primary components:

1. Storage Medium
2. Power Conversion System (PCS)
3. Balance of Plant (BOP)

3.1 Storage Medium

The storage medium is the 'energy reservoir' that retains the potential energy within a storage device. It ranges from mechanical (PHES), chemical (BES) and electrical (SMES) potential energy.

3.2 Power Conversion System (PCS)

It is necessary to convert from alternating current (AC) to direct current (DC) and vice versa, for all storage devices except mechanical storage devices e.g. PHES and CAES [8]. Consequently, a PCS is required that acts as a rectifier while the energy device is charged (AC to DC) and as an inverter when the device is discharged (DC to AC). The PCS also conditions the power during conversion to ensure that no damage is done to the storage device.

The customization of the PCS for individual storage systems has been identified as one of the primary sources of improvement for energy storage facilities, as each storage device operates differently during charging, standing and discharging [8]. The PCS usually costs from 33% to 50% of the entire storage facility. Development of PCSs has been slow due to the limited growth in distributed energy resources e.g. small scale power generation technologies ranging from 3 to 10,000 kW [9].

3.3 Balance-of-Plant (BOP)

These are all the devices that:

- Are used to house the equipment
- Control the environment of the storage facility
- Provide the electrical connection between the PCS and the power grid

It is the most variable cost component within an energy storage device due to the various requirements for each facility. The BOP "typically includes electrical interconnections, surge protection devices, a support rack for the storage medium, the facility shelter and environmental control systems" [8].

"The balance-of-plant includes structural and mechanical equipment such as protective enclosure, heating/ventilation/air conditioning (HVAC), and maintenance/auxiliary devices. Other BOP features include the foundation, structure (if needed), electrical protection and safety equipment, metering equipment, data monitoring equipment, and communications and control equipment. Other cost such as the facility site, permits, project management and training may also be considered here" [2].

4 Energy Storage Applications

Later this report will outline how unique each energy storage technique is. Due to these unique characteristics of the various techniques available, there are a wide range of applications for energy storage devices. These include [2]:

1. End-use applications
2. Emergency back-up
3. Transmission and distribution stabilisation
4. Transmission upgrade deferral
5. Load management
6. Renewable energy integration
7. Demand Side Management (DSM)

4.1 End-Use Applications

The most common end-use application for energy storage is power quality, which primarily consists of voltage and frequency control. Transit and end-use ride-through are applications requiring short power durations and fast response times, in order to level fluctuations, prevent voltage irregularities, and provide frequency regulation. This is primarily used on sensitive processing equipment and thus the capacities required are usually less than 10 MW.

4.2 Emergency Back-Up

This is a type of uninterruptable power supply (UPS) except the units must have longer energy storage capacities. The energy storage device must be able to provide power while generation is cut altogether. Power ratings of 1 MW for durations up to one day are most common.

4.3 Transmission and Distribution Stabilisation

Energy storage devices are required to stabilise the system after a fault occurs on the network by absorbing or delivering power to generators when needed to keep them turning at the same speed. These faults induce phase angle, voltage, and frequency irregularities that are corrected by the storage device. Consequently, fast response (seconds) and high power ratings (1 MW to 10 MW) are essential.

4.4 Transmission Upgrade Deferral

Transmission line upgrades are usually separated by decades and must be built to accommodate likely load and generating expansions. Consequently, energy storage devices are used instead of upgrading the transmission line until such time that it becomes economical to do so. Typically, transmission lines must be built to handle the maximum load required and hence it is only partially loaded for the majority of each day. Therefore, by installing a storage device the power across the transmission line can maintained a constant even during periods of low demand. When the demand increases, the storage device is discharged to prevent the need for extra capacity on the transmission line. Therefore, upgrades in transmission line capacities can be avoided. Storage devices for this application typically have a power capacity ranging from the kW scale to several hundred megawatts along with a storage capacity of 1 to 3 hours. Currently the most common alternative is portable generators; with diesel and fossil fuel power generators as long term solutions and biodiesel generators as a short term solution.

4.5 Load Management

There are two different aspects to load management: load levelling and load following. Load levelling uses off-peak power to charge the energy storage device which can then be discharged during peak demand. Many international electricity markets trade on a spot market utilising half-hourly trading periods, each with a unique cost per unit of electricity generated (€/MWh). This price can vary significantly over a 24-hour period due to the relative change in electricity demand. For example, Figure 4-1 indicates that in 2009, the average electricity price at 18:30 was approximately 300% the average electricity price at 04:00 on the Irish electricity market. Therefore, energy storage devices can be charged during these off-peak hours at night and then used to generate electricity when it is the most expensive, during short peak production periods in the evening. Not only does this enable the energy storage unit to maximise its profits, but it can also reduce the cost of operating the system.

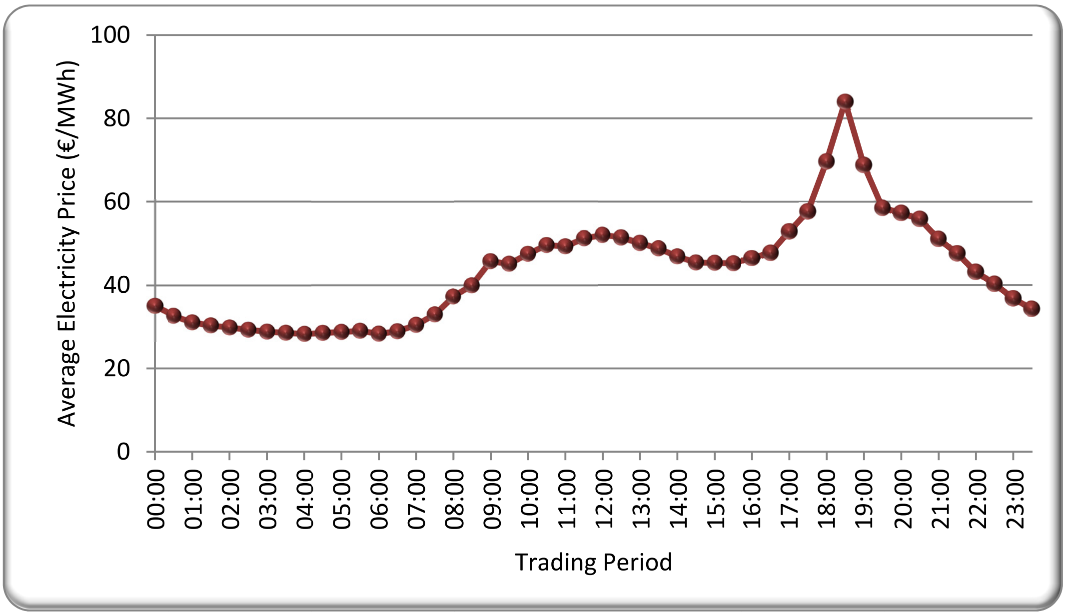


Figure 4-1: Average ex-post electricity price for each trading period on the Irish electricity in 2009 [10].

For load following, the energy storage device acts as a sink when demand falls below production levels and as a source when demand is above production levels. Therefore, the storage can be used to maintain ancillary services and reserve on the electricity grid. Spinning reserve is classified under two categories: fast response and conventional. For fast response spinning reserve, the power capacity must be kept in a state of 'hot standby' so it can respond to network abnormalities in seconds. For conventional spinning reserve, the power capacity requires a slower response of approximately 5-15 minutes.

Energy storage devices used for load management usually require power ratings of 10 MW to 400 MW and fast response times. It utilised for spinning reserve, then the energy storage will usually be required between 20 to 50 times per year.

4.6 Renewable Energy Integration

When analysing the implications of large-scale wind energy on electricity grids, Weisser and Garcia stated that there should be no technical issues for instantaneous wind penetrations up to 20% [11]. In the future, Lundsager et al. estimates that a maximum wind penetration of 25-50% is feasible within the electricity sector [12]. However, Lundsager et al. also stated that the feasibility of very high wind penetrations decreases dramatically when the size of the electricity grid increases from 100 kW to 10 MW: for a 100 kW grid a wind penetration of 80% is feasible, but for a 10 MW grid a wind penetration of only 20% is feasible [12]. The authors concluded that primary reason for this dramatic reduction in feasible wind penetrations was due to the lack of energy storage on the grid [12]. Besides wind, this conclusion can also be made for many other forms of intermittent renewable energy such as solar, tidal, and photovoltaic.

Using its load following capabilities, energy storage can be used to match the output from renewable resources to the demand required. This is displayed in Figure 4-2 using the electricity demand and extrapolated wind data from the Irish energy system based on the 17th April 2008. During the night-time valley wind exceeded demand and thus it was sent to the storage device. When there was a shortfall at approximately 07:00, the storage discharged to ensure demand was met. Alternatively, the storage could be used to maximise the profits from a wind farm by storing renewable energy which is generated during off-peak time periods, but discharging during peak hours, which Figure 4-1 illustrates have much larger electricity prices. Finally, energy storage could also be used to smooth the output fluctuations from an individual wind farm and thus increase the quality of power being delivered from it.

A storage system used with renewable energy could have a power capacity ranging from 10 kW to several hundred megawatts, depending on the capacity of renewable energy and structure of the energy system being considered. Also, it must have a very fast response time (less than a second in some cases), excellent cycling characteristics, and a good lifespan (100 to 1,000 cycles per year).

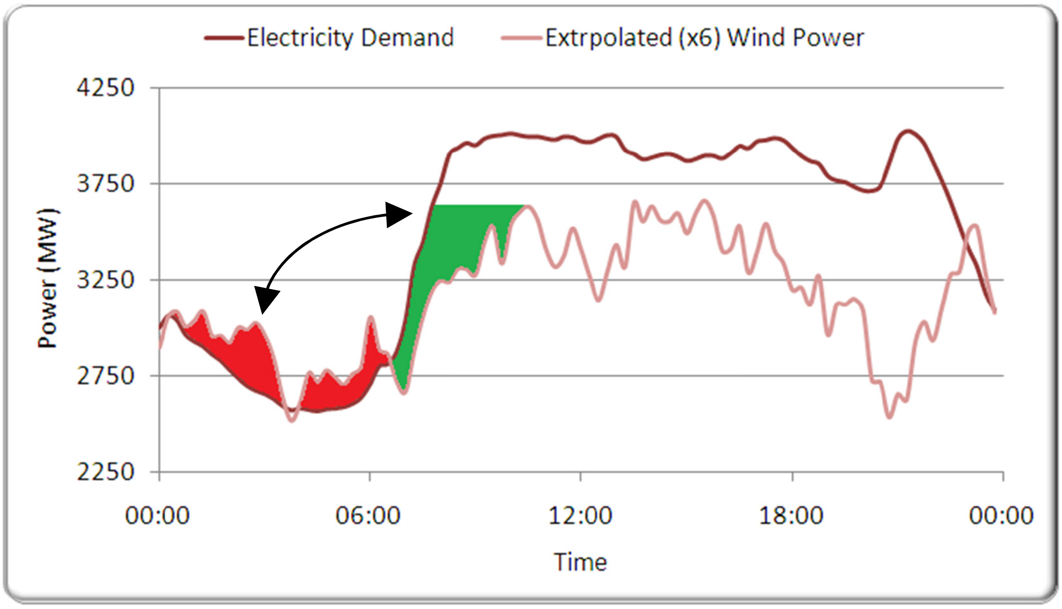
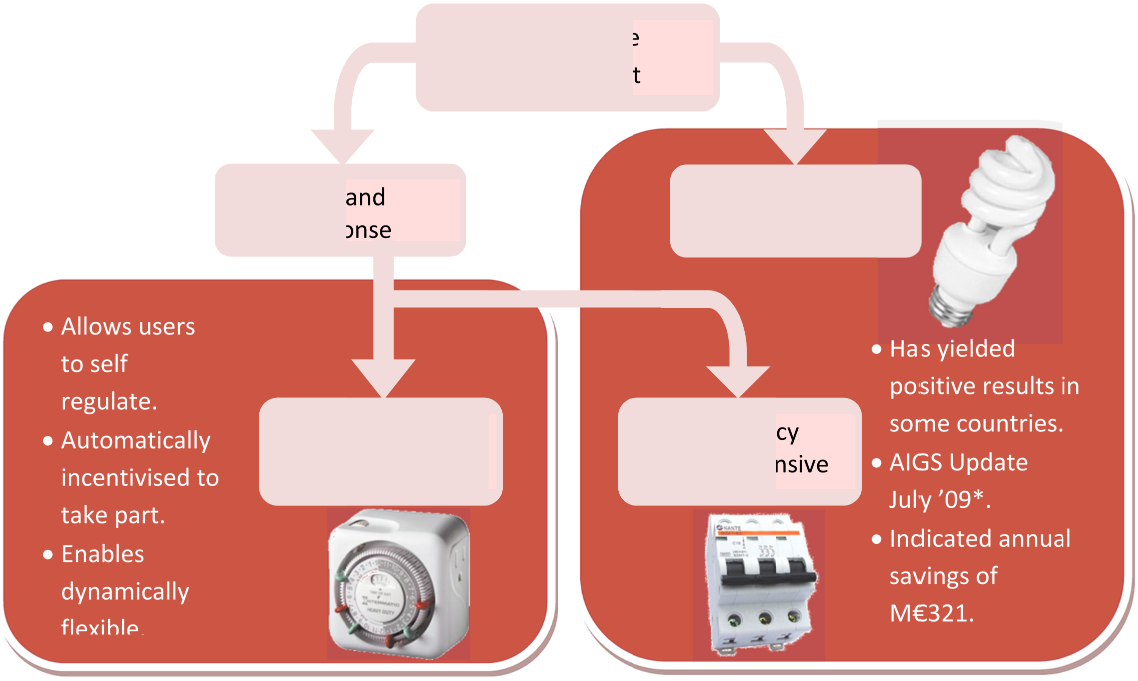


Figure 4-2: Integration of extrapolated (x6) wind power using energy storage on the Irish electricity grid.

4.7 Demand Side Management (DSM)

DSM involves actions that encourage end-users to modify their level and pattern of energy usage. As outlined in Figure 4-3, the level of energy is usually reduced using energy efficiency, which is not generally associated with energy storage. However, the pattern of energy usage is typically altered using price responsive or load responsive demand shifting. Hence, energy storage can aid each of these by creating flexibility as well as providing backup generation. Conversely, DSM can be used to reduce the amount of energy storage capacity required in order to improve the network. Currently, many countries are promoting the use of DSM as a tool for the integration of renewable resource using similar principals to energy storage. Therefore, as smart networks become more advanced, DSM either with or instead of energy storage could become a realistic alternative.



***The AIGS [6] is the basis for Ireland's renewable energy targets. It was updated in 2009 to include DSM [13].**

Figure 4-3: Role of demand side management on electricity grids [14].

5 Energy Storage Techniques

In this section, each of the energy storage techniques identified are analysed under the following key headings: operation and advantages; applications; cost; disadvantages; and future potential. In total 11 types were considered, which included:

1. Pumped hydroelectric energy storage (PHES)
2. Underground pumped hydroelectric energy storage (UPHES)
3. Compressed air energy storage (CAES)
4. Battery energy storage (BES), which included:
   - 4.1 Lead-acid (LA)
   - 4.2 Nickel-cadmium (NiCd)
   - 4.3 Sodium-sulphur (NaS)
5. Flow battery energy storage (FBES), which included:
   - 5.1 Vanadium-redox (VR)
   - 5.2 Polysulphide-bromide (PSB)
   - 5.3 Zinc-bromine (ZnBr)
6. Flywheel energy storage (FES)
7. Supercapacitor energy storage (SCES)
8. Supermagnetic energy storage (SMES)
9. Hydrogen energy storage system (HESS)
10. Thermal energy storage (TES), which included:
    - 10.1 Air-conditioning thermal energy storage (ACTES)
    - 10.2 Thermal energy storage system (TESS)
11. Electric vehicles (EVs)

The various techniques are purposely explained in this order based on their capabilities and hence typical applications. This is discussed in more detail when the various energy storage techniques are compared in section 6. No energy storage technologies were excluded prior to this investigation and hence, every energy storage technology associated with the integration of fluctuating renewable energy in the literature was included for consideration.

5.1 Pumped Hydroelectric Energy Storage (PHES)

Pumped hydroelectric energy storage is the most mature and largest storage technique available. It consists of two large reservoirs located at different elevations and a number of pump/turbine units (see Figure 5-1). During off-peak electrical demand, water is pumped from the lower reservoir to the higher reservoir where it is stored until it is needed. Once required (i.e. during peak electrical production) the water in the upper reservoir is released through the turbines, which are connected to generators that produce electricity. Therefore, during production a PHES facility operates in a similar way to a conventional hydroelectric system.

The efficiency of modern pumped storage facilities is in the region of 70% - 85%. However, variable speed machines are now being used to improve this [15]. The efficiency is limited by the efficiency of the pump/turbine unit used in the facilities [2].

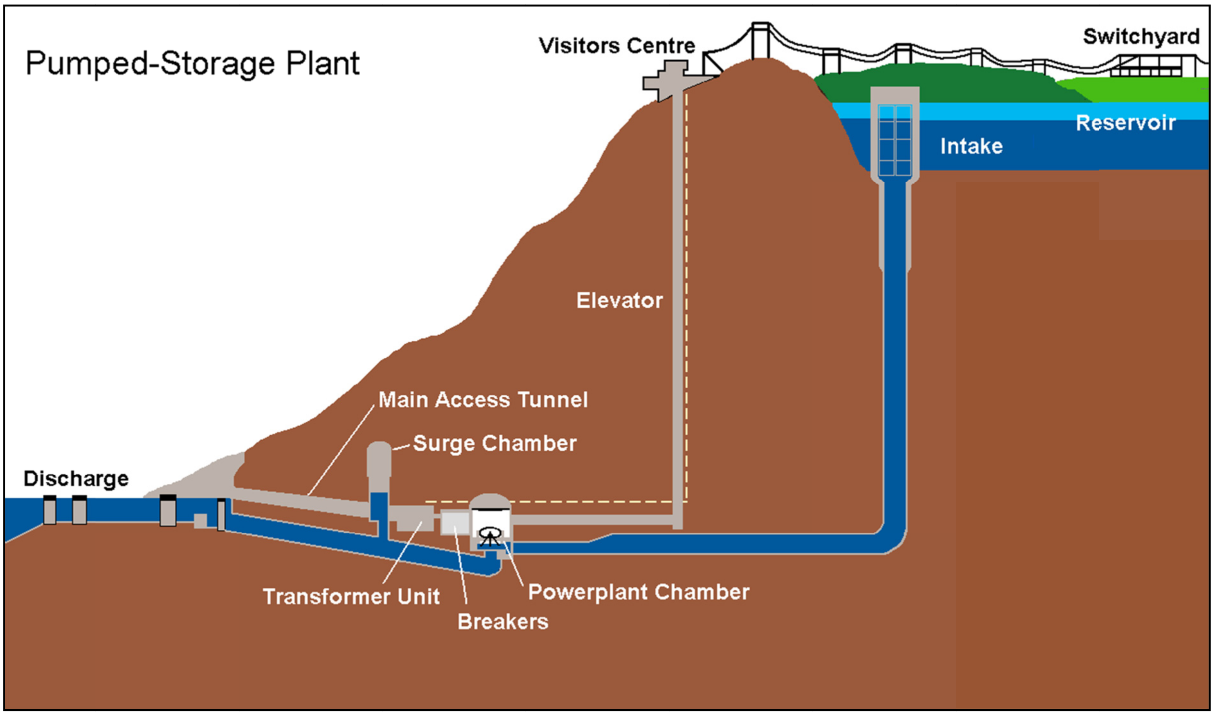


Figure 5-1: Layout of a pumped hydroelectric energy storage facility [16].

Until recently, PHES units have always used fresh water as the storage medium. However, in 1999 a PHES facility using seawater as the storage medium was constructed [17], see Figure 5-2; corrosion was prevented by using paint and cathodic protection. A typical PHES facility has 300 m of hydraulic head (the vertical distance between the upper and lower reservoir). The power capacity (kW) is a function of the flow rate and the hydraulic head, whilst the energy stored (kWh) is a function of the reservoir volume and hydraulic head. To calculate the mass power output of a PHES facility, the following relationship can be used [18]:

$$P_C = \rho g Q H \eta \qquad (1)$$

Where:
P_C = power capacity in Watts (W)
ρ = mass density of water in kg/m^3
g = acceleration due to gravity in m/s^2
Q = discharge through the turbines in m^3/s
H = effective head in m
η = efficiency of the PHES when pumping or generating

And to evaluate the storage capacity of the PHES the following must be used [19]:

$$S_C = \frac{\rho g H V \eta_G}{3.6x10^9} \qquad (2)$$

Where:
S_C = storage capacity in megawatt-hours (MWh)
V = volume of water that is drained and filled each day in m^3
ρ = mass density of water in kg/m^3
g = acceleration due to gravity in m/s^2
H = effective head in m
η_G = efficiency of the PHES when generating

It is evident that the power and storage capacities are both dependent on the head and the volume of the reservoirs. However, facilities are usually designed with the greatest hydraulic head possible rather than largest upper reservoir possible due to cost. It is much cheaper to construct a facility with a large hydraulic head and small reservoirs, than to construct a facility of equal capacity with a small hydraulic head and large reservoirs because:

1. Less material needs to be removed to create the reservoirs required
2. Smaller piping is necessary, hence, smaller boreholes during drilling
3. The turbine is physically smaller

Currently, there is over 90 GW in more than 240 PHES facilities in the world, which is roughly 3% of the world's global generating capacity. Each individual facility can store from 30 MW to 4,000 MW (15 GWh) of electrical energy [2].

Figure 5-2: Photograph of a pumped hydroelectric storage facility using seawater [17].

5.1.1 Applications

As well as large storage capacities, PHES also has a fast reaction time and hence load-levelling is an ideal application. Figure 5-3 demonstrates how a real-world PHES facility provides load-levelling capabilities to an electric grid, by pumping using cheaper baseload power at night and generating during peak demand in the day. Facilities can have a reaction time as short as 10 minutes or less from complete shutdown (or from full reversal of operation) to full power [8]. In addition, if kept on standby, full power can even be reached within 10 to 30 seconds.

Also, with the recent introduction of variable speed machines, PHES systems can now be used for frequency regulation in both pumping and generation modes (this has always been available in generating mode). This allows PHES units to absorb power in a more cost-effective manner that not only makes the facility more useful, but also improves the efficiency by approximately 3% [8] and increases the lifetime of the facility. PHES can also be used for peak generation and black starts due to its large power capacity and sufficient discharge time. Finally, PHES provides a load for baseload generating facilities during off-peak production so cycling these units can be avoided, which improves their lifetime as well as their efficiency.

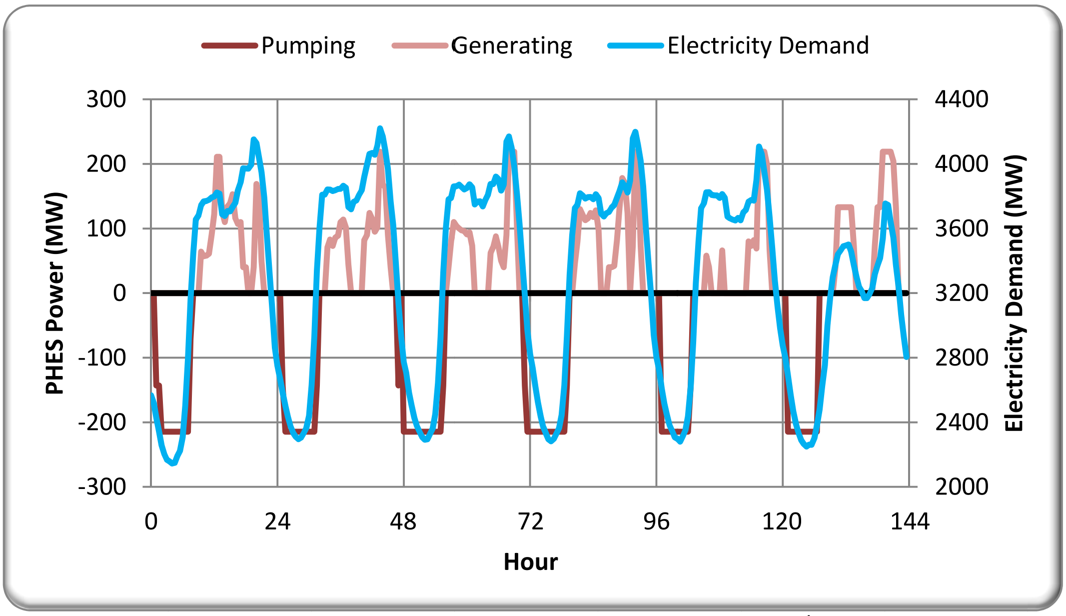


Figure 5-3: Load-levelling by Turlough Hill PHES in Ireland from the 1st to the 6th of October 2007 [20].

5.1.2 Cost

The cost of PHES ranges from $600/kW [2] to upwards of $2,000/kW [8], depending on a number of factors such as size, location, and connection to the power grid.

5.1.3 Disadvantages

In order to make PHES economically viable it is usually constructed on a large scale. Although the cost per kWh of storage is relatively economical in comparison to other techniques, this large-scale necessity results in a very high initial construction cost for the facility, therefore detracting investment in PHES e.g. Bath County storage facility in the United States which has a power capacity of 2,100 MW and cost $1.7 billion in 1985. Due to these design requirements of a PHES facility, the ultimate drawback is its dependence on specific geological formations [21-25]. A suitable site needs two large reservoirs with a sufficient amount of hydraulic head between which are located close enough to enable the construction of a PHES system. However, as well as being rare these geological formations normally exist in remote locations such as mountains, where construction is difficult and the power grid is not present. Although, recent reports illustrate that more suitable sites may exist for PHES than originally anticipated [17, 26-29].

5.1.4 Future

Currently, a lot of work is being carried out to upgrade old PHES facilities with new equipment such as variable speed devices which can increase capacity by 15% to 20%, and efficiency by approximately 3%. This is very popular as energy storage capacity is being developed without the high initial construction costs. Prospects of building new facilities are usually hindered by “high development costs, long lead times and design limitations” [8]. However, even with these issues, there is over 7 GW of new PHES planned within the EU over the next eight years alone [30]. In addition, new methodologies continue to locate more and more suitable PHES sites [17, 26-29]. Therefore, considering the maturity and cost of PHES, it is a very attractive option as an energy storage technology for aiding the integration of fluctuating renewable energy.

5.2 Underground Pumped Hydroelectric Energy Storage (UPHES)

An UPHES facility has the same operating principle as PHES system: two reservoirs with a large hydraulic head between them. The only major difference between the two designs is the locations of their respective reservoirs. In conventional PHES, suitable geological formations must be identified to build the facility, as discussed in section 5.1. However, UPHES facilities have been designed with the upper reservoir at ground level and the lower reservoir deep below the earth's surface. The depth depends on the amount of hydraulic head required for the specific application, see Figure 5-4.

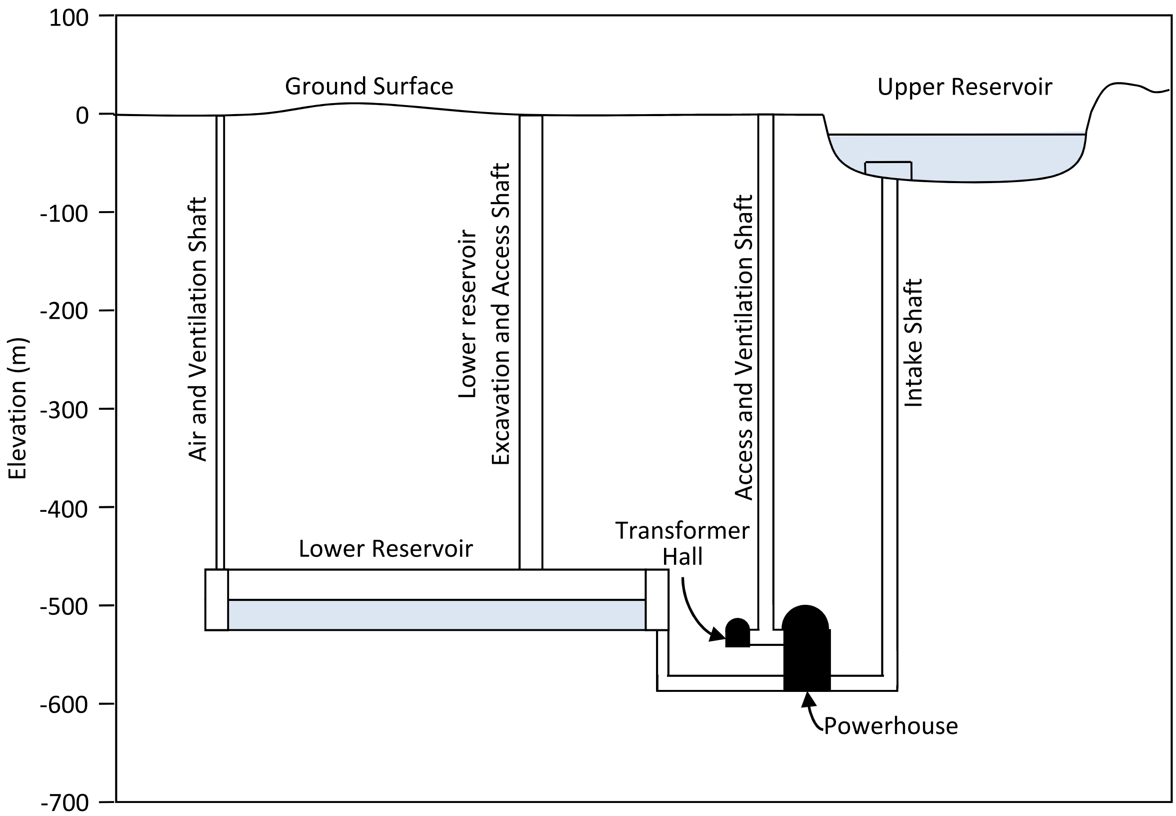


Figure 5-4: Proposed layout of an underground pumped hydroelectric storage facility [18].

5.2.1 Applications

UPHES can provide the same services as PHES: load-levelling, frequency regulation, and peak generation. However, as UPHES does not need to be built on mountainous terrain, it can be constructed in areas which are not as secluded as those for PHES. If economical excavation techniques can be established, then UPHES could be placed anywhere that had enough space for the upper reservoir and hence, it could be positioned in ideal locations for wind farms, the power grid, specific areas of electrical irregularities, etc.

5.2.2 Cost

The capital cost of UPHES is the deciding factor for its future. As it operates in the same way as PHES, it is a very reliable and cost effective storage technique with low maintenance costs. However, depending on the capital costs involved, UPHES might not be a viable option as other technologies begin to develop larger storage capacities e.g. flow batteries. Currently, no costs have been identified for UPHES, primarily due to the lack of facilities constructed. A number of possible cost-saving ideas have been put forward such as using old mines for the lower reservoir of the facility [18, 31]. Also, if something valuable can be removed to make the lower reservoir, it can be sold to make back some of the cost.

5.2.3 Disadvantages

The major disadvantage for UPHES is its commercial youth. To date there is very few, if any, UPHES facilities in operation. Therefore, it is very difficult to analyse the performance of this technology. Currently, there is very little evidence to suggest that economical excavation techniques will be developed in the near future. Consequently, the technical immaturity of UPHES needs to be addressed and typical construction costs defined before it is used as a mainstream energy storage technology.

5.2.4 Future

UPHES could be a viable alternative for energy storage if cost-effective excavation techniques can be identified for its construction. Its relatively large-scale storage capacities, combined with its potential location independence, provide a storage technique with unique characteristics. However, as well as cost, a number of areas need to be investigated further in this area such as its design, power and storage capacities, and its environmental impact to prove it is a viable option. In addition, if more suitable sites are found for conventional PHES, then the desire for UPHES is likely to decline.

5.3 Compressed Air Energy Storage (CAES)

A CAES facility consists of a power train motor that drives a compressor (to compress the air into the cavern), a high pressure turbine (HPT), a low pressure turbine (LPT), and a generator, see Figure 5-5.

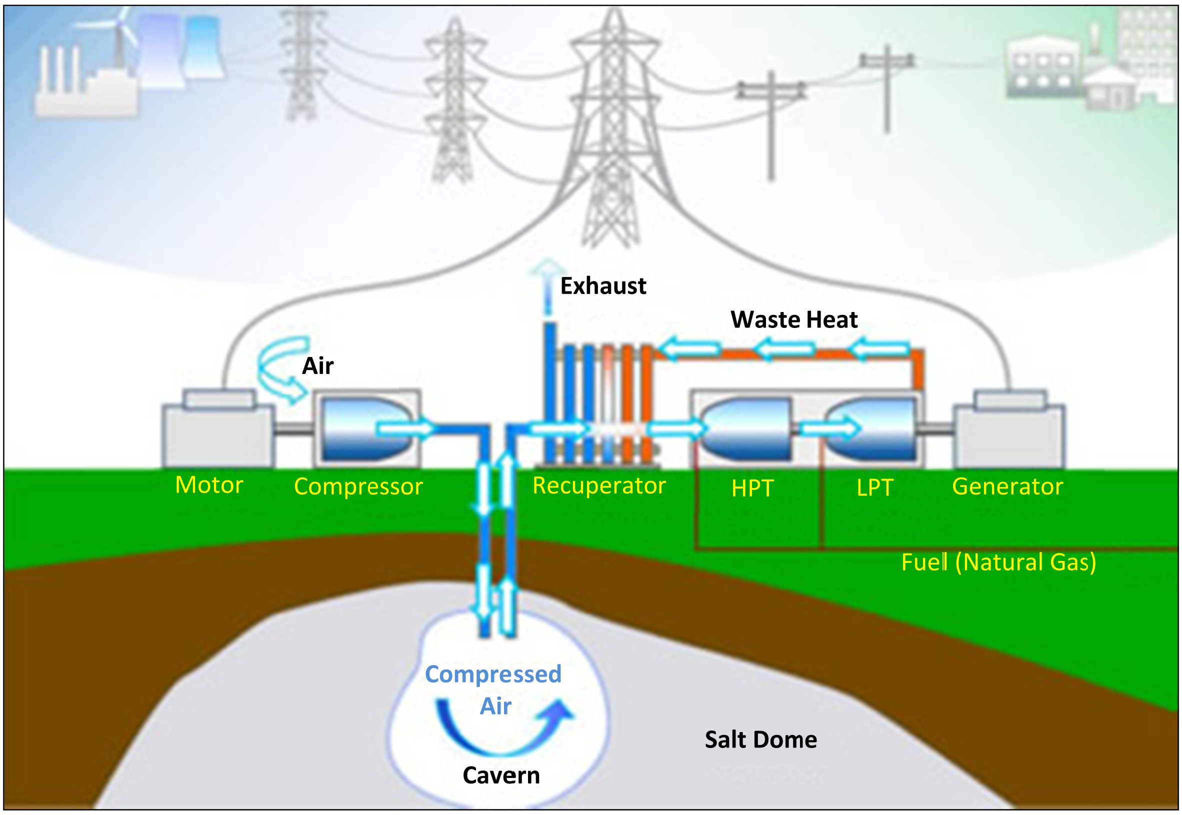


Figure 5-5: Layout of a compressed air energy storage facility [32].

In conventional gas turbines (GT), 66% of the gas used is required to compress the air at the time of generation. Therefore, CAES pre-compresses the air using off-peak electrical power which is taken from the grid to drive a motor (rather than using gas from the GT plant) and stores it in large storage reservoirs. When the GT is producing electricity during peak hours, the compressed air is released from the storage facility and used in the GT cycle. As a result, instead of using expensive gas to compress the air, cheaper off-peak base load electricity is used. Although, when the air is released from the cavern it must be mixed with a small amount of gas before entering the turbine. If there was no gas added, the temperature and pressure of the air would be problematic. If the pressure using air alone was high enough to achieve a significant power output, the temperature of the air would be far too low for the materials and connections to tolerate [1]. The amount of gas required is so small that a GT working simultaneously with CAES can produce three times more electricity than a GT operating on its own, using the same amount of natural gas.

The reservoir can be man-made, but this is expensive so CAES locations are usually decided by identifying natural geological formations that suit these facilities. These include salt caverns, hard-rock caverns, depleted gas fields or an aquifer. Salt caverns can be designed to suit specific requirements. Fresh water is pumped into the cavern and left until the salt dissolves and saturates the fresh water. The water is then returned to the surface and the process is repeated until the required volume cavern is created. This process is expensive and can take up to two years. Hard-rock caverns are even more expensive, usually 60% higher than salt caverns. Finally, aquifers cannot store the air at high pressures and therefore have a relatively lower energy capacity.

CAES uses both electrical energy and natural gas so its efficiency is difficult to quantify. It is estimated that the efficiency of the cycle based on the compression and expansion cycles is in the region of 68% [33] to 75% [8]. Typical plant capacities for CAES are in the region of 50 MW – 300 MW. The life of these facilities is proving to be far longer than existing gas turbines and the charge/discharge ratio is dependent on the size of the compressor used, as well as the size and pressure of the reservoir.

5.3.1 Applications

CAES is the only very large scale storage technique other than PHES. CAES has a fast reaction time with plants usually able to go from 0% to 100% in less than ten minutes, 10% to 100% in approximately four minutes and from 50% to 100% in less than 15 seconds [2]. As a result, it is ideal for acting as a large sink for bulk energy supply and demand and also, it is able to undertake frequent start-ups and shutdowns. Furthermore, traditional GT suffer a 10% efficiency reduction from a 5°C rise in ambient temperatures due a reduction in the air density. CAES use compressed air so they do not suffer from this effect. Also, traditional gas turbines suffer from excessive heat when operating on partial load, while CAES facilities do not. These flexibilities mean that CAES can be used for ancillary services such as frequency regulation, load following, and voltage control [8]. As a result, CAES has become a serious contender in the wind power energy storage market. A number of possibilities are being considered such as integrating a CAES facility with a number of wind farms within the same region. The excess off-peak power from these wind farms could be used to compress air for a CAES facility. *Iowa Association of Municipal Utilities* is currently planning a project of this nature [34].

5.3.2 Cost

The cost of CAES facilities are $425/kW [2] to $450/kW [8]. Maintenance is estimated between $3/kWh [35] and $10/kWh [36]. Costs are largely dependent on the reservoir construction. Overall, CAES facilities expect to have costs similar to or greater than conventional GT facilities. However, the energy cost is much lower for CAES systems.

5.3.3 Disadvantages

The major disadvantage of CAES facilities is their dependence on geographical location. It is difficult to identify underground reservoirs where a power plant can be constructed, is close to the electric grid, is able to retain compressed air and is large enough for the specific application. As a result, capital costs are generally very high for CAES systems. Also, CAES still uses a fossil fuel (gas) to generate electricity. Consequently, the emissions and safety regulations are similar to conventional gas turbines. Finally, only two CAES facilities currently exist, meaning it is still a technology of potential not experience.

5.3.4 Future

Reservoir developments are expected in the near future due to the increased use of natural gas storage facilities. The US and Europe are more likely to investigate this technology further as they possess acceptable geology for an underground reservoir (specifically salt domes). Due to the limited operational experience, CAES has been considered too risky by many utilities [36].

A number of CAES storage facilities have been planned for the future including:

- 25 MW CAES research facility with an aquifer reservoir in Italy.
- 3 x 100 MW CAES plants in Israel.
- Norton Energy Storage LLC in America is planning a CAES with a limestone mine acting as the reservoir. The first of four phases is expected to produce between 200 MW and 480 MW at a cost of $50 to $480 million. The final plant output is planned to be 2,500 MW.

Finally, proposals have also been put forward for a number of similar technologies such as micro CAES and thermal and compressed air storage (TACAS). However, both are in the early stages of development and their future impact is not decisive. Although Joe Pinkerton, CEO of *Active Power,* declared that TACAS "is the first true minute-for-minute alternative to batteries for UPS industry" [8].

5.4 Battery Energy Storage (BES)

There are three important types of large-scale BES. These are:

1. Lead-Acid (LA)
2. Nickel-Cadmium (NiCd)
3. Sodium-Sulphur (NaS)

These operate in the same way as conventional batteries, except on a large scale i.e. two electrodes are immersed in an electrolyte, which allows a chemical reaction to take place so current can be produced when required.

5.4.1 Lead-Acid (LA) battery

This is the most common energy storage device in use at present. Its success is due to its maturity (research has been ongoing for an estimated 140 years), relatively low cost, long lifespan, fast response, and low self-discharge rate. These batteries are can be used for both short-term applications (seconds) and long-term applications (up to 8 hours).

There are two types of lead-acid (LA) batteries; flooded lead-acid (FLA) and valve regulated lead-acid (VRLA). FLA batteries are made up of two electrodes that are constructed using lead plates which are immersed in a mixture of water (65%) and sulphuric acid (35%), see Figure 5-6. VRLA batteries have the same operating principle as FLA batteries, but they are sealed with a pressure regulating valve. This eliminates air from entering the cells and also prevents venting of the hydrogen. VRLA batteries have lower maintenance costs, weigh less and occupy less space. However, these advantages are coupled with higher initial costs and shorter lifetime.

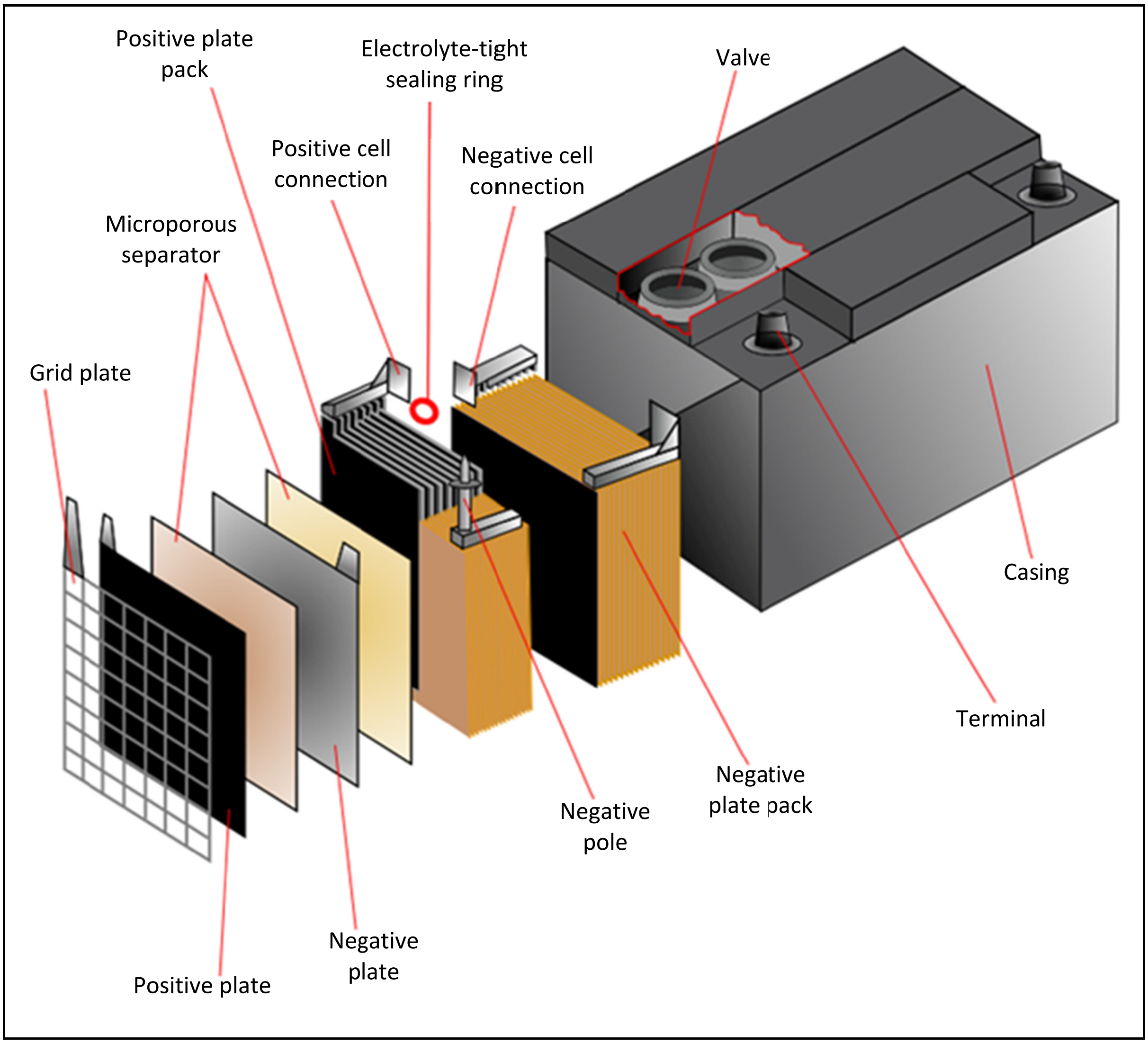


Figure 5-6: Structure of a lead-acid battery [37].

Both the power and energy capacities of lead-acid batteries are based on the size and geometry of the electrodes. The power capacity can be increased by increasing the surface area for each electrode, which means greater quantities of thinner electrode plates in the battery. However, to increase the storage capacity of the battery, the mass of each electrode must be increased, which means fewer and thicker plates. Consequently, a compromise must be met for each application.

LA batteries can respond within milliseconds at full power. The average DC-DC efficiency of a LA battery is 75% to 85% during normal operation, with a life of approximately 5 years or 250-1,000 charge/discharge cycles, depending on the depth-of-discharge [8].

5.4.1.1 Applications

FLA batteries have 2 primary applications [8]:

1. Starting and ignition, short bursts of strong power e.g. car engine batteries
2. Deep cycle, low steady power over a long time

VRLA batteries are very popular for backup power, standby power supplies in telecommunications and also for UPS systems. A number of LA storage facilities are in operation today as can be seen in Table 5-1.

Table 5-1: Details of the largest LA and VRLA battery installations worldwide [2].

Plant	Year of installation	Rated Energy (MWh)	Rated Power (MW)	Battery system alone		Total cost of the storage system*	
				Cost in $1995 ($/kWh)	Cost in $1995 ($/kWh)	Cost in $1995 ($/kWh)	Cost in $1995 ($/kWh)
CHINO California	1988	40	10	201	805	456	1823
HELCO Hawaii (VRLA)	1993	15	10	304	456	777	1166
PREPA Puerto Rico	1994	14	20	341	239	1574	1102
BEWAG Germany	1986	8.5	8.5	707	707	n/a	n/a
VERNON Calif. (VRLA)	1995	4.5	3	305	458	944	1416

* Includes Power Conditioning System and Balance-of-Plant.

5.4.1.2 Cost

Costs for LA battery technology have been stated as $200/kW - $300/kW [2], but also in the region of $580/kW [8]. Looking at Table 5-1 above, the cost variation is evident.

5.4.1.3 Disadvantages

LA batteries are extremely sensitive to their environments. The typical operating temperature for a LA battery is roughly 27°C, but a change in temperature of 5°C or more can cut the life of the battery by 50%. However, if the DoD exceeds this, the cycle life of the battery will also be reduced. Finally, a typical charge-to-discharge ratio of a LA battery is 5:1. At faster rates of charge, the cell will be damaged.

5.4.1.4 Future

Due to the low cost and maturity of the LA battery it will probably always be useful for specific applications. The international *Advanced Lead-Acid Battery Consortium* is also developing a technique to significantly improve storage capacity and also recharge the battery in only a few minutes, instead of the current hours [2]. However, the requirements of new large-scale storage devices would significantly limit the life of a LA battery. Consequently, a lot of research has been directed towards other areas. Therefore, it is unlikely that LA batteries will be competing for future large-scale multi MW applications.

5.4.2 Nickel-Cadmium (NiCd) battery

A NiCd battery is made up of a positive with nickel oxyhydroxide as the active material and a negative electrode composed of metallic cadmium. These are separated by a nylon divider. The electrolyte, which undergoes no significant changes during operation, is aqueous potassium hydroxide. During discharge, the nickel oxyhydroxide combines with water and produces nickel hydroxide and a hydroxide ion. Cadmium hydroxide is produced at the negative electrode. To charge the battery the process can be reversed. However, during charging, oxygen can be produced at the positive electrode and hydrogen can be produced at the negative electrode. As a result some venting and water addition is required, but much less than required for a LA battery.

There are two NiCd battery designs: sealed (Figure 5-7) and vented (Figure 5-8). Sealed NiCd batteries are the common, everyday rechargeable batteries used in a remote control, lamp etc. No gases are released from these batteries, unless a fault occurs. Vented NiCd batteries have the same operating principles as sealed ones, but gas is released if overcharging or rapid discharging occurs. The oxygen and hydrogen are released through a low-pressure release valve making the battery safer, lighter, more economical, and more robust than sealed NiCd batteries.

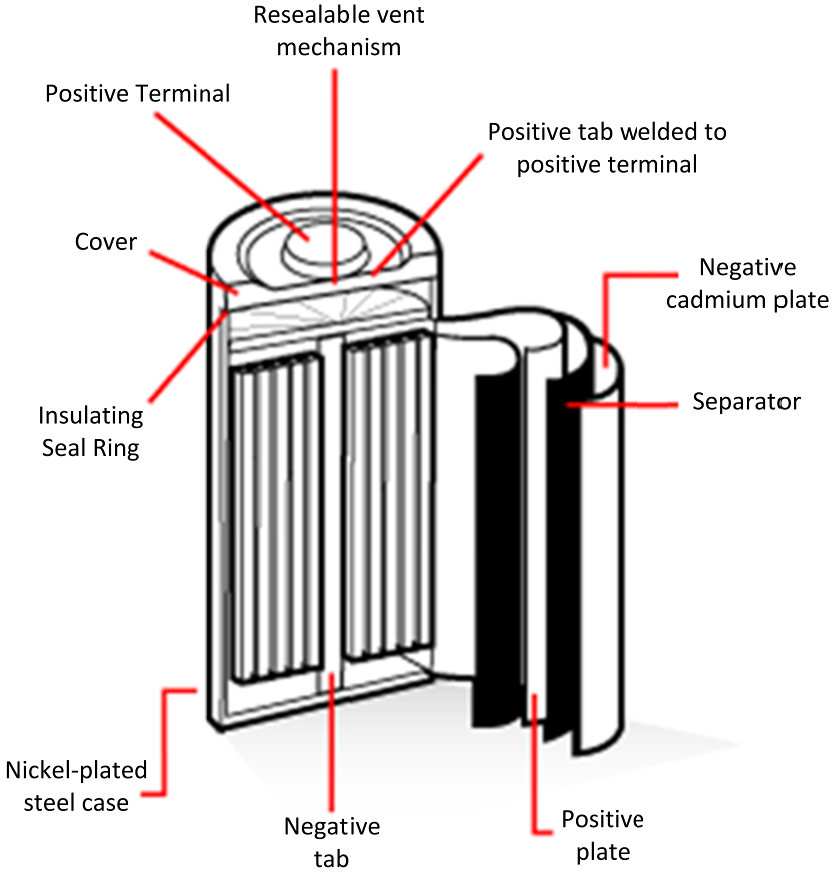


Figure 5-7: Structure of a sealed nickel-cadmium battery [38, 39].

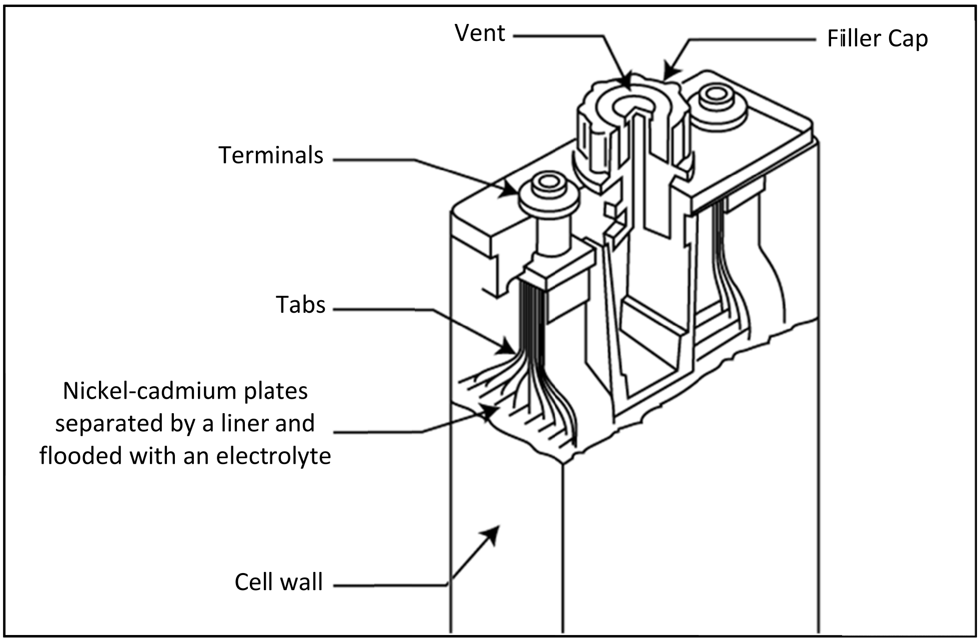


Figure 5-8: Structure of a vented nickel-cadmium cell [40, 41].

The DC-DC efficiency of a NiCd battery is 60%-70% during normal operation although the life of these batteries is relatively high at 10 to 15 years, depending on the application. NiCd batteries with a pocket-plate design have a life of 1,000 charge/discharge cycles, and batteries with sintered electrodes have a life of 3,500 charge/discharge cycles. NiCd batteries can respond at full power within milliseconds. At small DoD rates (approximately 10%) NiCd batteries have a much longer cycle life (50,000 cycles) than other batteries such as LA batteries. They can also operate over a much wider temperature range than LA batteries, with some able to withstand occasional temperatures as high as 50°C.

5.4.2.1 Applications

Sealed NiCd batteries are used commonly in commercial electronic products such as a remote control, where light weight, portability, and rechargeable power are important. Vented NiCd batteries are used in aircraft and diesel engine starters, where large energy per weight and volume are critical [8]. NiCd batteries are ideal for protecting power quality against voltage sags and providing standby power in harsh conditions. Recently, NiCd batteries have become popular as storage for solar generation because they can withstand high temperatures. However, they do not perform well during peak shaving applications, and consequently are generally avoided for energy management systems.

5.4.2.2 Cost

NiCd batteries cost more than LA batteries at $600/kW [8]. However, despite the slightly higher initial cost, NiCd batteries have much lower maintenance costs due to their environmental tolerance.

5.4.2.3 Disadvantages

Like LA batteries, the life of NiCd batteries can be greatly reduced due to the DoD and rapid charge/discharge cycles. However, NiCd batteries suffer from 'memory' effects and also lose more energy during due to self-discharge standby than LA batteries, with an estimated 2% to 5% of their charge lost per month at room temperature in comparison to 1% per month for LA batteries [8]. Also, the environmental effects of NiCd batteries have become a widespread concern in recent years as cadmium is a toxic material. This creates a number of problems for disposing of the batteries.

5.4.2.4 Future

It is predicted that NiCd batteries will remain popular within their current market areas, but like LA batteries, it is unlikely that they will be used for future large-scale projects. Although just to note, a 40 MW NiCd storage facility was constructed in Alaska; comprising of 13,760 cells at a cost of $35M [2]. The cold temperatures experienced were the primary driving force behind the use NiCd as a storage medium. NiCd will probably remain more expensive than LA batteries, but they do provide better power delivery. However, due to the toxicity of cadmium, standards and regulations for NiCd batteries will continue to rise.

5.4.3 Sodium-Sulphur (NaS) Battery

NaS batteries have three times the energy density of LA, a longer life span, and lower maintenance. These batteries are made up of a cylindrical electrochemical cell that contains a molten-sodium negative electrode and a molten-sulphur positive electrode. The electrolyte used is solid β-alumina. During discharging, sodium ions pass through the β-alumina electrolyte where they react at the positive electrode with the sulphur to form sodium polysulfide, see Figure 5-9. During charging, the reaction is reversed so that the sodium polysulfide decomposes, and the sodium ions are converted to sodium at the positive electrode. In order to keep the sodium and sulphur molten in the battery, and to obtain adequate conductivity in the electrolyte, they are housed in a thermally insulated enclosure that must keep it above 270°C, usually at 320°C to 340°C.

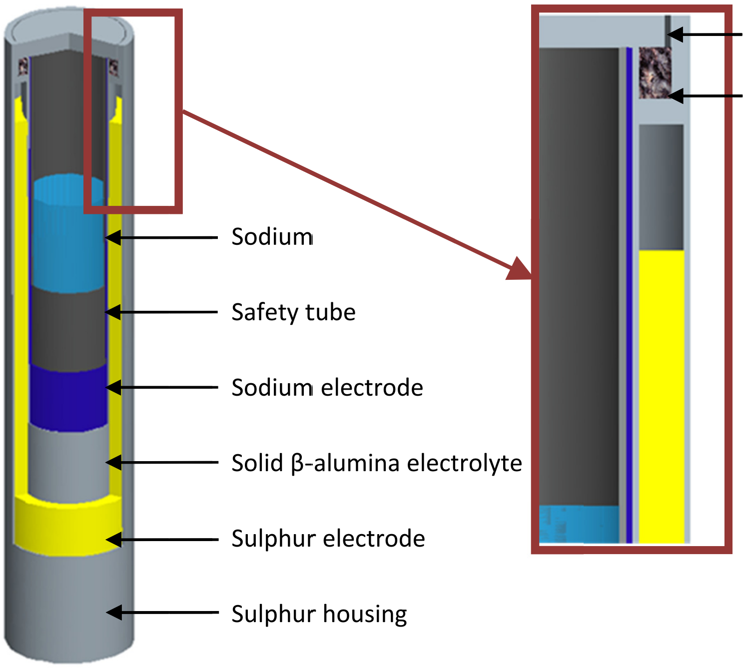


Figure 5-9: Structure of a sodium-sulphur cell.

A typical NaS module is 50 kW at 360 kWh or 50 kW at 430 kWh. The average round-trip energy efficiency of a NaS battery is 86% [2] to 89% [8]. The cycle life is much better than for LA or NiCd batteries. At 100% DoD, the NaS batteries can last approximately 2,500 cycles. As with other batteries, this increases as the DoD decreases; at 90% DoD the unit can cycle 4,500 times and at 20% DoD 40,000 times [8].

5.4.3.1 Applications

One of the greatest characteristics of NaS batteries is its ability to provide power in a single, continuous discharge or else in shorter larger pulses (up to five times higher than the continuous rating). It is also capable of pulsing in the middle of a long-term discharge. This flexibility makes it very advantageous for numerous applications such as energy management and power quality. NaS batteries have also been used for deferring transmission upgrades.

5.4.3.2 Cost

Currently, NaS batteries cost $810/kW, but it is only a recently commercialised product. This cost is likely to be reduced as production increases, with some predicting reductions upwards of 33% [8].

5.4.3.3 Disadvantages

The major disadvantage of NaS batteries is retaining the device at elevated temperatures above 270°C. It is not only energy consuming, but it also brings with it problems such as thermal management and safety regulations [42]. Also, due to harsh chemical environments, the insulators can be a problem as they slowly become conducting and self-discharge the battery.

5.4.3.4 Future

A 6 MW, 8 h unit has been built by *Tokyo Electric Power Company* (TEPCO) and *NGK Insulators, Ltd*., (NGK), in Tokyo, Japan with an overall plant efficiency of 75% and is thus far proving to be a success, see Figure 5-10. The materials required to create a NaS battery are inexpensive and abundant, and 99% of the battery is recyclable. The NaS battery has the potential to be used on a MW scale by combining modules. Combining this with its functionality to mitigate power disturbances, NaS batteries could be a viable option for smoothing the output from wind turbines into the power grid [8]. *American Electric Power* is planning to incorporate a 6 MW

NaS battery with a wind farm for a two year demonstration [43, 44]. The size of the wind farm has yet to be announced, but the results from this will be pivotal for the future of the NaS battery with renewable energy.

Figure 5-10: A 6 MW, 8 h sodium-sulphur energy storage facility in Tokyo, Japan [2].

5.5 Flow Battery Energy Storage (FBES)

There are three primary types of FBES:

1. Vanadium-Redox (VR)
2. Polysulphide-Bromide (PSB)
3. Zinc-Bromine (ZnBr)

They all operate in a similar fashion; two charged electrolytes are pumped to the cell stack where a chemical reaction occurs, allowing current to be obtained from the device when required. The operation of each will be discussed in more detail during the analysis.

5.5.1 Vanadium-Redox (VR) Flow Battery

A VR battery is made up of a cell stack, electrolyte tank system, control system and a PCS (see Figure 5-11). These batteries store energy by interconnecting two forms of vanadium ions in a sulphuric acid electrolyte at each electrode; with V^{2+}/ V^{3+} in the negative electrode, and V^{4+}/ V^{5+} in the positive electrode. The size of the cell stack determines the power capacity (kW) whereas the volume of electrolyte (size of tanks) indicates the energy capacity (kWh) of the battery.

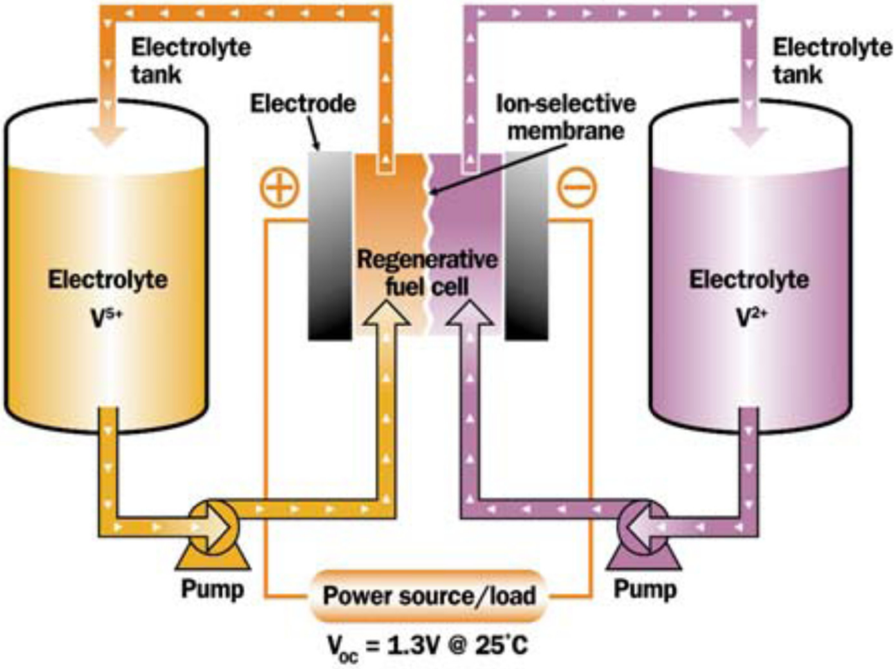


Figure 5-11: Structure of a vanadium-redox flow battery [45].

As the battery discharges, the two electrolytes flow from their separate tanks to the cell stack where H^+ ions are passed between the two electrolytes through the permeable membrane. This process induces self-separation within the solution thus changing the ionic form of the vanadium as the potential energy is converted to electrical energy. During recharge this process is reversed. VR batteries operate at normal temperature with an efficiency as high as 85% [2] and [8]. As the same chemical reaction occurs for charging and discharging, the charge/discharge ratio is 1:1. The VR battery has a fast response, from charge to discharge in 0.001 s and also a high overload capacity with some claiming it can reach twice its rated capacity for several minutes [2]. VR batteries can operate for 10,000 cycles giving them an estimated life of 7-15 years depending on the application. Unlike conventional batteries they can be fully discharged without any decline in performance [46]. At the end of its life (10,000 cycles), only the cell stack needs to be replaced as the electrolyte has an indefinite life and thus can be reused. VR batteries have been designed as modules so they can be constructed on-site.

5.5.1.1 Applications

As the power and energy capacities are decoupled, the VR flow battery is a very versatile device in terms of energy storage. It can be used for every energy storage requirement including UPS, load levelling, peak-shaving, telecommunications, electric utilities and integrating renewable resources. Although the versatility of flow batteries makes it extremely useful for a lot of applications, there are a number of competing devices within each area that perform better for their specific application. Consequently, although capable of performing for numerous applications, VR batteries are only considered where versatility is important, such as the integration of renewable resources.

Table 5-2: Sumitomo Electric Industries Ltd. vanadium-redox battery project experience [47]

Location	Application	Ratings	Operation
Kaskima Kita Power Stations, Japan	Load levelling	200 kW x 4 h	1996
Sumitomo Densetsu Co. Ltd.	Load levelling	100 kW x 8 h	Feb 2001
The Institute of Applied Energy	Stabilisation of wind turbine output	170 kW x 6 h	Mar 2001
Tottori SANYO Electric Co., Ltd.	Power quality (voltage sag compensation) and load levelling	1500 kW x 1 h (3000 kW x 1.5 s)	Apr 2001
Obayashi Corp. (Dunlop Golf Course)	Solar PV storage (DC only)	30 kW x 8 h	Apr 2001
Kwansei Gakuin University	Peak shaving	500 kW x 10 h	Jul 2001
CESI, Italy	Peak shaving	42 kW x 2 h	Nov 2001
Tomamac Wind Villa	Wind turbine output stabilization and storage	4000 kW x 90 min	2005

5.5.1.2 Cost

There are two costs associated with flow batteries: the power cost (kW), and the energy cost (kWh), as they are independent of each other. The power cost for VR batteries is $1,828/kW, and the energy cost is $300/kWh to $1,000/kWh, depending on system design [8].

5.5.1.3 Disadvantages

VR batteries have the lowest power density and require the most cells (each cell has a voltage of 1.2 V) in order to obtain the same power output as other flow batteries. For smaller-scale energy applications, VR batteries are very complicated in relation to conventional batteries, as they require much more parts (such as pumps, sensors, control units) while providing similar characteristics. Consequently, when deciding between a flow battery and a conventional battery, a decision must be made between a simple but constrained device (conventional battery), and a complex but versatile device (flow battery).

5.5.1.4 Future

VR batteries have a lot of potential due to their unique versatility, specifically their MW power and storage capacity potential. However, the commercial immaturity of VR batteries needs to be changed to prove it is a viable option in the future.

5.5.2 Polysulphide-Bromide (PSB) Flow Battery

PSB batteries operate very similarly to VR batteries. The unit is made up of the same components; a cell stack, electrolyte tank system, control system and a PCS (see Figure 5-12). The electrolytes used within PSB flow batteries are sodium bromide as the positive electrolyte, and sodium polysulphide as the negative electrolyte. During discharge, the two electrolytes flow from their tanks to the cell where the reaction takes place at a polymer membrane that allows sodium ions to pass through. Like VR batteries, self-separation occurs during the discharge process and as before, to recharge the battery this process is simply reversed. The voltage across each cell is approximately 1.5 V.

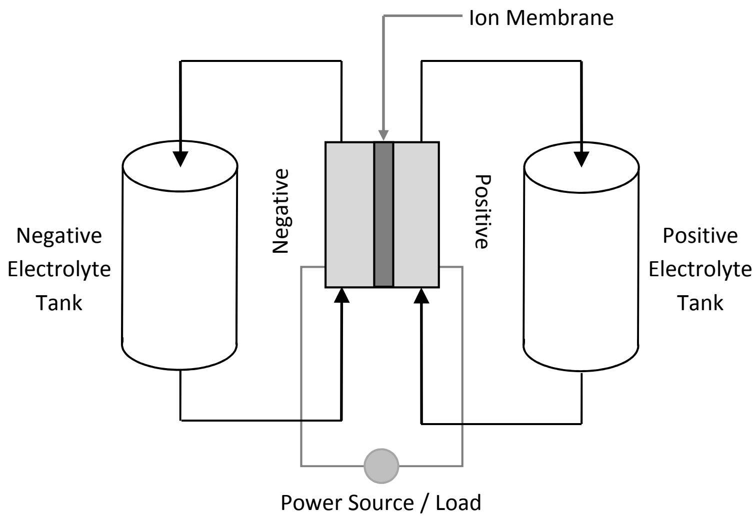


Figure 5-12: Structure of a polysulphide-bromide flow battery [8].

PSB batteries operate between 20°C and 40°C, but a wider range can be used if a plate cooler is used in the system. The efficiency of PSB flow batteries approaches 75% according to [2] and [8]. As with VR batteries, the discharge ratio is 1:1, since the same chemical reaction is taking place during charging and discharging. The life expectancy is estimated at 2,000 cycles but once again, this is very dependent on the application. As with VR batteries the power and energy capacities are decoupled in PSB batteries.

5.5.2.1 Applications

PSB flow batteries can be used for all energy storage requirements including load levelling, peak shaving, and integration of renewable resources. However, PSB batteries have a very fast response time; it can react within 20 milliseconds if electrolyte is retained charged in the stacks (of cells). Under normal conditions, PSB batteries can charge or discharge power within 0.1 s [2]. Therefore, PSB batteries are particularly useful for frequency response and voltage control.

5.5.2.2 Cost

The power capacity cost of PSB batteries is $1,094/kW and the energy capacity cost is $185/kWh [8].

5.5.2.3 Disadvantages

During the chemical reaction small quantities of bromine, hydrogen, and sodium sulphate crystals are produced. Consequently, biweekly maintenance is required to remove the sodium-sulphate by-products. Also, two companies designed and planned to build PSB flow batteries. *Innogy's Little Barford Power Station* in the UK wanted to use a 24,000 cell 15 MW 120 MWh PSB battery, to support a 680 MW combined cycle gas turbine plant. Tennessee Valley Authority (TVA) in Columbus wanted a 12 MW, 120 MWh to avoid upgrading the network. However, both facilities have been cancelled with no known explanation.

5.5.2.4 Future

Like the VR battery, PSB batteries can scale into the MW region and therefore must have a future within energy storage. However, until a commercial demonstration succeeds, the future of PSB batteries will remain doubtful.

5.5.3 Zinc-Bromine (ZnBr) Flow Battery

These flow batteries are slightly different to VR and PSB flow batteries. Although they contain the same components: a cell stack, electrolyte tank system, control system, and a PCS (see Figure 5-13), ZnBr flow batteries do not operate in the same way.

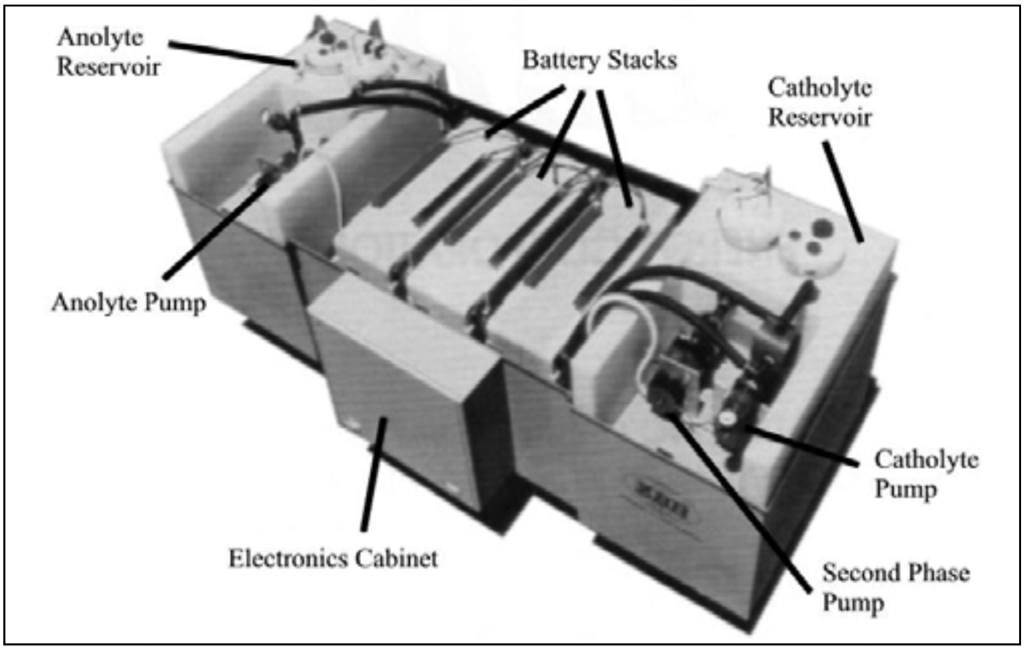


Figure 5-13: Structure of a zinc-bromine flow battery [48].

During charging the electrolytes of zinc and bromine ions (that only differ in their concentration of elemental bromine) flow to the cell stack. The electrolytes are separated by a microporous membrane. Unlike VR and PSB flow batteries, the electrodes in a ZnBr flow battery act as substrates to the reaction. As the reaction occurs, zinc is electroplated on the negative electrode and bromine is evolved at the positive electrode, which is somewhat similar to conventional battery operation. An agent is added to the electrolyte to reduce the reactivity of the elemental bromine. This reduces the self-discharge of the bromine and improves the safety of the entire system [48]. During discharge the reaction is reversed; zinc dissolves from the negative electrode and bromide is formed at the positive electrode. ZnBr batteries can operate in a temperature range of 20°C to 50°C. Heat must be removed by a small chiller if necessary. No electrolyte is discharged from the facility during operation and hence the electrolyte has an indefinite life. The membrane however, suffers from slight degradation during the operation, giving the system a cycle life of approximately 2,000 cycles. The ZnBr battery can be 100% discharged without any detrimental consequences and suffers from no memory effect. The efficiency of the system is about 75% [2] or 80% [8]. Once again, as the same reaction occurs during charging and discharging, the charge/discharge ratio is 1:1, although a slower rate is often used to increase efficiency [8]. Finally, the ZnBr flow battery has the highest energy density of all the flow batteries, with a cell voltage of 1.8 V.

5.5.3.1 Applications

The building block for ZnBr flow batteries is a 25 kW, 50 kWh module constructed from three 60-cell battery stacks in parallel, each with an active cell area of 2500 sq. cm [48]. ZnBr batteries also have a high energy density of 75 Wh/kg to 85 Wh/kg. As a result, the ZnBr batteries are relatively small and light in comparison to other conventional and flow batteries such as LA, VR and PSB. Consequently, ZnBr is currently aiming at the renewable energy backup market. It is capable of smoothing the output fluctuations from a wind farm [2], or a solar panel [48], as well as providing frequency control. Installations currently completed have used ZnBr flow batteries for UPS, load management and supporting microturbines, solar generators, substations and T&D grids [2].

5.5.3.2 Cost

The power capacity cost is $639/kW and the energy capacity cost is $400/kWh [8].

5.5.3.3 Disadvantages

It is difficult to increase the power and storage capacities into the large MW ranges as the modules cannot be linked hydraulically, hence the electrolyte is isolated within each module. Modules can be linked electrically though and plans indicate that systems up to 1.5 MW are possible. As stated the membrane suffers from slight degradation during the reaction so it must be replaced at the end of the batteries life (2,000 cycles).

5.5.3.4 Future

The future of ZnBr batteries is currently aimed at the renewable energy market. *Apollo Energy Corporation* plan to develop a 1.5 MW ZnBr battery to back up a 20 MW wind farm for several minutes. They hope to keep the wind farm operational for an additional 200+ hours a year [2]. The results from this will be very decisive for the future of ZnBr flow batteries.

5.6 Flywheel Energy Storage (FES)

A FES device is made up of a central shaft that holds a rotor and a flywheel. This central shaft rotates on two magnetic bearings to reduce friction, see Figure 5-14. These are all contained within a vacuum to reduce aerodynamic drag losses. Flywheels store energy by accelerating the rotor/flywheel to a very high speed and maintaining the energy in the system as kinetic energy. Flywheels release energy by reversing the charging process so that the motor is then used as a generator. As the flywheel discharges, the rotor/flywheel slows down until eventually coming to a complete stop.

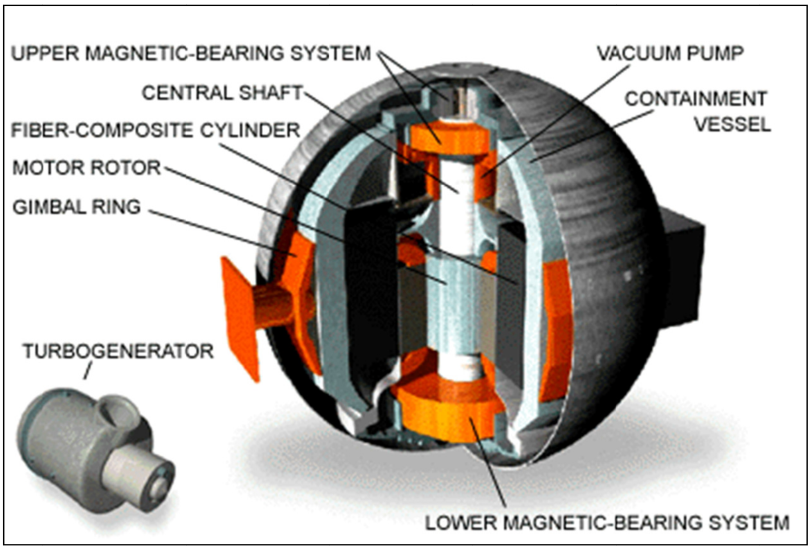


Figure 5-14: Components of a flywheel energy storage device [49].

The rotor dictates the amount of energy that the flywheel is capable of storing. Flywheels store power in direct relation to the mass of the rotor, but to the square of its surface speed. Consequently, the most efficient way to store energy in a flywheel is to make it spin faster, not by making it heavier. The energy density within a flywheel is defined as the energy per unit mass:

$$\frac{E_{KINETIC}}{m_f} = \frac{1}{2} v_{CIRCULAR}^2 = \frac{\sigma}{\rho} \tag{3}$$

Where:

$E_{KINETIC}$ = total kinetic energy in Joules (J)

m_f = mass of the flywheel in kg

$v_{CIRCULAR}$ = the circular velocity of the flywheel in m/s^2

σ = the specific strength of the material in Nm/kg

ρ = density of the material in kg/m^3

The power and energy capacities are decoupled in flywheels. In order to obtain the required power capacity, you must optimise the motor/generator and the power electronics. These systems, referred to as 'low-speed flywheels', usually have relatively low rotational speeds, approximately 10,000 rpm and a heavy rotor made form steel. They can provide up to 1650 kW, but for a very short time, up to 120 s.

To optimise the storage capacities of a flywheel, the rotor speed must be increased. These systems, referred to as 'high-speed flywheels', spin on a lighter rotor at much higher speeds, with some prototype composite flywheels claiming to reach speeds in excess of 100,000 rpm. However, the fastest flywheels commercially available spin at about 80,000 rpm. They can provide energy up to an hour, but with a maximum power of 750 kW.

Over the past number of years, the efficiency of flywheels has improved up to 80% [8], although some sources claim that it can be as high as 90% [1]. As it is a mechanical device, the charge-to-discharge ratio is 1:1.

5.6.1 Applications

Flywheels have an extremely fast dynamic response, a long life, require little maintenance, and are environmentally friendly. They have a predicted lifetime of approximately 20 years or tens of thousands of cycles. As the storage medium used in flywheels is mechanical, the unit can be discharged repeatedly and fully without any damage to the device. Consequently, flywheels are used for power quality enhancements such as Uninterruptable Power Supply (UPS), capturing waste energy that is very useful in electric vehicle applications and finally, to dampen frequency variation, making FES very useful to smooth the irregular electrical output from wind turbines.

5.6.2 Cost

At present, FES systems cost between $200/kWh to $300/kWh for low-speed flywheels, and $25,000/kWh for high-speed flywheels [2]. The large cost for high-speed flywheels is typical for a technology in the early stages of development. Battery technology such as the lead-acid battery is the main competitor for FES. These have similar characteristics to FES devices, and usually cost 33% less [8]. However, as mentioned previously (see section 3.7.1), FES have a longer lifespan, require lower maintenance, have a faster charge/discharge, take up less space and have fewer environmental risks [2].

5.6.3 Disadvantages

As flywheels are optimised for power or storage capacities, the needs of one application can often make the design poorly suited for the other. Consequently, low-speed flywheels may be able to provide high power capacities but only for very short time period, and high-speed flywheels the opposite. Also, as flywheels are kept in a vacuum during operation, it is difficult to transfer heat out of the system, so a cooling system is usually integrated with the FES device. Finally, FES devices also suffer from the idling losses: when flywheels are spinning on standby, energy is lost due to external forces such as friction or magnetic forces. As a result, flywheels need to be pushed to maintain its speed. However, these idling losses are usually less than 2%.

5.6.4 Future

Low maintenance costs and the ability to survive in harsh conditions are the core strengths for the future of flywheels. Flywheels currently represent 20% of the $1 billion energy storage market for UPS. Due to its size and cycling capabilities, FES could establish even more within this market if consumers see beyond the larger initial investment. As flywheels require a preference between optimisation of power or storage capacity, it is unlikely to be considered a viable option as a sole storage provider for power generation applications. Therefore, FES needs to extend into applications such as regenerative energy and frequency regulation where it is not currently fashionable if it is to have a future [8].

5.7 Supercapacitor Energy Storage (SCES)

Capacitors consist of two parallel plates that are separated by a dielectric insulator, see Figure 5-15. The plates hold opposite charges which induces an electric field, in which energy can be stored. The energy within a capacitor is given by

$$E = \frac{1}{2}CV^2 \tag{4}$$

where E is the energy stored within the capacitor (in Joules), V is the voltage applied, and C is the capacitance found from [1]

$$C = \frac{A}{d}\varepsilon_r \varepsilon_0 \tag{5}$$

where A is the area of the parallel plates, d is the distance between the two plates, ε_r is the relative permittivity or dielectric constant, and ε_0 is the permittivity of free space (8.854×10^{-12} F/m). Therefore, to increase the energy stored within a capacitor, the voltage or capacitance must be increased. The voltage is limited by the maximum Energy Field strength (after this the dielectric breaks down and starts conducting), and the capacitance depends on the dielectric constant of the material used.

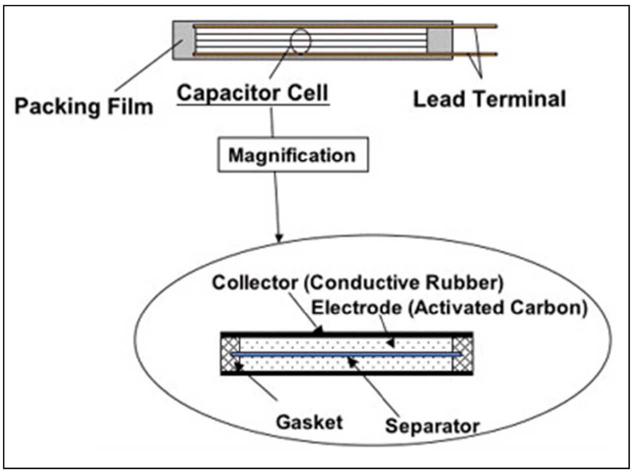


Figure 5-15: Components of a supercapacitor energy storage device [50].

Supercapacitors are created by using thin film polymers for the dielectric layer and carbon nanotube electrodes. They use polarised liquid layers between conducting ionic electrolyte and a conducting electrode to increase the capacitance. They can be connected in series or in parallel. SCES systems usually have energy densities of 20 MJ/m^3 to 70 MJ/m^3, with an efficiency of 95% [2].

5.7.1 Applications

The main attraction of SCES is its fast charge and discharge, combined with its extremely long life of approximately 1×10^6 cycles. This makes it a very attractive replacement for a number of small-scale (<250 kW) power quality applications. In comparison to batteries, supercapacitors have a longer life, do not suffer from memory effect, show minimal degradation due to deep discharge, do not heat up, and produce no hazardous substances [1]. As a result, although the energy density is smaller, SCES is a very attractive option for some applications such as hybrid cars, cellular phones, and load levelling tasks. SCES is primarily used where pulsed power is needed in the millisecond to second time range, with discharge times up to one minute [2].

5.7.2 Cost

SCES costs approximately $12,960/kWh [2] to $28,000/kWh [1]. Therefore, large scale applications are not economical using SCES.

5.7.3 Disadvantages

SCES has a very low energy storage density leading to very high capital costs for large scale applications. Also, they are heavier and bulkier than conventional batteries.

5.7.4 Future

Despite the small energy storage densities on offer, the exceptional life and cycling capabilities, fast response and good power capacity (up to 1 MW) of supercapacitors means that they will always be useful for specific applications. However, it is unlikely that SCES will be used as a sole energy storage device. One long-term possibility involves combining SCES with a battery based storage system. SCES could smooth power fluctuations, and the battery provides the storage capacity necessary for longer interruptions. However, other technologies (such as flow batteries) are more likely to be developed for such applications. As a result, the future of SCES is likely to remain within specific areas that require a lot of power, very fast, for very short periods.

5.8 Superconducting Magnetic Energy Storage (SMES)

A SMES device is made up of a superconducting coil, a power conditioning system, a refrigerator and a vacuum to keep the coil at low temperature, see Figure 5-16.

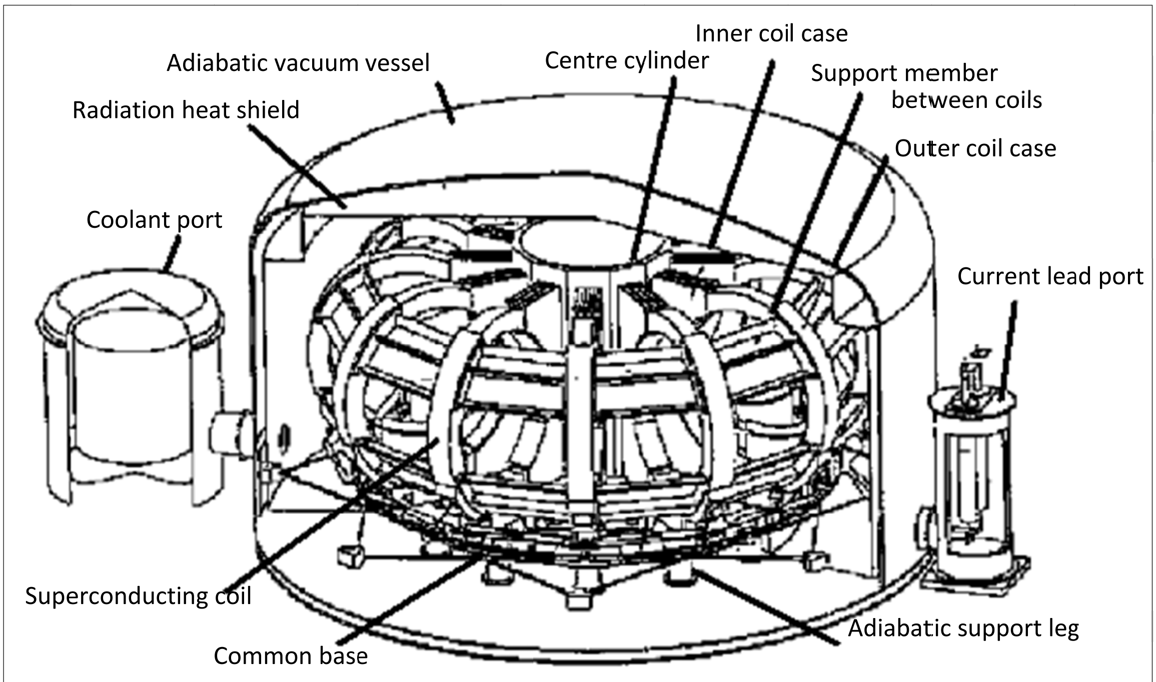


Figure 5-16: Components of a superconducting magnetic energy storage device [2].

Energy is stored in the magnetic field created by the flow of direct current in the coil wire. In general, when current is passed through a wire, energy is dissipated as heat due to the resistance of the wire. However, if the wire used is made from a superconducting material such as lead, mercury or vanadium, zero resistance occurs, so energy can be stored with practically no losses. In order to obtain this superconducting state within a material, it must be kept at a very low temperature. There are two types of superconductors; low-temperature superconductors that must be cooled from 0 K to 7.2 K, and high-temperature superconductors that have a temperature range of 10 K to 150 K, but are usually in the 100±10K region. The energy stored within the coil (in Joules), E_C, can be obtained from [1]

$$E_C = \frac{1}{2} L I^2 \quad (6)$$

where L is the inductance of the coil, and I is the current passing through it. Therefore, material properties are extremely important as temperature, magnetic field, and current density are pivotal factors in the design of SMES.

The overall efficiency of SMES is in the region of 90% [35] to 99% [8]. SMES has very fast discharge times, but only for very short periods of time, usually taking less than one minute for a full discharge. Discharging is possible in milliseconds if it is economical to have a PCS that is capable of supporting this. Storage capacities for SMES can be anything up to 2 MW, although its cycling capability is its main attraction. SMES devices can run for thousands of charge/discharge cycles without any degradation to the magnet, giving it a life of 20+ years.

5.8.1 Applications

Due to the high power capacity and instantaneous discharge rates of SMES, it is ideal for the industrial power quality market. It protects equipment from rapid momentary voltage sags, and it stabilises fluctuations within the entire network caused by sudden changes in consumer demand levels, lightening strikes or operation switches. As a result, SMES is a very useful network upgrade solution with some sources claiming that it can improve the capacity of a local network by up to 15% [8]. However, due to high energy consumption of the refrigeration system, SMES is unsuitable for daily cycling applications such as peak reduction, renewable applications, and generation and transmission deferral [2].

5.8.2 Cost

SMES cost approximately $300/kW [2] to $509/kW [8]. It is worth noting that it is difficult to compare the cost of SMES to other storage devices due to its scales and purpose. In practical terms SMES should be compared to other network upgrade solutions where it is often very competitive or even less costly. Finally, the cost of storing electricity within a superconductor is expected to decline by almost 30% which could make SMES an even more attractive option for network improvements [8].

5.8.3 Disadvantages

The most significant drawback of SMES is its sensitivity to temperature. As discussed the coil must be maintained at an extremely low temperature in order to behave like a superconductor. However, a very small change in temperature can cause the coil to become unstable and lose energy. Also, the refrigeration can cause parasitic losses within the system. Finally, although the rapid discharge rates provide some unique applications for SMES, it also limits its applications significantly. As a result, other multifunctional storage devices such as batteries are usually more attractive.

5.8.4 Future

Immediate focus will be in developing small SMES devices in the range of 1 MW to 10 MW for the power quality market which has foreseeable commercial potential. A lot of work is being carried out to reduce the capital and operating costs of high-temperature SMES devices, as it is expected to be the commercial superconductor of choice once manufacturing processes are more mature, primarily due to cheaper cooling. There is a lot of market potential for SMES due to its unique application characteristics, primarily in transmission upgrades and industrial power quality [8]. However, one of the greatest concerns for SMES is its reliability over a long period of time.

5.9 Hydrogen Energy Storage System (HESS)

HESS is the first of the three energy storage systems discussed in this report. HESS is the one of the most immature but also one of the most promising energy storage techniques available. As an energy storage system, HESS acts as a bridge between all three major sectors of an energy system: the electricity, heat and transport sectors. It is the only energy storage system that allows this level of interaction between these sectors and hence it is becoming a very attractive option for integrating large quantities of intermittent wind energy. There are three stages in HESS:

1. Create hydrogen
2. Store hydrogen
3. Use hydrogen (for required application)

5.9.1 Create Hydrogen

There are three primary techniques to create hydrogen:

1. Extraction from Fossil Fuels
2. Reacting steam with methane
3. Electricity (Electrolysis)

However, as producing hydrogen from fossil fuels is four times more expensive than using the fuel itself, and reacting steam with methane produces pollutants, electrolysis has become the most promising technique for hydrogen production going forward.

An electrolyser uses electrolysis to breakdown water into hydrogen and oxygen. The oxygen is dissipated into the atmosphere and the hydrogen is stored so it can be used for future generation. Due to the high cost of electrical production, only a small proportion of the current hydrogen production originates from electrolysis. Therefore, the most attractive option for future production is integrating electrolyser units with renewable resources such as wind or solar. In order to achieve this, an electrolyser must be capable of operating:

1. with high efficiency
2. under good dynamic response
3. over a wide input range
4. under frequently changing conditions [2]

Recently a number of advancements have been made including higher efficiencies of 85%, wider input power capabilities, and more variable inputs. A new Proton Exchange Membrane (PEM) has been developed instead of the preceding alkaline membranes. This can operate with more impure hydrogen, faster dynamic response, lower maintenance, and increased suitability for pressurisation [2]. However, a PEM unit has lower efficiency (40% - 60%) so some development is still required.

Electrolysers are modular devices so the capacity of a device is proportional to the number of cells that make up a stack. The largest commercial systems available can produce 485 Nm^3/h, corresponding to an input power of 2.5 MW. The lifetime of an electrolyser is proving difficult to predict due to its limited experience. However, research has indicated that the electrolyser unit will have the shortest lifespan within HESS. Some have predicted a lifespan in the region of 5-10 years but this is only an estimate [2].

5.9.1.1 Cost

The estimated costs to produce power using an electrolyser are extremely varied. Predictions are as low as €300/kW [51] up to €1,100/kW [2]. *ITM Power* in the UK claim to have produced an electrolyser that can operate with renewable sources, at a cost of $164/kW, and are currently planning to begin mass production in 2008 [52]. Maintenance costs are expected to be 3% of the capital cost [2].

5.9.1.2 Future

Immediate developments are investigating the possibility of producing an electrolyser that can pressurise the hydrogen during electrolysis, as compressing the hydrogen after production is expensive and unreliable. Like all areas of HESS, the electrolyser needs a lot more development as well as technical maturity.

5.9.2 Store Hydrogen

A number of different options are currently available to store hydrogen:

1. Compression: The hydrogen can be compressed into containers or underground reservoirs. The cost of storing hydrogen in pressure vessels is $11/kWh to $15/kWh [2]. However, for underground reservoirs it is only $2/kWh [53]. This is a relatively simple technology, but the energy density and efficiency (65% to 70%) are low. Also, problems have occurred with the mechanical compression. However, this is at present the most common form of hydrogen storage for the transport industry, with the hydrogen compressed to approximately 700 bar (the higher the storage pressure, the higher the energy density, see Figure 5-17). Although the energy required for the compression is a major drawback.

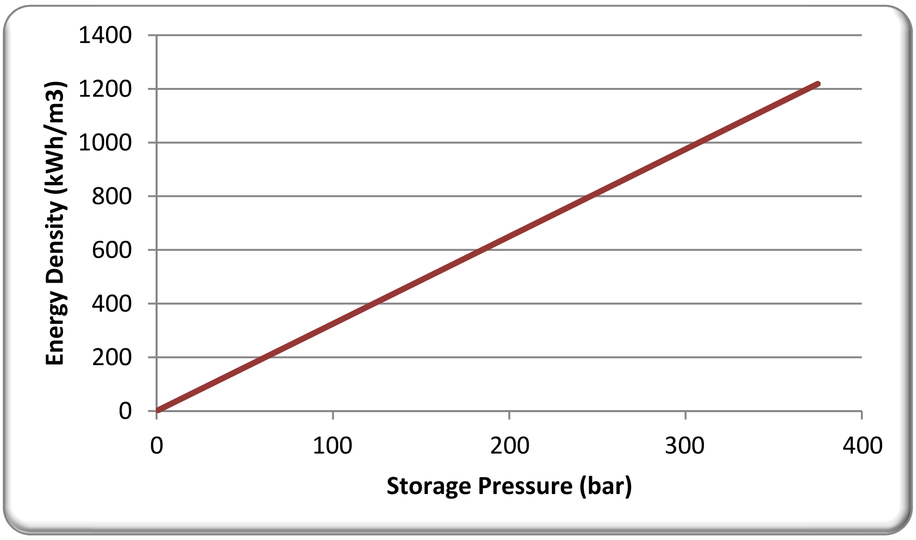


Figure 5-17: Energy density vs. pressure for a hydrogen gas storage [2].

2. Liquefied Hydrogen: The hydrogen can be liquefied by pressurising and cooling. Although the energy density is improved, it is still four times less than conventional petrol. Also, keeping the hydrogen liquefied is very energy intensive, as it must be kept below 20.27K [54]
3. Metal Hydrides: Certain materials absorb molecular hydrogen such as nanostructured carbons and clathrate hydrate. By absorbing the hydrogen in these materials, it can be easily transported and stored. Once required, the hydrogen is removed from the parent material. The energy density is similar to that obtained for liquefied hydrogen [54]. The extra material required to store the hydrogen is a major problem with this technique as it creates extra costs and mass. This is still a relatively new technology, so with extra development it could be a viable option; especially if the mass of material is reduced. Carbon-based absorption can achieve higher energy densities but it has higher costs and even less demonstrations [2]. Both metal-hydride or carbon-based absorption use thermal energy. This thermal heat could be got from the waste heat of other processes with HESS, such as the electrolyser or fuel cell, to improve overall efficiency.

Each storage technique is in the early stages of development and hence there is no optimum method at present with research being carried out in each area.

5.9.3 Use Hydrogen

There are two superior ways of using hydrogen:

1. Internal Combustion Engine (ICE)
2. Fuel Cell (FC)

It is expected that the ICE will act as a transition technology while fuel cells are improving, because the modifications required to convert an ICE to operate on hydrogen are not very significant. However, the FC, due to its virtually emission-free, efficient and reliable characteristics, is expected to be the generator of choice for future hydrogen powered energy applications.

5.9.3.1 Fuel Cell

A fuel cell converts stored chemical energy, in this case hydrogen, directly into electrical energy. A fuel cell consists of two electrodes that are separated by an electrolyte, see Figure 5-18.

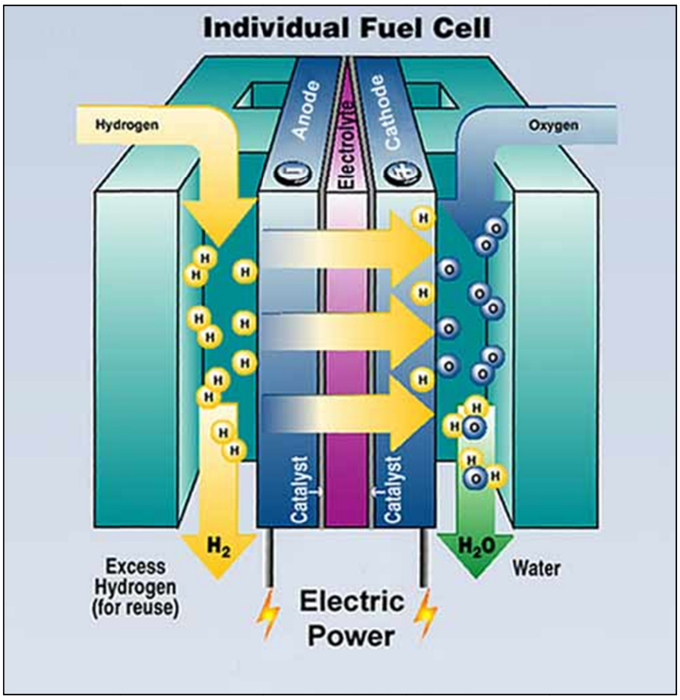


Figure 5-18: Structure of a fuel cell [55].

Hydrogen is passed over the anode (negative) and oxygen is passed over the cathode (positive), causing hydrogen ions and electrons to form at the anode. The electrons flow through an external circuit to produce electricity, whilst the hydrogen ions pass from the anode to the cathode. Here the hydrogen ions combine with oxygen to produce water. The energy produced by the various types of cells depends on the operation temperature, the type of fuel cell, and the catalyst used; see Table 5-3. Fuel cells do not produce any pollutants and have no moving parts. Therefore, theoretically it should be possible to obtain a reliability of 99.9999% in ideal conditions [56].

5.9.3.2 Cost

All fuel cells cost between €500/kW and €8,000/kW which is very high, but typical of an emerging technology [2]. These costs are expected to reduce as the technology ages and commercialisation matures.

5.9.3.3 Future

Immediate objectives for fuel cells include harnessing the waste heat more effectively to improve co-generation efficiency and also, combining fuel cells with electrolysers as a single unit. The advantage being lower capital costs although resulting in lower efficiency and increased corrosion [2]. Fuel cells are a relatively new technology with high capital costs. However, with characteristics such as no moving parts, no emissions, lightweight, versatility and reliability, this is definitely a technology with a lot of future potential.

Table 5-3: Properties of the various fuel cell technologies currently available [1].

Fuel Cell	Electrolyte	Catalyst	Efficiency (%)	Operating temp (°C)	Power output (kW)	Applications	Additional notes
Alkaline Fuel Cell (AFC)	Potassium Hydroxide	Platinum	70	150 - 200	0.3 - 12	Widely used in the space industry (NASA)	Water produced by cell is drinkable. Can be easily poisoned by carbon dioxide (CO_2)
Polymer Electrolyte Membrane **or** Proton Exchange Membrane (PEM)	Solid Organic Polymer	Platinum	45	80	50 - 250	Portable applications such as cars	Cell is sensitive to impurities so hydrogen used must be good quality
Phosphoric Acid Fuel Cell (PAFC)	Phosphoric Acid	Platinum	40	150 - 200	200	Large stationary generation. Also Co-generation (increases efficiency to 85%)	Can use impure hydrogen such as hydrogen from fossil fuels
Molten Carbonate Fuel Cell (MCFC)	Potassium, Sodium or Lithium Carbonate	Variety of non-precious metals	60	650	10 – 2000	Co-generation (increases efficiency to 85%)	High operating temperature and corrosive electrolyte result in short cell lifetime
Solid Oxide Fuel Cells (SOFC)	Solid Zirconium Oxide	Variety of non-precious metals	60	1000	100	Utility applications. Prototype for Co-generation exists (85% efficient)	High temperature causes slow start-up

5.9.4 Disadvantages

The primary disadvantage with hydrogen is the huge losses due to the number of energy conversions required. Typically in a system that has high wind energy penetrations, by the time that hydrogen is actually being used for its final purpose it has gone through the following processes with corresponding efficiencies: 1) Hydrogen is created by electrolysis – 85% efficient, 2) the hydrogen is stored – 65% to 70% efficient, 3) hydrogen is consumed in a fuel cell car, power plant, or CHP unit – efficiency of 40% to 80%. This results in an overall efficiency ranging from 22% to 48%. In addition, this process assumes only one storage stage within the life of the hydrogen where as typically more than one storage stage would be necessary i.e. stored when created, and stored at the location of use. Therefore, by implementing a "hydrogen economy", the efficiency of the system is very low that could result in very high energy costs and very poor utilisation of limited resources such as wind or biomass. In summary, although the hydrogen energy storage system offers huge flexibility, this flexibility is detrimental to the overall energy system efficiency.

5.9.5 Future of HESS

The use of hydrogen within the transport and electricity generation industries is expected to grow rapidly as electrolysis, storage techniques, and fuel cells become more commercially available.

There are very ambitious hydrogen programs in the EU, US, and Japan, indicating increasing interest in hydrogen technology. Iceland is attempting to become the first 'hydrogen country' in the world by producing hydrogen from surplus renewable energy and converting its transport infrastructure from fossil fuels to hydrogen. In Norway, *Statkraft* plans to connect an electrolysis unit to a large wind turbine and *Norsk Hydro* is continuing a project to provide Utsira Island with a wind-hydrogen system. In Germany, *Siemens* and *P&T Technologies* are developing a wind-hydrogen engine using an ICE. In the UK *Wind Hydrogen Limited* intend to develop large scale wind-hydrogen schemes. Finally, *HyGen* in California is developing a multi megawatt hydrogen generating and distributing network [2].

Car manufacturers are driving research in hydrogen for both the transport and infrastructure divisions. The automotive industry has engaged in setting up a strategy for the introduction of hydrogen to the transport sector with a number of single prototype projects advancing to fleet demonstrations [2].

Hydrogen is a serious contender for future energy storage due to its versatility. Once hydrogen can be produced effectively, it can be used for practically any application required. Consequently, producing hydrogen from renewable resources using electrolysis is currently the most desirable objective available. Primarily due to the versatility and potential of hydrogen to replace conventional fuel, "It is envisaged that the changeover to a hydrogen economy is less than fifty years from now" [2].

5.10 Thermal Energy Storage (TES)

Thermal energy storage involves storing energy in a thermal reservoir so that it can be recovered at a later time. A number of thermal applications are used instead of electricity to provide heating and cooling including Aquifer Thermal Storage (ATS), and Duct Thermal Storage (DTS). However, these are heat generation techniques rather than energy storage techniques and therefore will not be discussed in detail here. In terms of storing energy, there are two primary thermal energy storage options. The first option is a technology which is used to supplement air conditioning in buildings and is displayed in Figure 5-19. The second option is an energy storage system rather than a technology which will be discussed in more detail later.

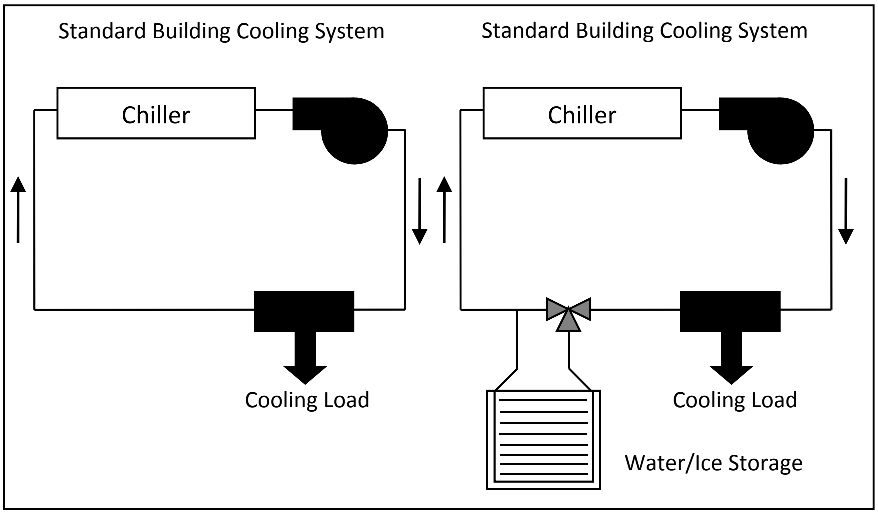


Figure 5-19: Structure of an air-conditioning thermal energy storage unit [8].

5.10.1 Air-Conditioning Thermal Energy Storage (ACTES)

The Air-Conditioning Thermal Energy Storage (ACTES) units work with the air conditioning in buildings by using off-peak power to drive the chiller to create ice. During the day, this ice can be used to provide the cooling load for the air conditioner. This improves the overall efficiency of the cycle as chillers are much more efficient when operated at night time due to the lower external temperatures. Also, if ACTES units are used, the size of the chiller and ducts can be reduced. Chillers are designed to cope with the hottest part of the hottest day possible, all day. Therefore, they are nearly always operating below full capacity. If ACTES facilities are used, the chiller can be run at full capacity at night to make the ice and also at full capacity during the day; with the ice compensating for shortfalls in the chiller capacity. ACTES units lose approximately 1% of their energy during storage [8].

5.10.1.1 Cost

If ACTES is installed in an existing building, it costs from $250 to $500 per peak kW shifted, and it has a payback period from one to three years. However, if installed during construction, the cost saved by using smaller ducts (20% to 40% smaller), chillers (40% to 60% smaller), fan motors, air handlers and water pumps will generally pay for the price of the ACTES unit. As well as this, the overall air conditioning cost is reduced by 20% to 60% [8].

5.10.1.2 Future

Due to the number of successful installations that have already occurred, this technology is expected to grow significantly where air-conditioning is a necessity. It is however, dependent on the future market charges that apply, as this technology benefits significantly from cheaper off-peak power and demand charges. Finally, ACTES units will have to compete with other building upgrades such as lighting and windows, for funding in the overall energy saving strategies enforced [8].

5.10.2 Thermal Energy Storage System (TESS)

The thermal energy storage system can also be used very effectively to increase the flexibility within an energy system. As mentioned previously in this report, by integrating various sectors of an energy system, increased wind penetrations can be achieved due to the additional flexibility created. Unlike the hydrogen energy storage system which enabled interactions between the electricity, heat and transport sectors, thermal energy storage only combines the electricity and heat sectors with one another. By introducing district heating into an energy system, then electricity and heat can be provided from the same facility to the energy system using Combined Heat and Power (CHP) plants. This brings additional flexibility to the system which enables larger penetrations of intermittent renewable energy sources. To illustrate the flexibility induced by thermal energy storage on such a system, a snapshot of the power during different scenarios is presented below. The system in question contains a CHP plant, wind turbines, a thermal storage, a hot water demand, and an electrical demand as illustrated in Figure 5-20.

During times of low wind power, a lot of electricity must be generated by the CHP plants to accommodate for the shortfall power production. As a result, a lot of hot water is also being produced from the CHP plant as seen in Figure 5-20a. The high production of hot water means that production is now greater than demand, and consequently, hot water is sent to the thermal storage. Conversely, at times of high wind power, the CHP plants produce very little electricity and hot water. Therefore, there is now a shortage in of hot water so the thermal storage is used to supply the shortfall, as seen in Figure 5-20b.

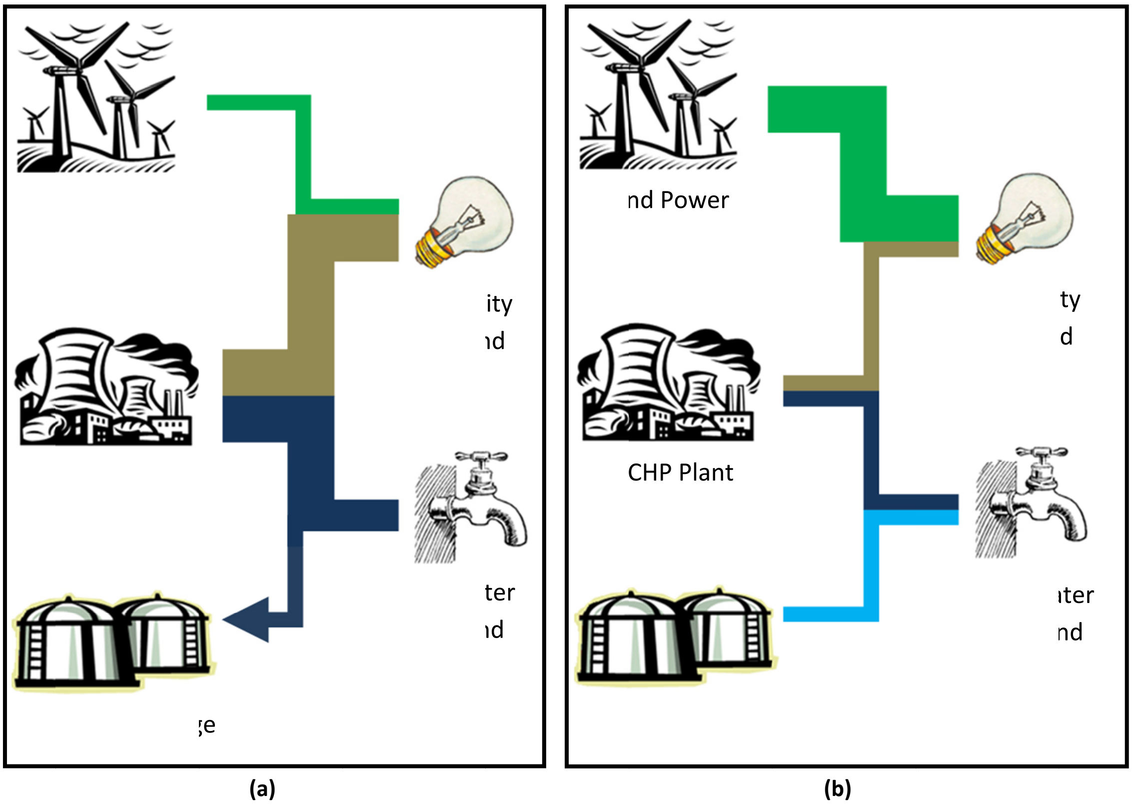


Figure 5-20: Thermal energy storage system during (a) a low wind scenario and (b) a high wind scenario.

This system has been put into practice in Denmark which has the highest wind penetration in the world. Also, Lund has outlined a roadmap for Denmark to use this setup in achieving a 100% renewable energy system [57].

5.10.2.1 Disadvantages

Similar to the hydrogen energy storage system, the primary disadvantage with a thermal energy storage system is the large investments required to build the initial infrastructure. However, the thermal energy storage system has two primary advantages: 1) the overall efficiency of the energy system is improved with the implementation of a TESS. CHP production is approximately 85% to 90% efficiecnt while conventional power plants are only 40% efficient, and 2) this technique has already been implemented in Denmark so it is a proven solution. On the negative side, as stated previously, thermal energy storage does not improve flexibility within the transport sector like the hydrogen energy storage system, but this is inferior to the advantages it possesses. Therefore, in summary, the thermal energy storage system does have disadvantages, but these are small in comparison to the advantages.

5.10.2.2 Future

Due to the efficiency improvements and maturity of this system, it is very likely that it will become more prominent throughout the world. Not only does it enable the utilisation of more intermittent renewable energy (such as wind), but it also maximises the use of fuel within power plants, something that will become critical as biomass becomes more prominent. This system has been put into practice in Denmark which has the highest wind penetration in the world. In addition, Lund has outlined a roadmap for Denmark to use this setup in achieving a 100% renewable energy system at a lower cost than a conventional energy system [57]. Therefore, it is evident this technology can play a crucial role in future energy systems.

5.11 Electric Vehicles (EVs)

The final energy storage system that will be discussed in this report is the implantation of electric vehicles. Once again, system flexibility and hence feasible wind penetrations are increased with the introduction of electric vehicles into the transport sector. As illustrated in Figure 20, electric vehicles can feed directly from the power grid while stationary, at individual homes or at common recharging points, such as car parks or recharging stations. By implementing electric vehicles it is possible to make large-scale battery energy storage economical, combat the huge oil dependence `within the transport sector and drastically increase system flexibility (by introducing the large-scale energy storage) [58]. Consequently, similar to the HESS and the TESS, electric vehicles also provide a method of integrating existing energy systems more effectively.

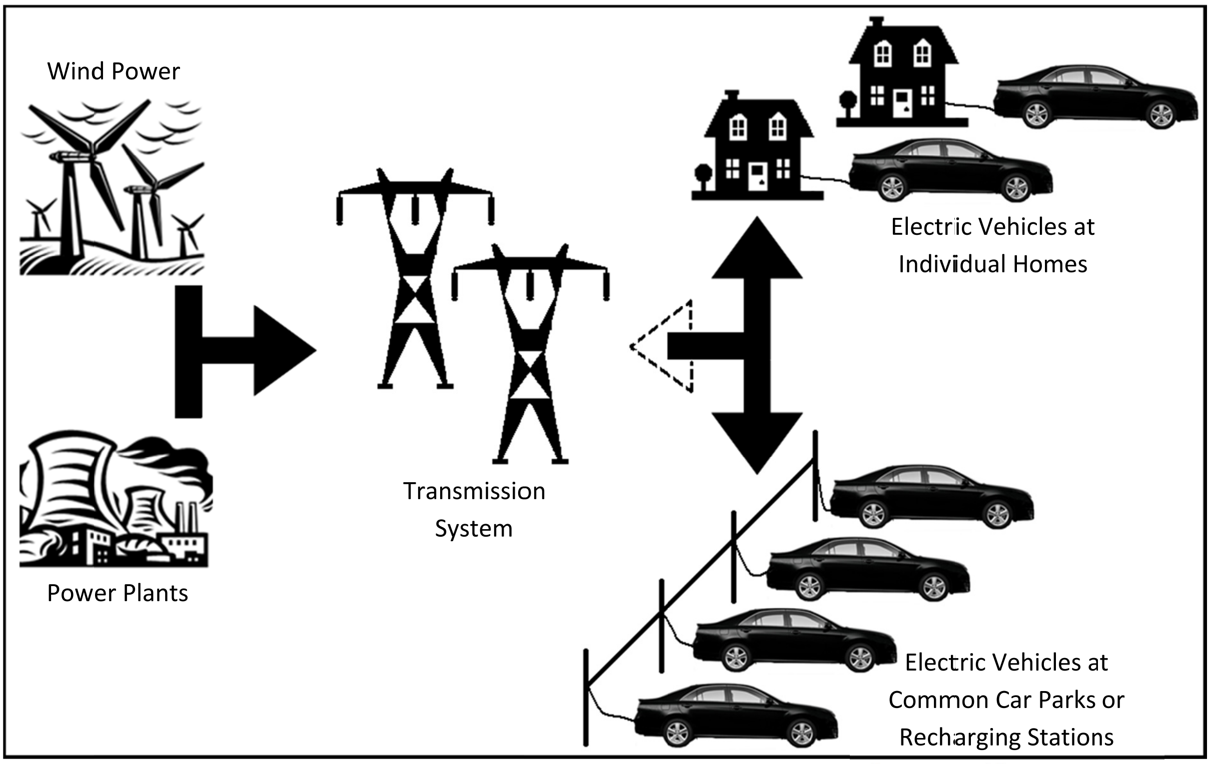


Figure 5-21: Schematic of electric vehicles interacting with the electric power grid.

5.11.1 Applications

Electric vehicles can be classified under three primary categories: Battery Electric Vehicles (BEV), Smart Electric Vehicles (SEV), and Vehicle to Grid (V2G). BEVs are plugged into the electric grid and act as additional load. In contrast, SEVs have the potential to communicate with the grid. For example, at times of high wind production, it is ideal to begin charging electric vehicles to avoid ramping centralised production. In addition, at times of low wind production, charging vehicles should be avoided if possible until a later stage. V2G electric vehicles operate in the same way as SEVs, however, they have the added feature of being able to supply power back to the grid. This increases the level of flexibility within the system once again. All three types of electric vehicles could be used to improve wind penetrations feasible on a conventional grid, with each advancement in technology increasing the wind penetrations feasible from approximately 30% to 65% [58] (from BEV to V2G).

5.11.2 Cost

The costs associated with electric vehicles are different to the costs quoted for other storage technologies. Consumers are not buying electric vehicles to provide energy storage capacity for the grid, instead they are buying electric vehicles as a mode of transport. Therefore, it is difficult to compare the costs of electric vehicles under the conventional $/kW and $/kWh that other storage systems are compared with. As a result, below is a comparison between the price of electric vehicles and conventional vehicles, as this comparison is more relevant when considering the uptake of electric vehicles. Figure 21 illustrated the cost of owning a BEV and a conventional electric vehicle over a 105,000 km lifetime, with 25% of its life in urban areas. It is evident from Figure 21 that BEVs are approximately 20% more expensive than conventional vehicles: while SEVs and V2G would be even more expensive but these are still at the development stage. As SEVs and V2G electric vehicles will enable significantly larger wind penetrations on the power grid that BEVs [58], it is likely that economic incentives will be necessary to attract consumers to purchase SEV and V2G vehicles.

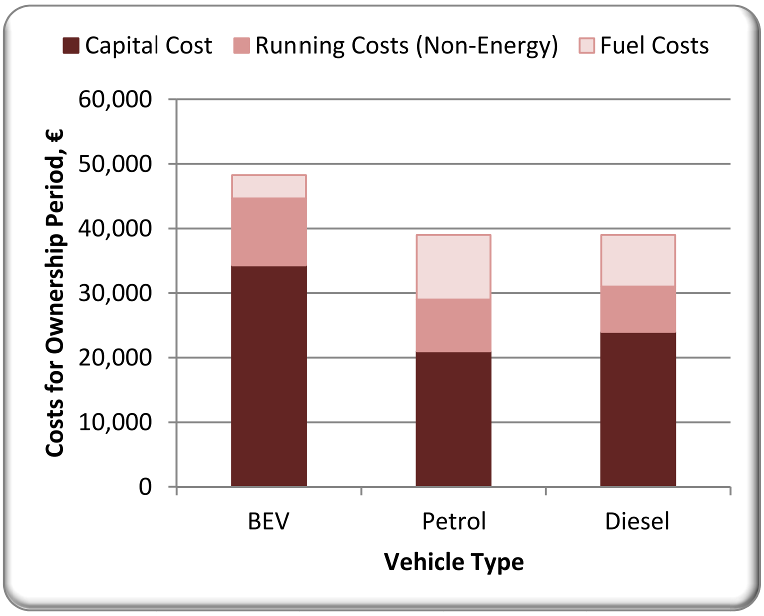


Figure 5-22: Cost of battery electric and conventional vehicles over a lifetime of 105,000 km (25% urban driving) [59].

5.11.3 Disadvantages

The primary disadvantage with electric vehicles is the initial investment to establish the required infrastructure. Transmission lines will need to be upgraded to allow for high power capacities to and (in the case of V2G) from the electric cars, battery banks or charging stations will be required to replace conventional refuelling stations, and maintenance services will need to be established as we transfer from conventional internal combustion engines to electric motors. In addition, travelling habits may need to be altered due to the alternative limitations associated with electric vehicles instead of conventional vehicles, such as driving styles and time required for refuelling. Finally, the remaining issue with electric vehicles is the driving range that can be obtained. Currently, hydrogen vehicles have a much larger range than electric vehicles, although hydrogen vehicles are much less efficient. Therefore, depending on which of these factors is more important for different energy systems will most likely decide which of these technologies is preferred.

5.11.4 Future

Electric vehicles are most likely going to be a key component in a number of future energy systems with large penetrations of intermittent renewable energy. This is primarily due to the two advantages mentioned in the introduction to this section: they reduce oil dependence and provide affordable large-scale energy storage. However, as mentioned already, alternative options such as hydrogen vehicles may reduce the attraction to electric vehicles within energy systems which prioritise range over energy efficiency.

6 Energy Storage Comparison

As outlined in section 4, energy storage can be utilised for a broad range of applications. However, the type of technology which is suitable for these is applications, is primarily defined by their potential power and storage capacities that can be obtained. From section 5 it was clear that each energy storage facility is capable of different power and storage capacities. Therefore, to provide a fair comparison between the various energy storage technologies, they have been grouped together based on the size of power and storage capacity that they can achieve. Four categories have been created: devices with large power (>50 MW) and storage (>100 MWh) capacities; devices with medium power (1-50 MW) and storage capacities (5-100 MWh); devices with small power (<10 MW) and storage capacities (<10 MWh); and finally, a section on energy storage systems. These are energy storage technologies that will be discussed along with their corresponding categories:

1. PHES
2. UPHES
3. CAES

} Large Power and Storage Capacities

4. BES
5. FBES

} Medium Power and Storage Capacities

6. FES
7. SCES
8. SMES

} Small Power and Storage Capacities

9. HESS
10. TESS
11. EVs

} Energy Storage Systems

Below there is an initial comparison of the remaining storage technologies within the first three categories defined above. This is followed by an overall comparison across all of these categories. The HESS, TESS, and EVs have unique characteristics as these are energy systems i.e. they require a number of different technologies which can be controlled differently. As a result, these have not been included in the comparison below. Instead, they are discussed briefly after the comparison in general terms rather than with specific figures. A separate more-detailed study has been carried out using a complete energy system analysis tool called EnergyPLAN [60], to begin evaluating the implications of these systems [61, 62].

6.1 Large power and energy capacities

The only devices identified in this report capable of large power (>50 MW) and energy capacities (>100 MWh) are PHES, UPHES and CAES.

New PHES facilities are unlikely to be built as upgrades continue to prove successful. Once upgrades have been completed on existing PHES facilities, the potential for PHES will depend heavily on the availability of suitable sites like all other large-scale energy storage technologies. It is widely believed that there are a limited number of suitable sites remaining for PHES. Although, recent studies completed have illustrated the potential for seawater PHES [17, 29] as well as the potential for many more freshwater PHES sites than originally anticipated [26-28]. Therefore, if results continue in this fashion, PHES may only be constrained by economics and not technical feasibility, indicating that it could become a very important technology as fuel prices continue to rise in the future.

In theory UPHES could be a major contender for the future as it operates under the same operating principals as PHES: therefore, almost all of the technology required to construct such a facility is already available and at a very mature stage. In addition, sites for UPHES will not be dependent on locations in mountainous areas like PHES, which could be advantageous as there are often isolated regions where construction is difficult and expensive. However, UPHES will still have unique site constraints of its own as it will require a suitable underground reservoir. Until such time that an extensive investigation is completed analysing the availability of such reservoirs, the future of UPHES will remain uncertain.

Finally, the attractiveness of CAES depends on the price and availability of gas as well as the potential for suitable locations. It is a flexible, reliable, and efficient technology but it still needs gas to operate. CAES by its nature is capital intensive and hence a long-term commitment is required (~30 years) when constructing this technology. Therefore, if the energy system considering CAES has long term ambitions to eliminate a dependence on gas, due to price, security of supply, etc., then this should be accounted for when analysing the feasibility of CAES. Also, although vessels can be used for the compressed air, underground storage reservoirs are usually required to make CAES an economical alternative. Consequently, like PHES and UPHES, the potential for CAES will also depend heavily on the availability of suitable locations.

In conclusion, it is evident that large-scale energy storage facilities all share one key issue: the availability of suitable locations. However, based on recent studies, suitable sites for PHES may be more prominent than originally anticipated, which gives PHES a significant advantage especially in an Irish context. However, one other key consideration is the maturity of the various technologies. UPHES and CAES utilising vessels are still only concepts and thus unproven. CAES using underground reservoirs is often considered a mature technology as there are currently only two facilities operating worldwide. In comparison, there is over 90 GW of PHES (at over 240 facilities) currently in operation as well as 7 GW of additional plants planned in Europe alone over the next eight years [30]. Based on the potential availability of sites and the maturity of PHES, it is most likely large-scale energy storage technology feasible, especially for the Irish energy system.

6.2 Medium power and energy capacities

This section includes BES and FBES. The only major contender from the BES storage technologies for future large-scale projects is the NaS battery. LA and NiCd will probably be used for their existing applications, but further breakthroughs are unlikely. FBES technologies (including VR, PSB and ZnBr) are all currently competing in the renewable energy market. Demonstration results for these batteries will be decisive for their future. It is worth noting that flow batteries are much more complex than conventional batteries. This is the reason conventional batteries still remain an attractive alternative. Conventional batteries are simple, but constrained (power and storage capacities are coupled) while flow batteries are flexible, but complex (power and storage capacities are independent, but a number of extra parts are required). The other key issue for this category will be the development of electric vehicles. If technological advancements continue within electric vehicles, then stand-alone battery energy storage may could be replaced by distributed batteries in EVs. Therefore, the future of this sector is very uncertain as various technologies continue to develop. Future demonstration projects for NaS, FBES, and EVs will all play a decisive role in defining the future of this sector.

6.3 Small power capacities and storage capacities

FES, SCES and SMES primarily differ in terms of the power capacity which can be achieved, as their storage capabilities are generally less than one hour. FES is used for the smallest power requirements (typically up to 750 kW), SCES for medium power (up to 1 MW), and SMES for large power issues (up to 10 MW). The optimum technology depends on the power required for the specific application being considered. Due to the unique ratio of their capacities, these technologies are likely to be used for their specific purposes such as uninterruptable power supply and ancillary service, well into the future. However, they are unlikely to be utilised as a core technology for the large-scale integration of fluctuating renewable energy.

6.4 Overall comparison of energy storage technologies

It is very difficult to compare the various types of energy storage techniques to one another as they are individually ideal for certain applications but no technology is perfect for everything. Consequently, for the purposes of this section, a number of illustrations are provided indicating the capabilities of each energy storage technology in relation to one another, see Figure 6-1 to Figure 6-5. This is followed by a table specifying the applications that each storage technology is suitable for, see Table 6-1, which have been defined earlier in section 4. Finally, there is a table outlining the detailed characteristics of each storage technology (see Table 6-2) and a table indicating the cost of each technology (see Table 6-3).

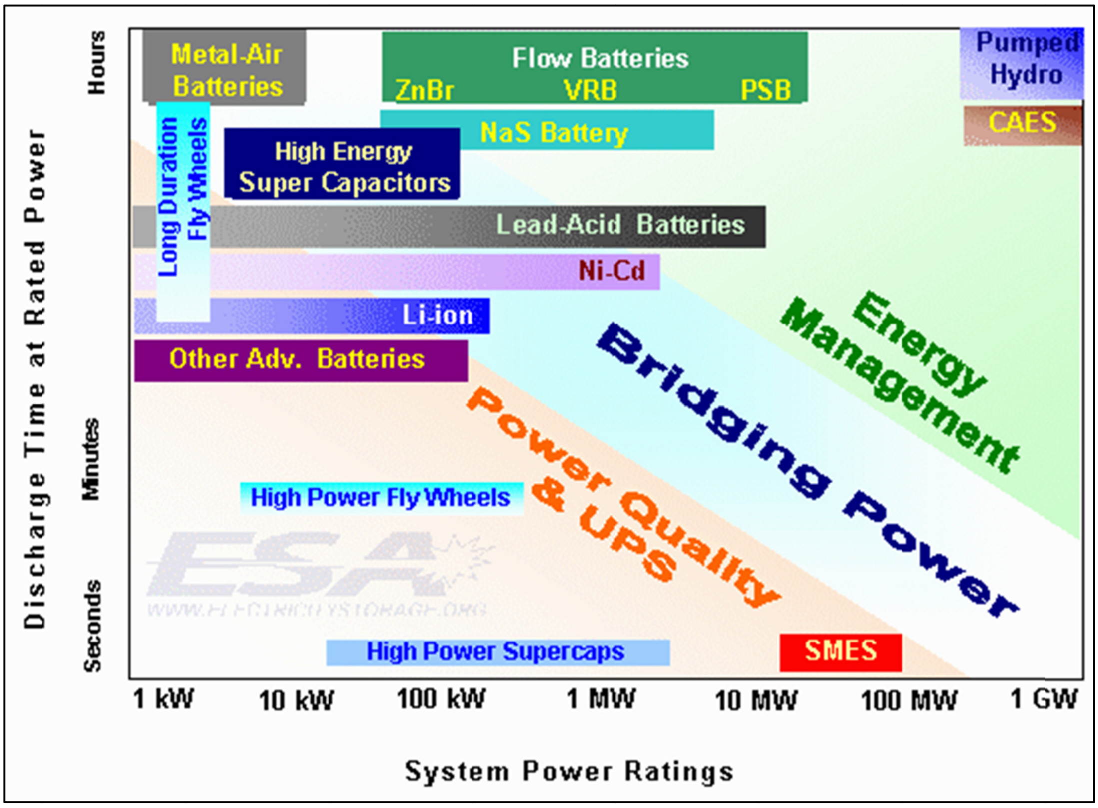


Figure 6-1: Discharge Time vs. Power Ratings for each storage technology [63].

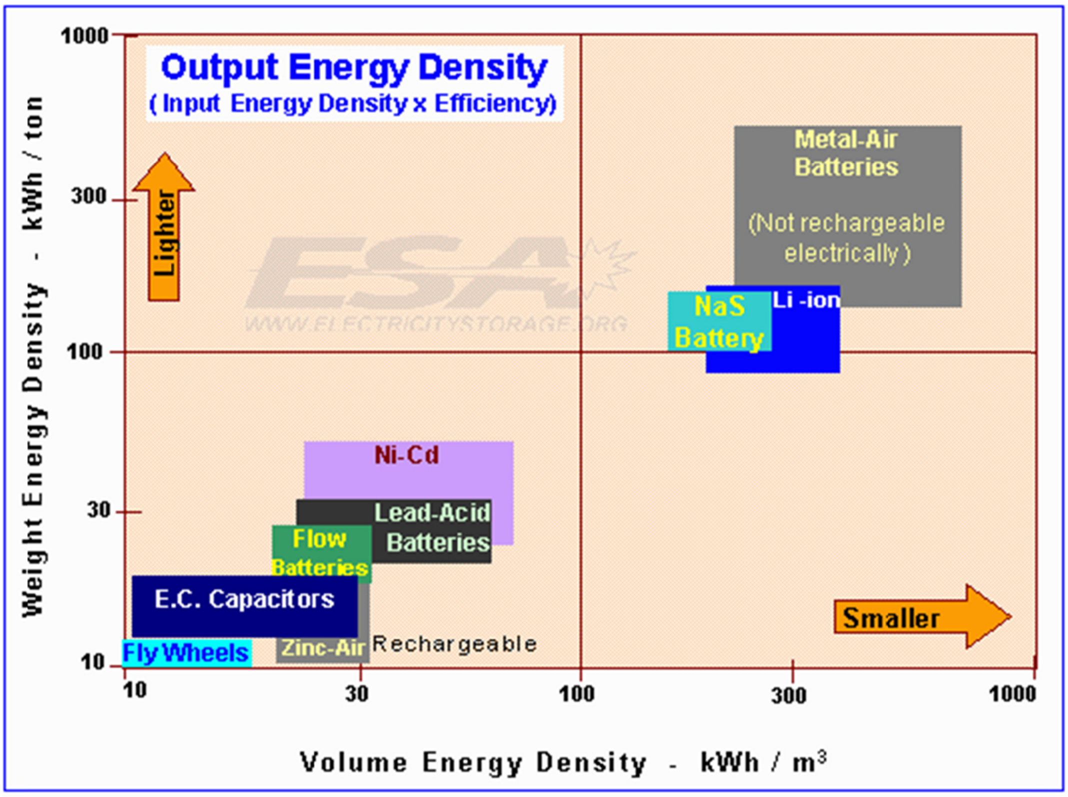


Figure 6-2: Weight Energy Density vs. Volume Energy Density for each technology [63].

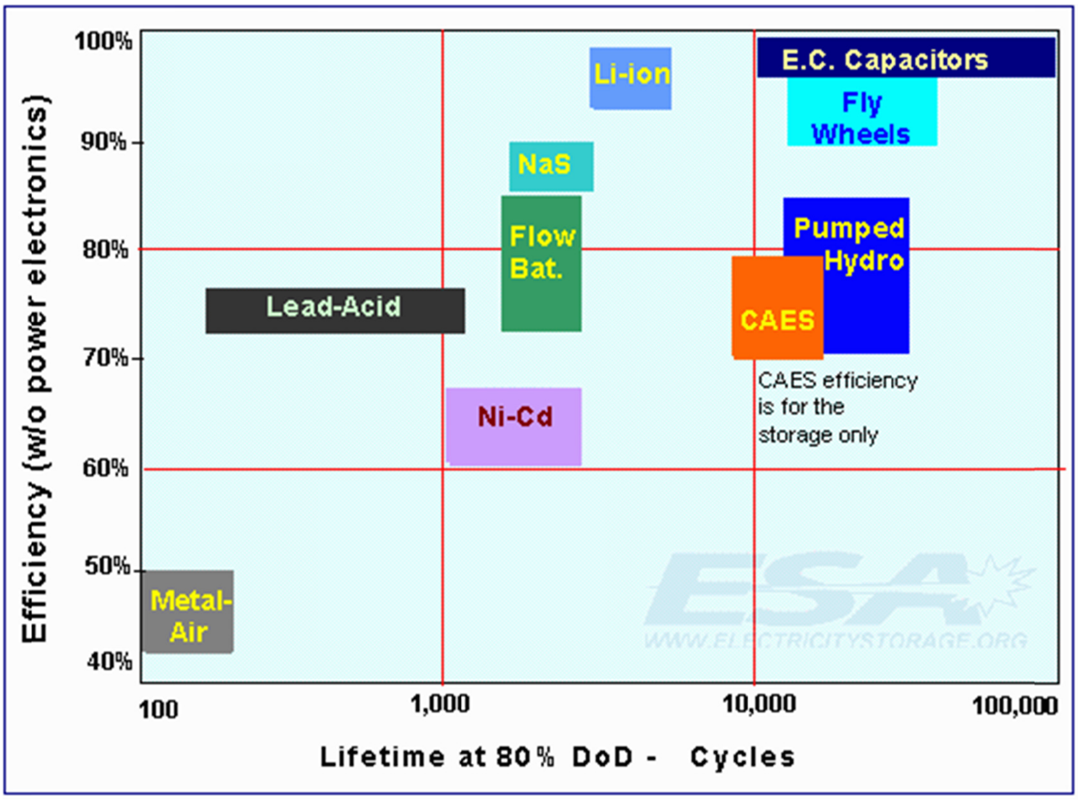


Figure 6-3: Efficiency & Lifetime at 80% DoD for each technology [63].

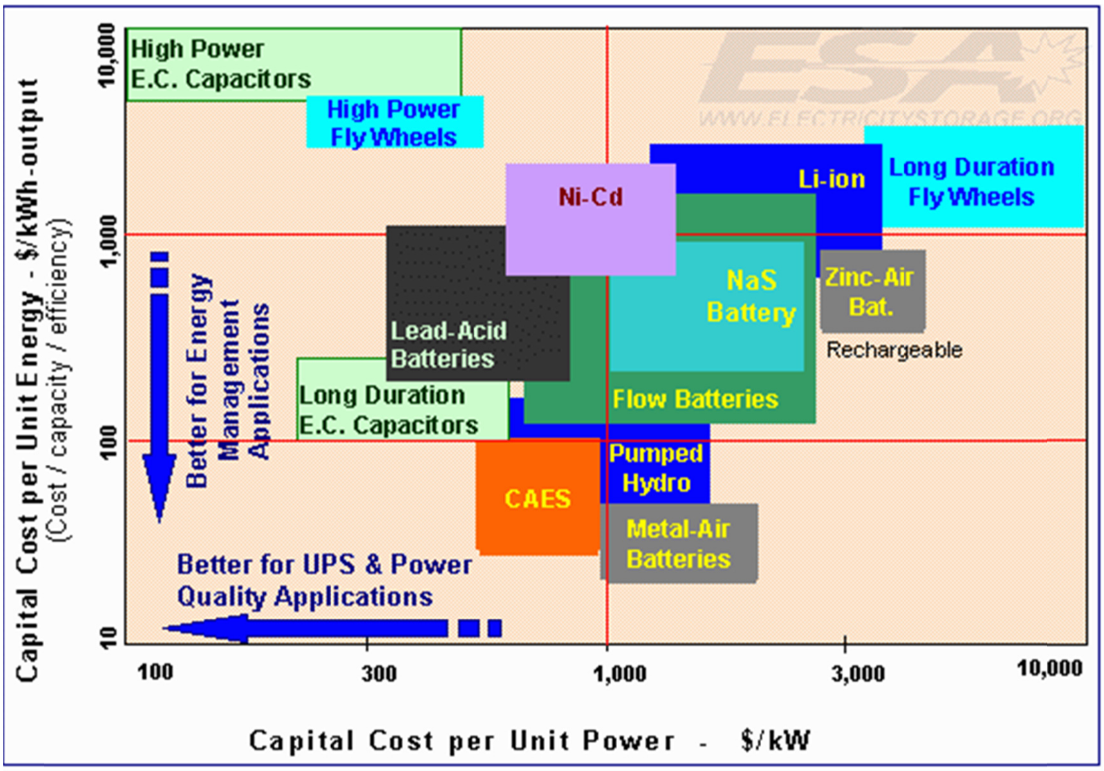


Figure 6-4: Capital Cost for each technology [63].

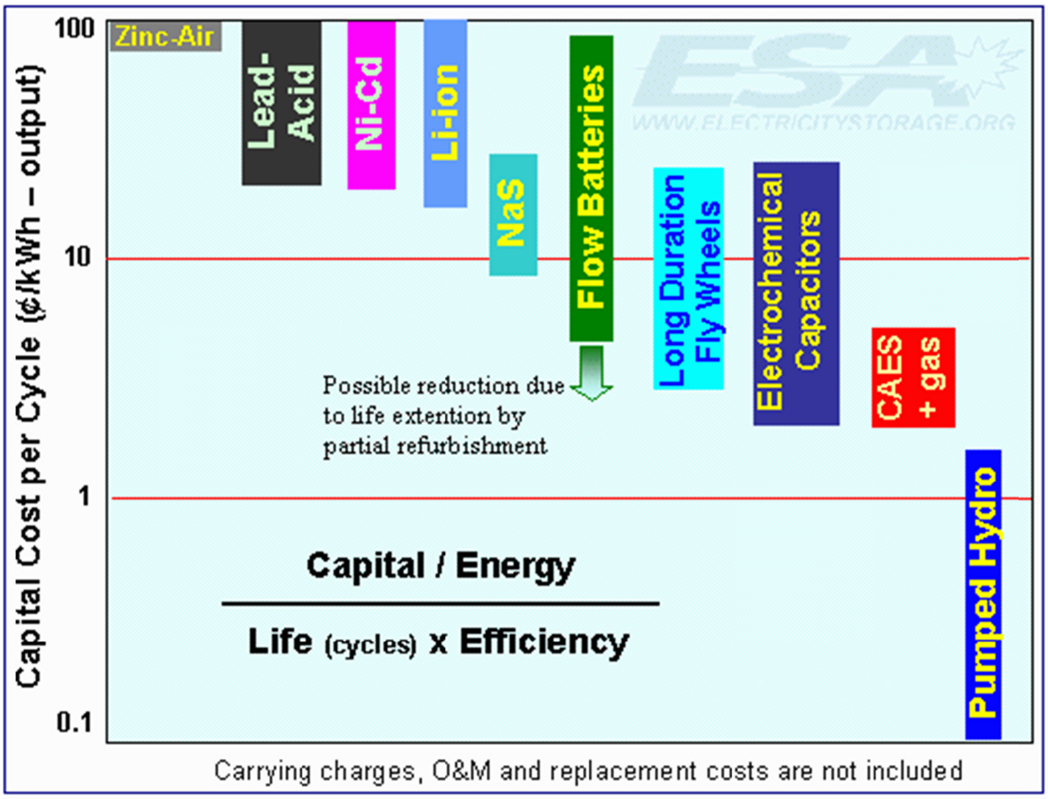


Figure 6-5: Cost per cycle for each technology [63].

Table 6-1: Technical suitability of storage technologies to different applications [2, 30, 64, 65].

	Storage Technology	Pumped hydro	Underground pumped hydro	Compressed air	Lead-acid batteries	Advanced batteries	Flow batteries	Flywheels	Supercapacitors	Superconducting magnetic	Hydrogen fuel cell	Hydrogen engine
Storage Application												
Transit and end-use ride-through					X		X	X	X	X	X	
Uninterruptible power supply					X	X	X	X			X	X
Emergency back-up		X	X	X	X	X	X				X	X
T&D stabilisation and regulation		X	X	X	X		X			X	X	
Load levelling		X	X	X	X	X	X				X	X
Load following		X	X	X	X	X	X				X	X
Peak generation		X	X	X	X	X	X	X			X	X
Fast response spinning reserve		X	X	X	X	X	X	X			X	X
Conventional spinning reserve		X	X	X	X	X	X	X			X	X
Renewable integration		X	X	X	X	X	X	X			X	
Renewables back-up		X	X	X	X	X	X				X	

Table 6-2: Characteristics of storage technologies [2, 8, 18, 47, 63].

Technology	Power rating	Discharge duration	Response time	Efficiency (%)	Parasitic losses	Lifetime	Maturity
Pumped hydro	100 – 4000 MW	4 – 12 h	sec - min	70 - 85	Evaporation	30 – 50 y	Commercial
Underground pumped hydro	100 – 4000 MW	4 – 12 h	sec – min	70 – 85	Evaporation	30 – 50 y	Concept
Compressed air (in reservoirs)	100 – 300 MW	6 – 20 h	sec - min	64	-	30 y	Commercial
Compressed air (in vessels)	50 – 100 MW	1 – 4 h	sec - min	57	-	30 y	Concept
Lead-acid battery	< 50 MW	1 min – 8 h	< ¼ cycle	85	Small	5 – 10 y	Commercial
Nickel-cadmium battery	< 50 MW	1 min – 8 h	n/a	60 – 70	~2 - 5%	3500 cycles	Commercial
Sodium-sulphur battery	< 10 MW	< 8 h	n/a	75 - 86	5 kW/kWh	5 y	In development
Vanadium-redox flow battery	< 3 MW	< 10 h	n/a	70 - 85	n/a	10 y	In test
Polysulphide-bromide flow battery	< 15 MW	< 20 h	n/a	60 - 75	n/a	2000 cycles	In test
Zinc-bromine flow battery	< 1 MW	< 4 h	< ¼ cycle	75*	Small	2000 cycles	In test / commercial units
Low-speed flywheel	< 1650 kW	3 – 120 s	< 1 cycle	90	~1%	20 y	Commercial products
High-speed flywheel	< 750 kW	< 1 h	< 1 cycle	93	~3%	20 y	Prototypes in testing
Supercapacitor	< 100 kW	< 60 s	< ¼ cycle	95	-	10000 cycles	Some commercial products
Superconducting magnetic (Micro)	10 kW – 10 MW	1 – 60 s	< ¼ cycle	95	~4%	30 y	Commercial
Superconducting magnetic	10 – 100 MW	1 – 30 min	< ¼ cycle	95	~1%	30 y	Design concept
Hydrogen (fuel cell)	< 250 kW**	As needed	< ¼ cycle	34 - 40	n/a	10 – 20 y	In test
Hydrogen (engine)	< 2 MW**	As needed	Seconds	29 – 33	n/a	10 – 20 y	Available for demonstration

*AC-AC Efficiency
**Discharge device. An independent charging device (electrolyser) is required.

Table 6-3: Costs of storage technologies [2, 8, 18, 47, 63].

	Capital cost			O&M cost				
Technology	Power related cost ($/kW)	Energy related cost ($/kWh)	BOP ($/kWh)	Fixed ($/kW-y)	Variable (c$/kWh)	Cost certainty	Environmental issues	Safety issues
Pumped hydro	600 - 2000	0 – 20	Included	3.8	0.38	Price list	Reservoir	Exclusion area
Underground pumped hydro	n/a	n/a	n/a	3.8	0.38	Estimate	Reservoir	Exclusion area
Compressed air (in reservoirs)	425 - 480	3 - 10	50	1.42	0.01	Price quotes	Gas emissions	None
Compressed air (in vessels)	517	50	40	3.77	0.27	Estimate	Gas emissions	Pressure vessels
Lead-acid battery	200 - 580	175 - 250	~50	1.55	1	Price list	Lead disposal	Lead disposal, H_2
Nickel-cadmium battery	600 – 1500	500 – 1500	n/a	n/a	n/a	Estimate	Toxic cadmium	Toxic cadmium
Sodium-sulphur battery	259 - 810	245	~40	n/a	n/a	Project specific	Chemical handling	Thermal reaction
Vanadium-redox flow battery	1250 – 1800	175 - 1000	n/a	n/a	n/a	Project specific	Chemical handling	Chemical handling
Polysulphide-bromide flow battery	1000 - 1200	175 - 190	n/a	n/a	n/a	Project specific	Chemical handling	Chemical handling
Zinc-bromine flow battery	640 - 1500	200 - 400	Included	n/a	n/a	Project specific	Chemical handling	Chemical handling
Low-speed flywheel	300	200 - 300	~80			Price list	-	Containment
High-speed flywheel	350	500 - 25000	~1000	7.5	0.4	Project specific	-	Containment
Supercapacitor	300	82000	10000	5.55	0.5	Project specific	-	-
Superconducting magnetic (Micro)	300	72000	~10000	26	2	Price quotes	-	Magnetic field
Superconducting magnetic	300	2000	~1500	8	0.5	Estimate	-	Magnetic field
Hydrogen (fuel cell)	1100 - 2600	2 - 15	n/a	10	1	Price quotes	-	-
Hydrogen (engine)	950 – 1850	2 - 15	n/a	0.7	0.77	Price list	Emissions	-

6.5 Energy storage systems

As energy systems transform from a fossil fuel system based on centralised production, to a renewable energy system, based on intermittent decentralised production, it is imperative that system flexibility is maximised. An ideal option to achieve this is by integrating the three primary sectors within any energy system: the electricity, heat and transport sectors. HESS, TESS, and EV's provide unique opportunities to integrate these three sectors and hence increase the renewable energy penetrations feasible. However, it is difficult to compare HESS, TESS and EV's to the other energy storage technologies directly as energy storage is only part of the system they are composed of.

The HESS provides an excellent level of flexibility within an energy system, by enabling the electricity, heat and transport sectors to interact with one another. However, the primary disadvantage is the poor efficiencies achieved due to the number of conversions required between creating hydrogen and using hydrogen. In contrast, the TESS increases the efficiency of the overall energy system by replacing conventional power plants with CHP. However, TESS does not incorporate the transport sector. As a result, EVs (the third energy system discussed) are often combined with the TESS. This has been analysed in a separate study which compared a HESS and a combined TESS/EV energy system [61, 62]. It was found that the TESS/EV energy system only needs 85% of the fuel that a HESS requires [61, 62]. In addition, the TESS has already been implemented in Denmark and thus is a much more mature solution that a hydrogen economy. However, in the long-term if baseload renewable energy (i.e. biomass) is limited, the inefficiencies of the hydrogen energy system may be an attractive replacement. Therefore, a lot of potential exists but more research is required to truly quantify the benefits and drawbacks of each system.

Finally, it is evident from the research carried out to date that energy storage systems could be a more promising solution for the integration of intermittent renewable energy than individual technologies. Energy storage technologies will most likely improve the penetrations of renewable energy on the electricity network, but often disregard the heat and transport sectors. Consequently, it is imperative that uncertainties surrounding the costs and potential of energy storage systems are investigated, considering the promise they possess relative to the stand-alone technologies.

7 Conclusions

No one technology has all the ideal characteristics required for optimal grid integration of renewables. By looking at the energy storage systems used during island[1] investigations, it becomes apparent that very large storage capacities are necessary to obtain high wind penetrations (>90%). Bakos [66] and Kaldellis [67] concluded that a storage capacity in the region of 1 to 3 days of the electricity grids power requirement is necessary to obtain wind penetrations above 90%. Although larger energy systems will probably require less energy storage than island systems, primarily due to the possibilities of creating additional flexible loads such as electric vehicles or demand side management (DSM), these island case studies indicate that large-scale energy storage capacities will most likely be necessary if energy storage is used for integration fluctuating renewable penetrations.

Pumped hydroelectric energy storage (PHES) is the largest and most mature form of energy storage available. It is widely believed that suitable locations to construct PHES facilities are becoming rare [21-25], which has become the primary weakness for PHES development in recent years. However, as recent reports illustrate that Ireland has many more suitable PHES sites than originally anticipated [26-29], it was concluded from this review that PHES is the most likely stand alone energy storage technology that will be utilised in the coming years for the integration of fluctuating renewable energy.

In addition to PHES, all three energy storage systems discussed in this report warrant further investigate primarily based on their potential to improve renewable energy penetrations in the future. The hydrogen energy storage system (HESS) is evolving rapidly especially in the transport sector. Even if hydrogen is not used to generate electricity, it could still be required in the future for other applications such as heating or transport. Therefore, it is an area that has a lot of future potential even though it can be an inefficient process. The thermal energy storage system (TESS) is not only capable of increasing the wind penetration feasible within an energy system, but it also increases the overall efficiency of the energy system. Even more importantly, this technology has already been proven within the Danish energy system and hence does not carry the same risks as other alternatives. However, the primary drawback of the TESS in comparison to the HESS is the transport sector: TESS does not account for the transport sector. However, this can be overcome by combining the TESS with electric vehicles (EVs). Electric vehicles (EVs) are more efficient than both hydrogen and conventional vehicles. They also have the potential to make large-scale battery energy storage economical and hence vastly improve the flexibility within an energy system. By combining EVs with the TESS, the overall fuel demand can be reduced and fluctuating renewable energy penetrations can be increased. Also, Lund and Mathiesen have shown that this technique can be extended further to create a 100% renewable energy system [57]. As a result, this combination is one of the most promising solutions to in the transition from a fossil fuel to a renewable based energy system.

In relation to the other technologies discussed in this report, BES, FES, SMES, SCES, and ACTES are will most likely be used in some form within the power sector in the future, but major operational breakthroughs are unlikely. FBES is another potential option for the future, but it may not have the scale necessary to co-exist with a successful rollout of EVs. In some countries CAES might be more feasible than PHES for large-scale storage due to the availability of suitable sites. However, due to the number of potential sites currently being identified in Ireland, PHES is the most attractive large-scale energy storage technology for the Irish energy system for the integration of fluctuating renewable energy.

To conclude, from a stand-alone perspective, PHES will most likely be the most attractive option in years to come for Ireland, but it is also imperative that uncertainties surrounding the HESS, TESS, and EVs are also assessed based on the potential flexibility they can also create.

[1]Island energy-systems refers to small-scale stand-alone energy systems where the installed generating-capacities ranging from 1 to 10 MW.

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Appendix B

Connolly D, MacLaughlin S, Leahy M. Development of a computer program to locate potential sites for pumped hydroelectric energy storage. Energy 2010;35(1):375-381.

Energy 35 (2010) 375–381

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Development of a computer program to locate potential sites for pumped hydroelectric energy storage

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ARTICLE INFO

Article history:
Received 17 April 2009
Received in revised form
22 September 2009
Accepted 8 October 2009
Available online 30 October 2009

Keywords:
Pumped Hydro
Pumped Hydroelectric
Energy Storage
Location
Site
Area
Place

ABSTRACT

Pumped hydroelectric energy storage (PHES) is the largest and most mature form of energy storage currently available. However, the capital costs required for PHES are extremely large and the availability of suitable sites is decreasing. Therefore, identifying the remaining sites available for PHES is becoming vital so that the most beneficial location is chosen: in terms of capacity and economics. As a result, the aim of this work is to develop a computer program that will scan a terrain and identify if there are any feasible PHES sites on it. In this paper, a brief description of the program is provided, including the limitations identified during the initial development. Also, the program was used to evaluate a 20 km × 40 km area in the South West of Ireland so the results obtained from this study are discussed. Finally, future improvements to advance the program's capabilities are identified. The program has proven to date that it can identify feasible locations for PHES, however, further investigation is necessary to improve the site selection.

1. Introduction

As intermittent renewable energy becomes more prominent, there is a need for greater flexibility within modern energy-systems. This is due to a number of problems that occur within the electricity sector when large quantities of wind power are introduced [1–8]. These issues include:

1. Grid capacity constraints such as the voltage profile exceeding specified limits and network congestion.
2. Harmonics can be created by the addition of wind on the grid. Also, a wind farm can modify network impedances and thus affect the remote control-signal.
3. Protection issues occur as wind farms can trigger protection equipment on the grid.
4. Dynamic behaviour and stability problems may occur as wind farms could interfere with the grid's dynamic behaviour and consequently, it must be checked under various operating conditions for the wind farm such as start-up, cut-off, wind speed variations, etc.
5. Lack of Ancillary Services: Wind turbines can consume and generate a very limited amount of reactive power, and therefore have limited voltage control. Also, wind turbines have limited frequency control capabilities primarily due to the stochastic behaviour of the wind.

Considering these issues, Weisser and Garcia stated that there should be no technical issues for instantaneous wind penetrations up to 20% on an electric grid [3]. In the future, Lundsager et al. estimates that a maximum wind penetration of 25–50% is feasible within the electricity sector [7]. However, Lundsager et al. also stated that the feasibility of very high wind penetrations decreases dramatically when the size of the electricity grid increases from 100 kW to 10 MW: for a 100 kW grid a wind penetration of 80% is feasible, but for a 10 MW grid a wind penetration of only 20% is feasible [7]. The authors concluded that primary reason for this dramatic reduction in feasible wind penetrations was due to the lack of energy storage on the grid [7].

By looking at the energy storage systems used during island[1] investigations, it becomes apparent that very large storage capacities are necessary to obtain high wind penetrations (>90%). Bakos

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[1] Island energy-systems refers to small-scale stand-alone energy-systems where the installed generating-capacities ranging from 1 to 10 MW.

0360-5442/$ – see front matter
doi:10.1016/j.energy.2009.10.004

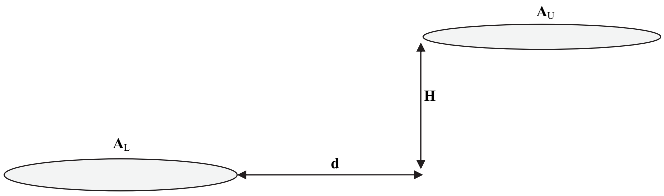

Fig. 1. Area layout investigated by computer program.

[9] and Kaldellis [10] concluded that a storage capacity in the region of 1 – 3 days of the energy-systems power requirement is necessary to obtain wind penetrations above 90%. Although larger energy-systems will probably require less energy storage than island systems, primarily due to the possibilities of creating flexible loads such as electric vehicles or demand side management (DSM), these island case studies indicate that large-scale energy storage will most likely be necessary for large renewable penetrations. Pumped hydroelectric energy storage (PHES) is the largest and most mature form of energy storage available and therefore, it is likely that PHES will become more important within energy-systems as renewable energy penetrations increase.

Although the benefits of PHES are usually recognised, it is widely believed that suitable locations to construct PHES facilities are becoming rare [11]. This has become the primary weakness for PHES development in recent years, as a number of discussions about the advantages of PHES are cut short based on the belief that it is no longer a realistic option. Consequently, the aim of this work is to avoid analysing the benefits of PHES, and to focus on whether or not PHES is still technically a feasible option. In order to answer this question, a program has been created that will scan a terrain specified by the user, and identify the locations available for the construction of PHES.

2. Methodology

As stated above, the objective is to create a program that will search for suitable PHES locations. However, before creating the software to search for PHES locations, suitable terrain data had to be found. 'Digital Terrain Model' (DTM) data files were sourced from Ordinance Survey Ireland (OSI) [12], that provide a regular grid of x, y, and z points, at 10 m intervals for any area in Ireland. For the model development, data representing a 20 km × 40 km area in the South West of Ireland was obtained. This data was imported into Atlas Computers Ltd's Survey Control Centre (SCC) [13] software and processed to form a Delaunay Triangulated Irregular Network model (TIN). A TIN model displays the x, y, and z data as a 3D terrain that can then be analysed using different constraints (TIN modelling and its applications are discussed further in Hjelle [14]).

To search the TIN model that was created by the SCC for pumped hydro facilities, an additional algorithm was written for the SCC to search for suitable PHES sites. This was based on searching the TIN to find adjacent polygonal areas of acceptable flatness, A_U and A_L, with a minimum acceptable vertical separation, H, and a maximum acceptable horizontal separation, *d*, as portrayed in Fig. 1. The program created could only identify regular shaped polygons as the areas for the reservoirs, and hence a circle was chosen.

The upper and lower reservoir areas identified by the program had to be flat. Flatness in this case is specified in terms of the maximum allowable 'cut' and 'fill' excavation volumes, E_U and E_L, which are required to construct a polygon at an arbitrary datum, where the software selects an optimal value for that datum. In other words, the level of flatness required was specified by quantifying the maximum amount of earth that could be moved in order to make the site flat, *E*, as displayed in Fig. 2. The earth that needs to be moved to make the area flat must be obtained within the investigated site i.e. the circular area. There was an E value for the upper reservoir, E_U, and an E value for the lower reservoir, E_L.

Initially, the search was iterated at a specified plan interval, *FR*, in the x and y axes over the entire area being analysed for potential lower reservoir sites. On finding such a site, the border of that site was searched radially for upper reservoir sites over a specified interval, *SR*. Determining 'flatness' required modelling the polygon representing the reservoir area, and vertically searching over a specified interval, *SV*, for an optimal datum where the volumes of cut and fill material to be excavated to construct the reservoir were the same. Thus the parameters required for each search are displayed in Table 1 below.

The principal challenge in implementing the above search was speed. Given the combinatorial complexity of the above parameters, and the amount of data involved, a 'brute force' solution was shown not to give acceptable performance. For example, a test of a 'brute force' search for PHES facilities over a 1 km^2 area took about 4 h to process on a mid-range Windows workstation; thus processing a 20 km × 40 km area would take approximately 20 weeks.

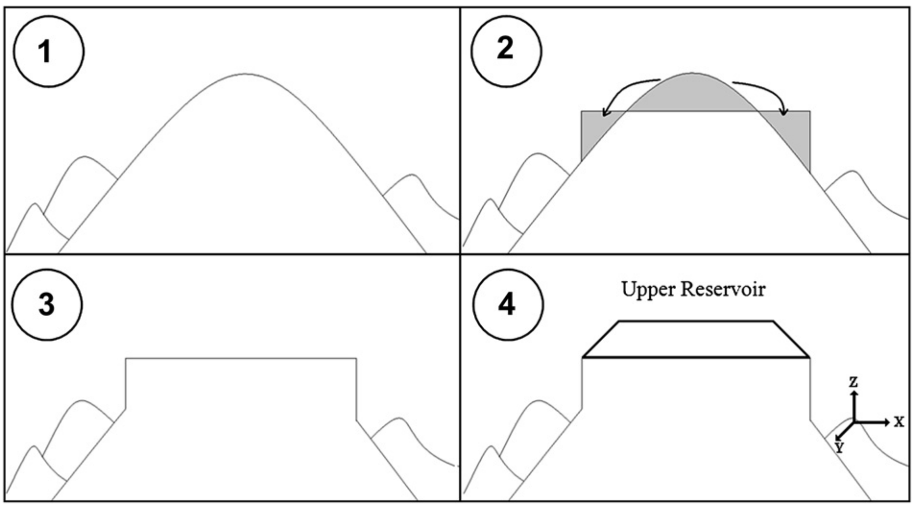

Fig. 2. Earth moving procedure within the program to make the investigated area flat.

Table 1
Parameters used by SCC to identify potential PHES facilities.

Name	Symbol	Unit
Polygon area for upper reservoir	A_U	m^2
Polygon area for lower reservoir	A_L	m^2
Minimum acceptable vertical separation	H	m
Maximum acceptable horizontal separation	d	m
Flatness/maximum excavation volume for upper reservoir	E_U	m^3
Flatness/maximum excavation volume for lower reservoir	E_L	m^3
Grid search interval for lower reservoir	FR	m
Radial search interval for upper reservoir	SR	m
Vertical search tolerance for 'flatness'	SV	m

The solution was optimised to mask out large areas that did not contain the required vertical separation. The TIN model was also optimised to remove all unnecessary points that were co-planar with their nearest neighbours. This yielded a routine that took 6–10 days to process a given scenario on a 20 km $\times$ 40 km area, with variation based on the parameters used and input data provided. The final analysis for a number of scenarios was distributed over a network of 8 Windows XP workstations to further reduce the time required.

It is common practice to describe computational geometry algorithms such as the above using abbreviated C pseudocode. The C pseudocode displayed in Fig. 3 below describes the algorithm used to search for PHES facilities in its un-optimised form. It assumes a library capable of generating and manipulating TIN models. The actual code was written in C++, and it contained a considerable amount of additional optimisation over and above the algorithms shown. Note that detailed algorithms for the TIN model creation, cut and fill balancing, sectioning, and boundary analysis have not been provided as they are beyond the scope of this paper. For a discussion of relevant computational geometry algorithm development techniques, see O'Rourke [15] on the subject.

3. Error analysis

The software package used for TIN surface model generation, SCC, has been benchmarked against a range of similar packages in

```
PHESSearch (TIN, AU, AL, EU, EL, FR, SR, H, d, SV)
{
    // Given TIN, with plan limits TX1 to TX2 and TY1 to TY2
    for (x = TX1; x < TX2;  x += FR)
    {
        for (y=TY1;   y<TY2; y+=FR)
        {
            // place potential upper reservoir of area AU at (x, y)
            UpperReservoir = CreateReservoirModel (AU, x, y);
            // compute balanced cut and fill volume vu, between upper reservoir and TIN
            vu = BalanceCutFill (TIN, UpperReservoir, SV);
            if (vu < EU)
            {
                // Get upper reservoir centre
                Cxy = GetModelCentroid (UpperReservoir)
                // Get perimeter length of upper reservoir
                l = GetModelBoundaryLength (UpperReservoir)
                for (ch = 0;  ch < 1;  ch += SR)
                {
                    // Get point on upper reservoir perimeter at distance ch along perimeter
                    Pxy = DistanceAlongBoundary (UpperReservoir, ch);
                    // Compute a line extending from P in the direction C-P for a distance d
                    b = JoinBearing (Cxy, Pxy);
                    Qxy = PointBearingDistanceFrom (Pxy, b, d);
                    // Cut a section S through the TIN along line from Pxy to Qxy
                    S = CutSectionThroughModel (TIN, Pxy, Qxy);
                    zp = SurfaceHeight (Pxy)
                    // for each point S with level Sz and plan position Sx, y
                    for (sp = GetFirstSectionPoint (S);      sp <= GetLastSectionPoint (S); sp++)
                    {
                        Sz = SectionHeight (S, sp)
                        if (zp – Sz < H)
                        {
                            // place potential lower reservoir of area AL at Sx, y
                            Sxy = GetSectionPoint (S, sp)
                            LowerReservoir = CreateReservoirModel (AL, Sxy)
                            // compute balanced cut and fill volume vl, between lower reservoir and TIN
                            vl = BalanceCutFill (TIN, LowerReservoir, SV)
                            if (vl < EL)
                            {
                                // Positive match found, store details
                                StoreResults (UpperReservoir, LowerReservoir, Pxy, Sxy)
                            }
                        }
                    }
                }
            }
        }
    }
}
```

Fig. 3. C pseudocode used to search for PHES facilities in its un-optimised form.

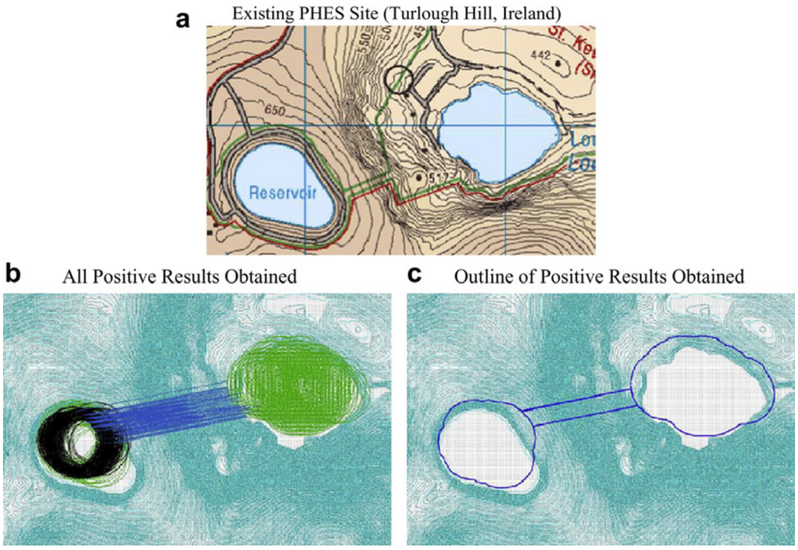

Fig. 4. Results obtained (b, c) when the program was tested on an existing PHES facility: Turlough Hill in Ireland (a).

use in industry on a number of occasions, and has been shown to be in good agreement. It is also used by Ordnance Survey Ireland to generate national DTMs for the Republic of Ireland [12]. Therefore, the ability of the TIN model to accurately analyse 3D terrains has been verified prior to this study.

In order to verify the PHES algorithm above worked as designed, a series of test cases were created that comprised of artificially generated terrain data. Boundary value analysis [16] was employed to produce a suitable set of test cases. These test terrains were generated containing locations where all search criteria were met, to ensure the search worked as anticipated. Subsequently, additional test cases where all but one of the search criteria were met, were also created in order to ensure that the algorithm did not produce any false positives. Multiple versions of each test case were generated at either side of the boundaries of each parameter under test, to verify the search tolerances were working correctly. Once testing was completed using artificial data, the software was then tested using an existing PHES site, Turlough Hill (see Fig. 4a). As displayed in Fig. 4b, the program identified numerous positive results at this site indicating that the program is functioning correctly. In addition, the results could be combined with one another, which is displayed in Fig. 4c, to create an accurate representation of the maximum potential reservoir that could be constructed at that site. Due to the results obtained during testing, it was concluded that the program was operating correctly and hence the investigation for new PHES sites proceeded.

4. Results

To search for new potential PHES sites, an initial analysis was carried out on a 20 km × 40 km area in Ireland which is illustrated in Fig. 5. The region analysed was limited due to the costs associated with purchasing the required data files, and the cost of processing time for completing the analysis. However, the region in question provided a good indication of the results that can be achieved when analysing any terrain using the software.

4.1. First analysis

For the initial analysis, parameters specified in Table 2 were used by the program. These parameters were chosen for the first analysis as they are similar to those found at Ireland's only existing PHES facility, Turlough Hill [17]. Using these parameters, a single potential PHES site was identified which is illustrated in Fig. 6.

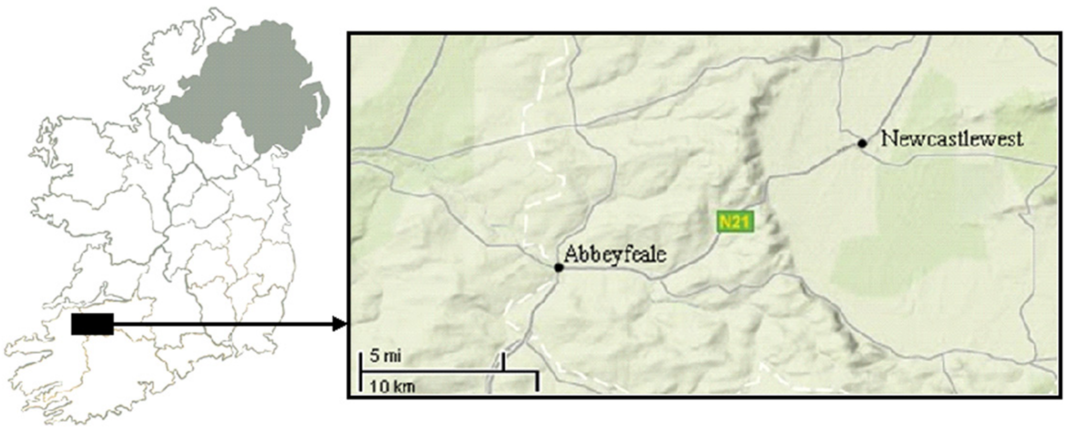

Fig. 5. Area analysed in Ireland for the investigation in this paper.

Table 2
Parameters used for the first analysis.

Name	Symbol	Value	Unit
Area of the upper reservoir	A_U	120,000	m^2
Area of the lower reservoir	A_L	120,000	m^2
Height between reservoirs	H	200	m
Horizontal distance between areas	d	1,000	m
Flatness/maximum earth moved to make upper reservoir flat	E_U	300,000	m^3
Flatness/maximum earth moved to make lower reservoir flat	E_L	300,000	m^3
Grid search interval for lower reservoir	FR	50	m
Radial search interval for upper reservoir	SR	10	m
Vertical search tolerance for 'flatness'	SV	0.5	m

4.2. Second analysis

Following the first analysis, a second study was carried out using the parameters displayed in Table 3. The head (H) was reduced from 200 m to 150 m and therefore, the area of the upper reservoir was increased (A_U) along with the volume of earth that could be moved to construct it (E_U). The ensured that a similar storage capacity could be obtained as in analysis one, even with a smaller head of 150 m. These parameters were used to identify how dependent new PHES sites were on finding a site with sufficient vertical head. With these parameters, the model identified four more potential PHES sites which are illustrated in Fig. 7.

4.3. Third analysis

The third and final analysis was completed using the parameters displayed in Table 4. The reservoir areas (A_U, A_L) were reduced along with the area of earth that could be moved to construct them (E_U, E_L), but the head (H) was increased back to 200 m. These parameters were used to analyse how constraining the reservoir area was in relation to locating new PHES sites. However, using these parameters the model returned no results.

5. Data manipulation

This section indicates how the results obtained from the program, can be manipulated to identify the capacities of the PHES facilities that were found by the program. The variables required to convert the results into capacities are displayed in Table 5.

The parameters used can be converted to power and storage capacities using the following steps. The power capacity, *P*, can be found in watts using

$$P = \rho g H Q \eta \quad (1)$$

where ρ is the density of water, g is acceleration due to gravity, *H* is the head, *Q* is the volumetric flow rate and η is the efficiency of the pump/turbine unit. The flow rate is dependent on the size of the turbine and penstock. Typically, a flow rate of approximately 75 m3/s and a pipe length ranging from a 500 m to 10,000 m can be used when building a PHES facility (see Table 6 [18]), but these are very site specific. The storage capacity, S, can be found in watt-hours (Wh) from

$$S = \frac{\rho g H V \eta}{3600} \quad (2)$$

where *V* is the volume of water available in the upper reservoir. The reservoir volume is not specified by the software but it can be calculated as follows: The program assumes that reservoirs can be constructed at the sites identified once the area is flat. To do this, a reservoir wall must be constructed similar to the one displayed in Fig. 8 [19]. The height of the reservoir wall is not specified by the program, as the software only tries to identify the flat areas required for the base of the PHES reservoirs. However, existing

Table 3
Parameters used for the second analysis.

Name	Symbol	Value	Unit
Area of the upper reservoir	A_U	180,000	m^2
Area of the lower reservoir	A_L	120,000	m^2
Height between reservoirs	H	150	m
Horizontal distance between areas	d	1,000	m
Flatness/maximum earth moved to make upper reservoir flat	E_U	400,000	m^3
Flatness/maximum earth moved to make lower reservoir flat	E_L	300,000	m^3
Grid search interval for lower reservoir	FR	50	m
Radial search interval for upper reservoir	SR	10	m
Vertical search tolerance for 'flatness'	SV	0.5	m

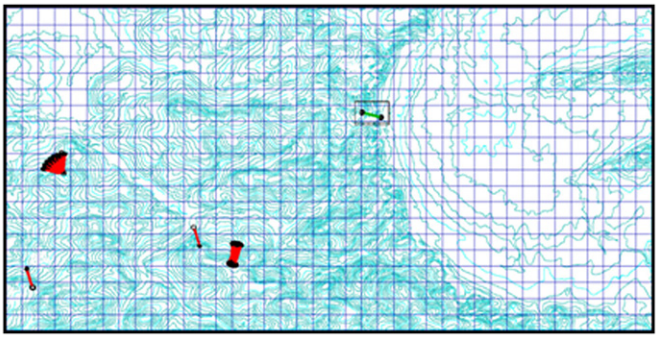

Fig. 7. Potential PHES sites identified after the second analysis (red) using the parameters displayed in Table 3.

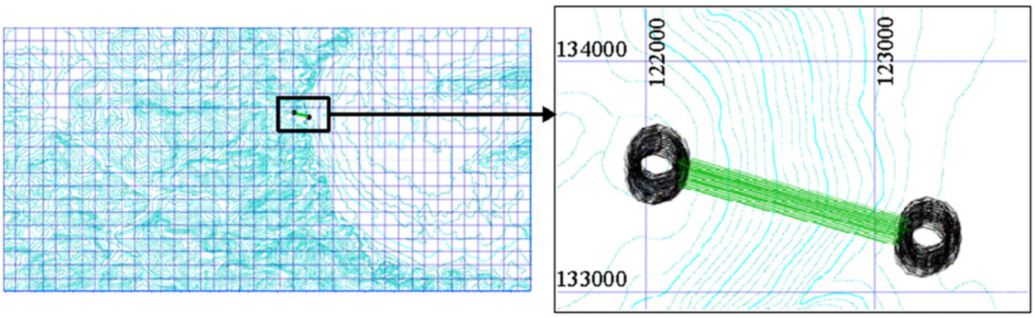

Fig. 6. Results obtained from the first analysis using the parameters displayed in Table 2.

Table 4
Parameters used for the third analysis.

Name	Symbol	Value	Unit
Area of the upper reservoir	A_U	70,000	m^2
Area of the lower reservoir	A_L	70,000	m^2
Height between reservoirs	H	200	m
Horizontal distance between areas	d	1,000	m
Flatness/maximum earth moved to make upper reservoir flat	E_U	200,000	m^3
Flatness/maximum earth moved to make lower reservoir flat	E_L	200,000	m^3
Grid search interval for lower reservoir	FR	40	m
Radial search interval for upper reservoir	SR	10	m
Vertical search tolerance for 'flatness'	SV	0.5	m

Table 5
Variables used for converting the program parameters into energy capacities.

Variable	Symbol	Value	Unit
Reservoir area	A	–	m^2
Head	H	–	m
Power Capacity	P	–	W
Volumetric flow rate through pump/turbine unit	Q	–	m^3/s
Reservoir wall height	R_H	–	m
Volume of water that can be utilised	V	–	m^3
Storage capacity	S	–	Wh
Acceleration due to gravity	g	9.81	m/s^2
Density of water	ρ	1,000	kg/m^3
Efficiency of pump/turbine unit	η	–	–

man-made reservoirs have been constructed in excess of 20 m. For example, Coo-Trois-Ponts PHES in Belgium has a reservoir wall that is 47 m high, Revin PHES in France has a reservoir that is 20 m high, and Turlough Hill PHES in Ireland has a reservoir that reaches heights up to 30 m. Therefore, the reservoir volume, *V*, can be calculated using the reservoir area, *A*, and the assumed reservoir wall height, R_H from

$$V = AR_H \quad (3)$$

Therefore, using Eq. 1 and Eq. 2, it is possible to convert the parameters used by the program into power and storage capacities.

For a number of the variables discussed above assumptions had to be made in the calculations. For the purposes of this initial investigation, all sites were analysed using the same efficiency and flow rate that exists at Ireland's only PHES facility, Turlough Hill. The average annual round-trip efficiency of Turlough Hill in 2007 was 63.9% [20], so a pump efficiency of 80% and a turbine efficiency of 80% were assumed. The flow rate at Turlough Hill is 113 m^3/s with a penstock diameter of 4.8 m [17]. Also, the upper reservoir at Turlough Hill was constructed at a maximum reservoir wall height of 30 m. Therefore, it is assumed during this study that the reservoirs can be constructed with a 30 m height also. This is a key parameter within the program as it defines the volume of water,

Fig. 8. PHES upper reservoir (of Taum Sauk PHES in the USA) with a man-made reservoir wall [19].

and hence the storage capacity available (see Eq. 2 and Eq. 3) at the sites identified. Two primary assumptions were made when converting program parameters into energy capacities:

1. The flat reservoir areas identified by the program are circular. It is assumed that any areas identified are unlikely to be a perfect circle. Therefore, it is likely that this circle can be extended into an irregular shape to take advantage of a greater area than the one identified by the program, as displayed in Fig. 4. As a result, it is assumed that the space required to build a 30 m reservoir wall will be available, while maintaining the area found by the program for the reservoir base, i.e. A_U or A_L.
2. Turlough Hill was constructed 40 years ago. Therefore, modern construction techniques should be capable of building reservoirs, penstocks, and pump/turbine units to at least the equivalent specifications today. This is a conservative assumption and hence, ensures that the calculations are not over optimistic.

6. Discussion

The first analysis identified a PHES site with a head of 200 m and a reservoir area of 120,000 m^2. Therefore, assuming a 30 m reservoir wall height, using Eq.3 the reservoir volume, *V*, feasible at this location is 3,600,000 m^3. The flow rate, *Q*, was assumed to be 113.2 m^3/s and the efficiency, η, to be 80% based on the flow rate and efficiency at Ireland's only existing PHES facility, Turlough Hill (which has 4 pump/turbine units each with a flow rate of 23.4 m^3/s). Considering these parameters and using Eq.1 and Eq.2, a facility built at the location identified by the algorithm would have a power capacity of 178 MW and a storage capacity of 1570 MWh. Therefore, the facility would take almost 9 h to completely discharge at full output.

The four PHES sites found during the second analysis had a lower head than the first investigation of 150 m, but a larger reservoir area of 180,000 m^2. These sites would enable PHES

Table 6
Various parameters for existing pumped hydroelectric energy storage (PHES) facilities [18].

PHES Plant	Country	Power Capacity (MW)	Storage Capacity (MWh)	Pipe Length (m)	Minimum Head (m)	Maximum Head (m)	Generating Flow Rate (m^3/s)	Pumping Flow Rate (m^3/s)
Yagisawa	Japan	240	1368	483	53	112.5	83.2	77.3
Revin	France	760	3600	969	211.2	242.4	70	55
Shin-Takasegawa	Japan	1280	8832	2792	202.7	264.4	155.5	100.6
Mingtan	Taiwan	1600	10720	4443	340.5	410.8	77.4	57

Table 7
Capacity of all PHES facilities identified during the analysis.

Option	Power Capacity (MW)	Total Power Capacity (MW)	Storage Capacity (MWh)	Total Storage Capacity (MWh)
1	178 + 4*133	710	1,570 + 4*1,766	8,634
2	179 + 4*200	979	1,570 + 4*1,766	8,634

facilities with a power capacity of 133 MW and a storage capacity of 1766 MWh, again assuming the same reservoir wall height, flow rate, and efficiency as before. However, this would mean that the PHES facility would take 13 h to discharge. Therefore, it is likely that these facilities would be designed with a larger flow rate. Considering this, a second option was analysed: by increasing the flow rate from 113.2 m^3/s to 169.8 m^3/s, the power capacity becomes 200 MW, and the discharge time is reduced to 8.8 h. The flow rate of 169.8 m^3/s would require 6 of the pump/turbine units which are currently used at the Turlough Hill PHES facility in Ireland.

In summary, from the first and second analysis, a total potential PHES power capacity of 710 MW to 979 MW, and storage capacity of 8634 MWh has been identified as shown in Table 7. It is worth noting at this point, that the area analysed was only 800 km^2, which is approximately 1% of the total island of Ireland [21,22]. Consequently, it is anticipated that numerous other potential locations could exist on the island.

The third and final analysis was carried out using a smaller reservoir area, but also less material could be moved in order to make the reservoirs flat. As there were no results from this analysis, it was concluded that sufficiently flat areas with a large head between them are difficult to locate without moving large amounts of earth.

7. Conclusions

In this paper a computer program has been developed that is capable of identifying potential PHES sites. The program is capable of identifying sites that may otherwise go unnoticed, as it can identify sites after the earth has been modified. As a result, from the initial investigation carried out, five potential sites have been located in an 800 km^2 area of Ireland, which have a cumulative estimated power capacity of 710 MW to 979 MW and a storage capacity of 8634 MWh. This is much larger than originally expected, especially when a number of the parameters used (such as the round-trip efficiency) are quiet conservative. Therefore, it can be concluded that the program is a positive first step for identifying new PHES facilities, but future improvements will enhance its abilities even more. Finally, it is evident from the initial results that the program developed in this study could greatly improve the worldwide potential of PHES in the future, as the program can be used to analyse any user-specified terrain.

8. Future work

In this study a program has been developed to search for new PHES facilities, but a number of additions could be made to improve the functionality of this program. Faster processing times could be achieved by avoiding residential or protected areas when searching for potential sites and by preventing the program from searching for sites on top of one another. Also, the program could be improved by adding a costs tool and utilising existing terrain more effectively, i.e. by using existing geological formations as reservoir walls. However, apart from improving the software created in this study, another important aspect that must be investigated are the benefits of building PHES once suitable locations are found i.e. does it enable larger renewable energy penetrations, improve the operation of power plants, reduce energy costs, etc.? Therefore, future work will also address this issue by simulating additional PHES on the Irish energy-system.

Acknowledgement

The findings in this article result from a research project at the University of Limerick, which has been supported financially by the Irish Research Council for Science, Engineering & Technology (IRCSET).

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Appendix C

Connolly D, MacLaughlin S. The Potential for Freshwater Pumped Hydroelectric Energy Storage in County Clare. Limerick Clare Energy Agency, 2010.

The Potential for Freshwater Pumped Hydroelectric Energy Storage in County Clare

August 2010

Report Researched & Written by : The University of Limerick & Atlas Computers Ltd.	Commissioned by : LCEA
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Executive Summary

This report was commissioned by the Limerick Clare Energy Agency. The objectives of the report are to:

1. Identify and quantify the characteristics of potential sites in County Clare for Pumped Hydro Electric Storage (PHES) utilising fresh water resources that may support the development of renewable electricity generation in County Clare.
2. Identify the location of potential candidate sites for PHES based on the criteria and parameters identified in this brief.
3. Estimate the power generation (MW) and storage (MWh) capacity of the most suitable site(s).
4. Estimate in general terms the typical capital costs and time scales associated with the most suitable site(s).

This report does not address itself to a detailed feasibility study of any particular site. Potential sites for fresh water Pumped Hydro Electric Storage (PHES) were identified using search criterion based upon the present parameters for commercially viable PHES, internationally. Using these parameters the research sought to identify locations where such sites are physically possible.

The method of identifying potential sites search was to utilise an innovative computer programme developed by Shane MacLaughlin of Atlas Computers Ltd. and David Connolly from the University of Limerick. The computer programme utilises Digital Elevation Model tiles from Ordnance Survey Ireland to create a 3D model of the search areas. For this study, the search areas were identified using the County Clare Wind Energy Strategy reference areas:

1. Strategic Areas; 9,150.00 ha approximately.
2. Acceptable in Principle; 38,465.50 ha approximately.
3. Open to consideration; 205,095.5 ha approximately.

Although areas defined as “Not Normally Permissible” were included in the search, any results within this area were deemed unacceptable. When completing the search, there was also a range of technical criteria used to identify a potential site. The most significant of these were a minimum vertical separation between the reservoirs of 200 m and a maximum horizontal separation between them of 3 km. Upon completion of the search, the following key conclusions could be made:

1. County Clare has 14 distinct locations to construct freshwater PHES facilities with a head of at least 200 m: 5 are within excluded areas, 1 used the River Shannon as a lower reservoir[1], 7 are partially within areas open to consideration and partially within the areas of strategic interest (or at least acceptable in principal), and 1 is located entirely within the area of strategic interest.
2. After applying the criteria specified in this study, there were 8 potential locations that could be used to build PHES in County Clare. Many of these locations contain numerous upper and lower reservoirs. Therefore, there are many more potential sites at each of these locations that could be chosen depending on their suitability.
3. Due to the large variety of potential sites available, an "Energy Storage Capacity and Cost Calculator" was developed during this study to extract the size and cost of the energy storage sites indentified. This will enable the Local Authority in County Clare to translate any of the results from the search into energy storage capacities and costs when relevant in the future.
4. The cost and capacity of three unique sites were evaluated here to assess the typical range of PHES sites available in County Clare. Based on typical parameters that are found at existing PHES facilities, the results indicate that the PHES sites analysed had very large storage capacities compared to their power capacities. Hence, the PHES facilities in County Clare will most likely be limited by their power capacity and not by their storage capacities[2].
5. Also, after evaluating the three unique sites identified, it became apparent that up to 570 MW of PHES is possible at one of these locations, while up to 405 MW and 340 MW is available at the remaining two. Considering Turlough Hill has a power capacity of 292 MW, these are significantly large facilities for Ireland. Therefore, as the power capacity is the limiting factor at the PHES facilities found, this indicates that County Clare has a significant freshwater PHES resource.
6. Finally, the total annual investment costs for these three sites were calculated. Results indicate that a freshwater PHES facility in County Clare would cost approximately 20-30 M€/year for a power capacity of approximately 300-600 MW respectively, which corresponds to a total investment over the lifetime of the facilities of 230-390 M€. However, it should be stressed that these costs are very sensitive to site-specific construction costs and also the cost of borrowing for the initial investment.

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[1] The site which used the River Shannon as a lower reservoir was excluded in the results as it is not a freshwater facility.

[2] Where economical viable, power capacities can be increased by constructing additional penstock connections between the upper and lower reservoirs, but this is site specific.

1 Introduction

This report has been prepared for the Limerick-Clare Energy Agency (LCEA) [1]. The LCEA was established in 2005 with equal investment from Limerick County Council and Clare County Council. The agency is also fortunate to enjoy the support of LEADER groups in Clare, West-Limerick and Ballyhoura; in addition to The University of Limerick and Aerobord Ltd.

The LCEA aims to provide energy solutions for sustainable development in the region. The agency will provide energy services to all economic sectors and the general public, promoting and facilitating efficiency and sustainability in the production and consumption of energy. The top ten areas of interest for the agency are:

1. Promote Public Awareness of Energy & Climate Change Issues
2. Evaluate Energy Consumption in Clare & Limerick.
3. Evaluate Energy related emissions for Clare & Limerick
4. Develop a Energy & emissions balance for Clare & limerick
5. Support & Develop Renewable Energy Production, Distribution & Training Programmes.
6. Energy Audits & Benchmarking of Public buildings and facilities in Clare & Limerick.
7. Promote Cooperation and links to community groups (LEADER etc.)
8. Promote Research & Development Partnerships with Third Level Education Bodies.
9. Promote Energy Efficiency and environmental awareness to all commercial energy consumers.
10. Promote the establishment of Low Carbon Commerce.

Large-scale renewable electricity generation is dominated at present by wind turbines as it provides clean and renewable energy. However, by its very nature this source is intermittent. Wind energy generation can also be asynchronous to demand, especially at night. These technical difficulties can be resolved by placing some form of “buffer storage” between the generation and demand cycles. For example, Figure 1 illustrates a hypothetical scenario in Ireland, when wind power exceeds electricity demand. Without energy storage or some other form of energy flexibility, this would simply be lost.

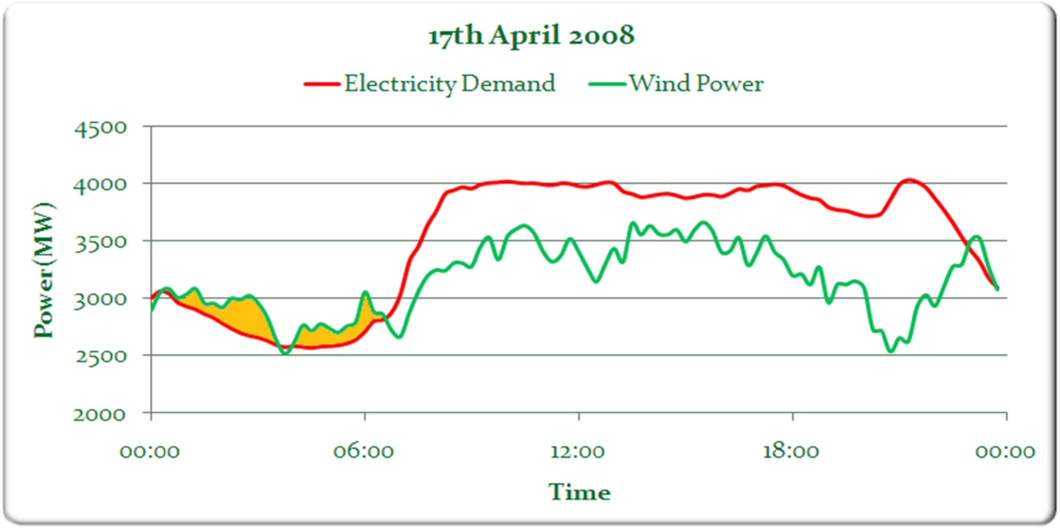

Figure 1: Extrapolated (x6) wind power output and the actual electricity demand in Ireland on the 17th April 2008 [2].

However, as outlined in Figure 2, if there was sufficient energy storage in Ireland, this excess wind power could be stored and used later in the day when there is not enough wind to supply demand. Hence, additional energy storage can lead to increased penetrations of fluctuating renewable energy such as wind power.

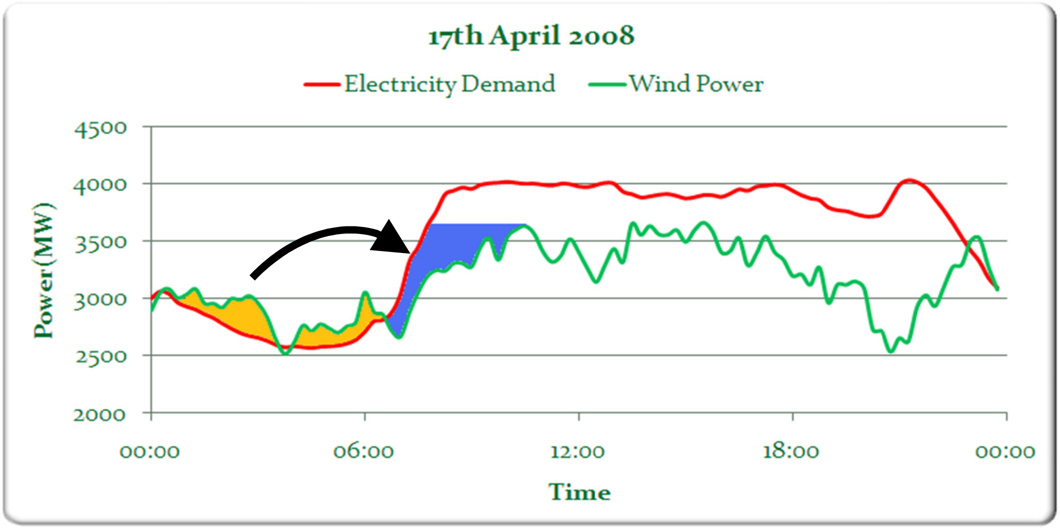

Figure 2: Extrapolated (x6) wind power output with energy storage and the actual ellectricity demand in Ireland on the 17th April 2008 [2].

2 Pumped hydroelectric energy storage

Pumped Hydroelectric Energy Storage (PHES) is the largest and most mature form of energy storage available in the world, with over 90 GW installed in approximately 240 facilities, which is approximately 3% of the world's electricity generating capacity. A typical PHES facility is illustrated in Figure 3. However, although PHES is a well established technology, it is widely believed that suitable locations to construct new facilities are limited. The electricity generation capacity of PHES will be dependent upon the:

1. Topographical & geological characteristics of the facility's location.
2. Availability of a naturally occurring water storage such as a lake or river.
3. Proximity of the facility to an adequate electricity grid.
4. Difference in height between the upper and lower water reservoirs (commonly known as the head).
5. Volume of water exchangeable between the two reservoirs.

Hence, the potential for PHES is usually not dependent on technological development or the awareness of its benefits, but on the ability to find a potential site, which provides the desired capacities at an affordable price. This signifies the importance of this study, which will search County Clare to identify if there are appropriate PHES sites available.

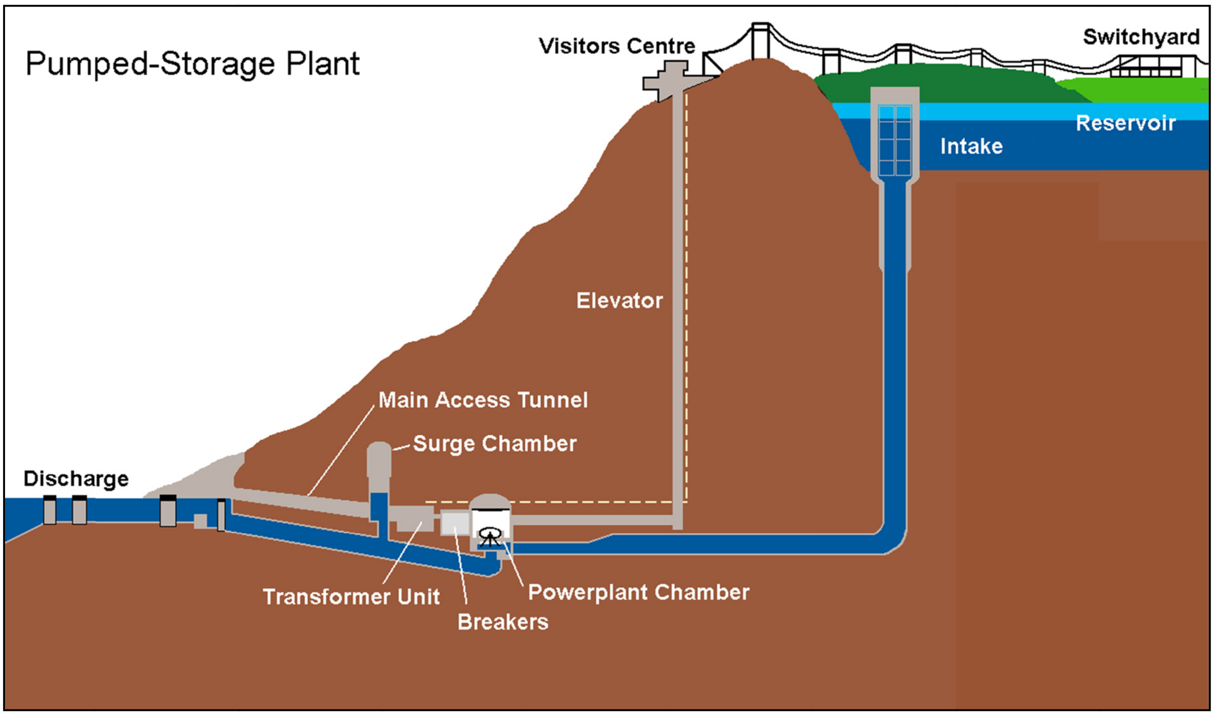

Figure 3: Layout of a pumped hydroelectric energy storage facility.

3 Objectives

The LCEA has commissioned this research project to address the following aims:

1. Identify and quantify the characteristics of potential sites in County Clare for PHES utilising fresh water resources that may support the development of renewable electricity generation in County Clare.
2. Identify the location of potential candidate sites for PHES based on the criteria and parameters identified in this brief.
3. Estimate the power generation (MW) and storage (MWh) capacity of the most suitable site(s).
4. Estimate in general terms the typical capital costs and time scales associated with the most suitable site(s).

It is proposed that suitable sites for PHES are identified with the aid of a computer programme, such as that developed by Shane MacLaughlin of Atlas Computers Ltd. & David Connolly from the University of Limerick. The computer programme will use Ordnance Survey Digital Elevation Model (DEM) tiles, each tile containing approximately 4 million points covering a 20 km x 20 km area. The search will acknowledge the Strategic Wind Farm Development Areas contained in the Clare Wind Energy Strategy 2009-2011. Therefore, the analysis will be carried out in the following order of preference by area (see Figure 4):

1. Strategic Areas (Blue): 9,150.00 ha, approximately.
2. Acceptable in Principle (Green): 38,465.50 ha, approximately.
3. Open to Consideration (White): 205,095.50 ha, approximately.

Although areas defined as "Not Normally Permissible (Red)" were included in the search, any results within this area were deemed unacceptable.

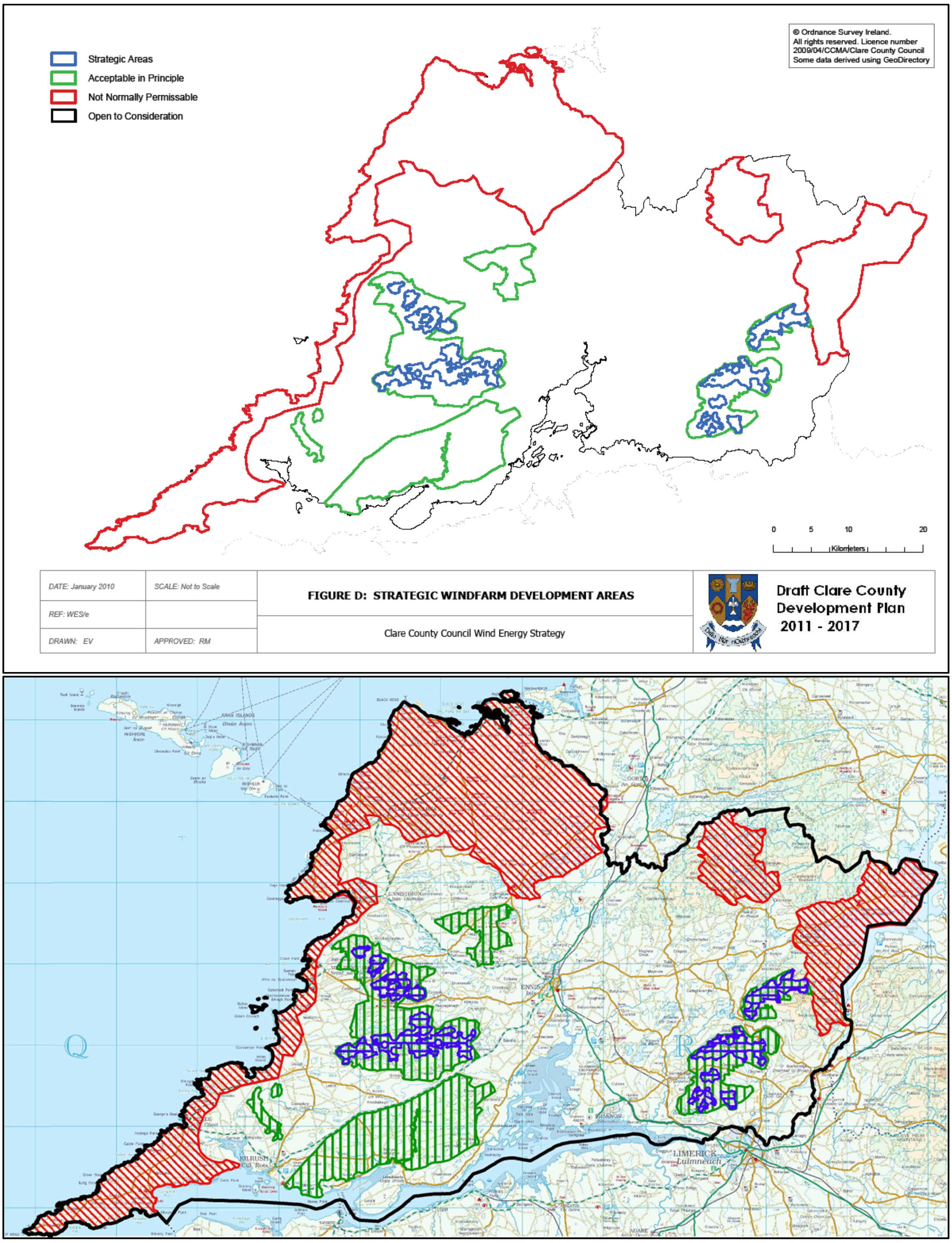

Figure 4: Division of County Clare for the PHES search.

4 Search Criteria

The initial search criteria were chosen based upon similar parameters used in the development of the software model [3]. These reflect typical parameters found within existing PHES facilities already constructed around the world [4]. The base 3D elevation data used for the modelling were Ordnance Survey of Ireland “20 km x 20 km x 10 m DEM tiles” for the Clare region. A detailed list of the search criteria used by the software to search County Clare for PHES sites is provided in Table 1. In order to locate potential reservoir sites that were shaped liked irregular polygons, initial searching was carried out using circles of 100 m in radius, and where multiple adjacent sites were found these were combined. After being combined, if the multiple adjacent sites did not meet the area criteria specified in Table 1, then they were discarded.

Table 1: Search criteria specified to identify potential locations for Pumped Hydroelectric Energy Storage.

Element	Symbol	Value	Unit
Area (minimum) of upper reservoir	A_U	120,000	m^2
Area (minimum) of lower reservoir	A_L	120,000	m^2
Height (minimum) between reservoirs	H	200	m
Distance (horizontal) between reservoirs	d	3,000	m
Flatness at upper reservoir (maximum earth to be moved to make a flat base)	E_U	500,000	m^3
Flatness at lower reservoir (maximum earth to be moved to make a flat base)	E_L	500,000	m^3
Vertical search tolerance for “flatness”	SV	00.50	m
Radial search interval for upper reservoir	SR	3.00	m
Grid search interval for lower reservoir	FR	50.00	m

5 Results

The search found 8 potential locations for the construction of PHES. Firstly, a range of potential locations were defined by collating a large number of positive results after the initial search, which looked for circular reservoirs with 100 m radii. All of these initial results are provided in raw format as a comma separated text file called “**PHES_COLLATED_RESULTS.CSV**” (size 37 MB), which includes coordinates for reservoir centres, height differences, horizontal distances, and volumes. In addition, the initial results are available in a Crystal Reports file, which enables easier analysis based on vertical separation, horizontal separation, and volumes. For example, in Figure 5 below, results are restricted to a vertical separation of at least 250 m, a horizontal separation of less than 2.5 km, and a total cut and fill volume of less than 250,000 m^3 per 100 m radius area under analysis. Crystal reports may also be used to sort the data in a preferred order (i.e. the results can be sorted in descending order of vertical separation) and to export data to other packages and formats. The populated Crystal Report file provided with this report is called “**PHESResults.rpt**” and is approx 10 MB in size. A free crystal reports viewer may be downloaded from [5].

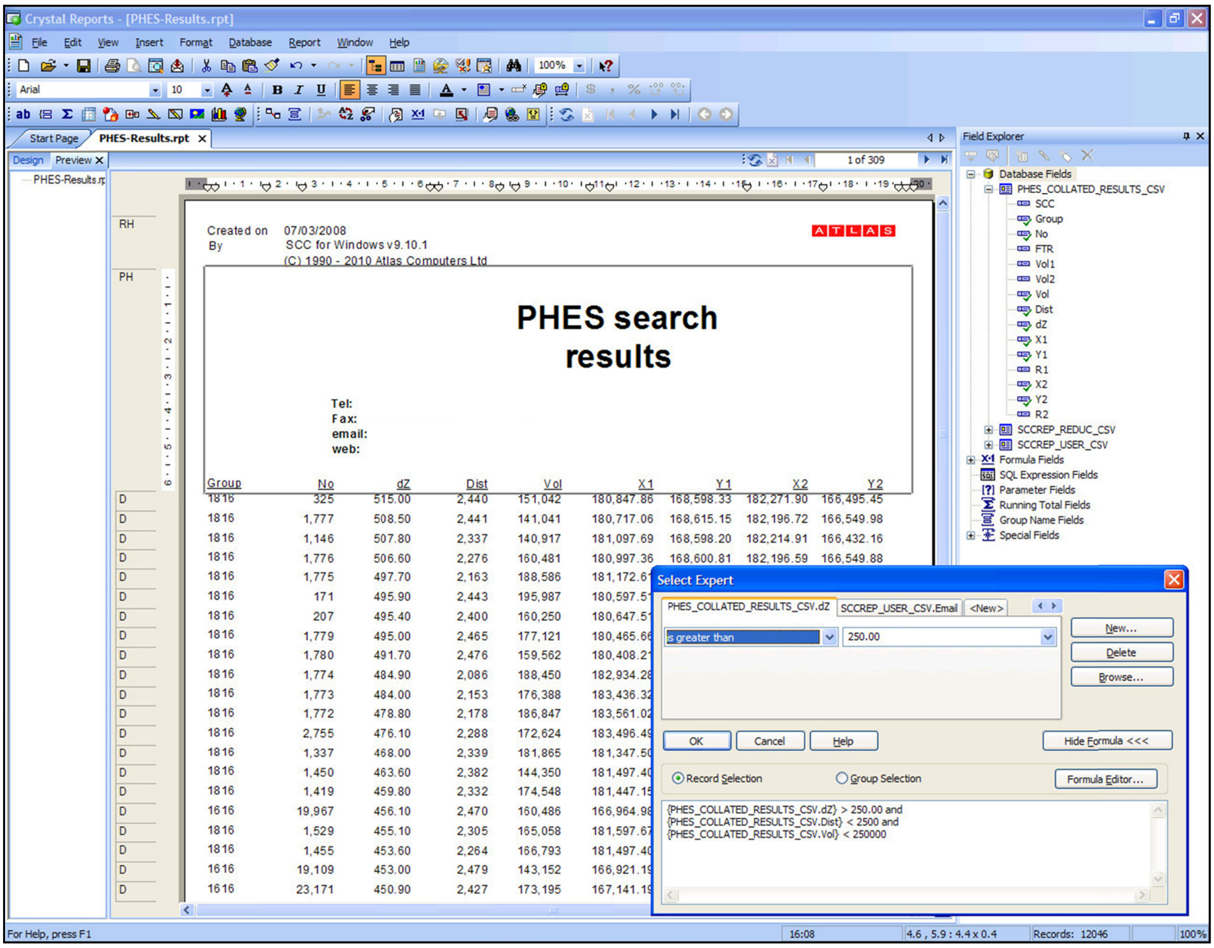

Figure 5: Illustration of results when portrayed in crystal report (.rpt) format.

Using this methodology, the initial results were refined using the criteria specified in Table 1. The site which used the river Shannon as a lower reservoir was also excluded as this is not a freshwater facility. As a result, there are a total of 8 potential PHES locations within County Clare, which are outlined in Figure 6. However, it should be noted that a range of different upper and lower reservoir combinations could be chosen at these sites. It is envisaged by the authors that the combination of reservoirs at each specific location could be defined by completing a more detailed analysis of each location, which is beyond the scope of this study. Therefore, although only 8 locations have been identified in this search, there is a wide range of potential PHES facilities that could be constructed, primarily due to the large variety of reservoir locations found at each location.

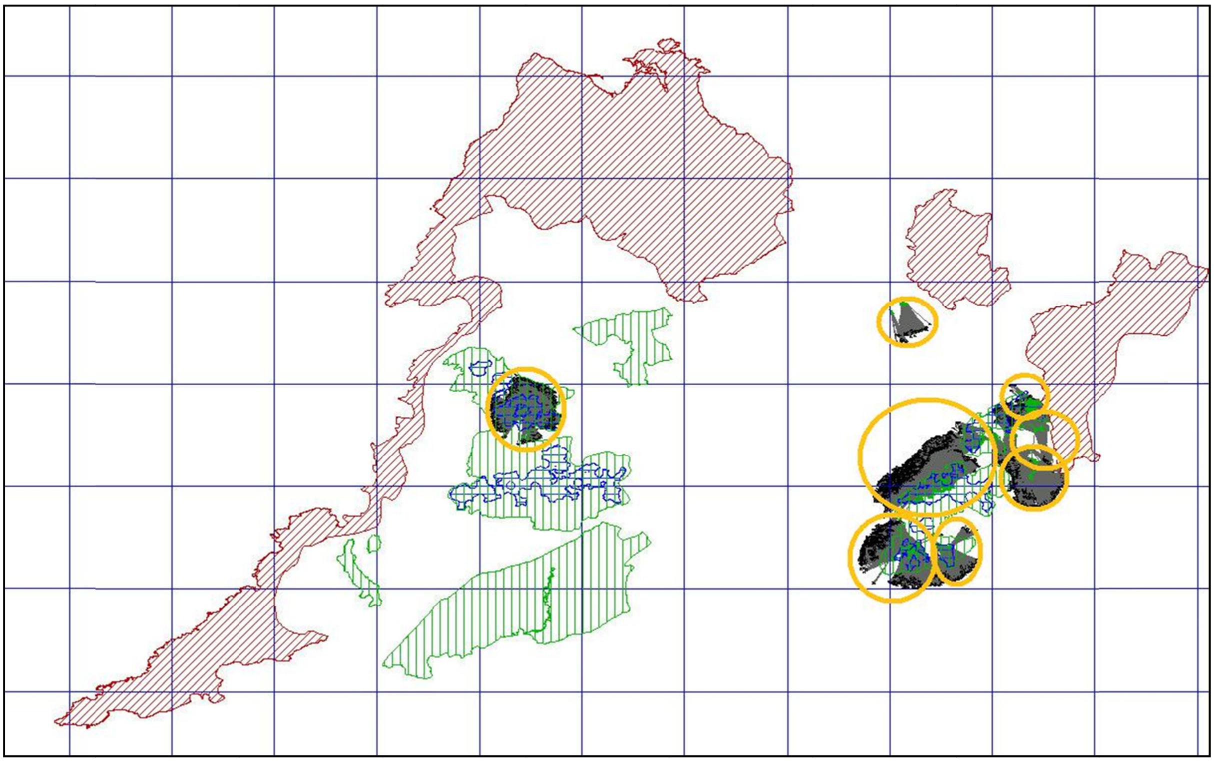

Figure 6: Potential PHES sites (orange cicrcles) found within acceptable areas of County Clare.

Due to the large quantity of sites identified during this analysis, it is difficult to identify any specific site which would be the most attractive to the Local Authority in the future. Consequently, to enable the Local Authority to analyse each site as required in the future, an "**Energy Storage Capacity & Cost Calculator**" was developed. This enables the Local Authority to independently translate the head and reservoir area parameters identified in the search into energy storage capacities and costs, when required in the future. A more detailed explanation of the calculator is provided in the Appendix, while a copy of the calculator has been provided with this report called "**Energy Storage Capacity & Cost Calculator.xlsx**".

Only sites with unique criteria were identified and evaluated here using the calculator. These will illustrate the type of sites which are available in County Clare. Firstly, the initial sites were limited to sites with a head greater than 250 m. As outlined in Figure 7, this reduced the number of potential locations to 5. Then, three unique sites were chosen for further analysis. The site chosen in Area 1 of Figure 7 is the only site which was entirely included in the area of strategic interest and will be called "TotalArea". The site in Area 2 has the largest reservoir area found and will be called "BigReservoir". Finally, the site in Area 3 has the largest vertical head identified and will be referred to as "BigHead". Below is a more detailed assessment of the capacity and cost of energy storage facilities at these sites using the "Energy Storage Capacity & Cost Calculator.xlsx".

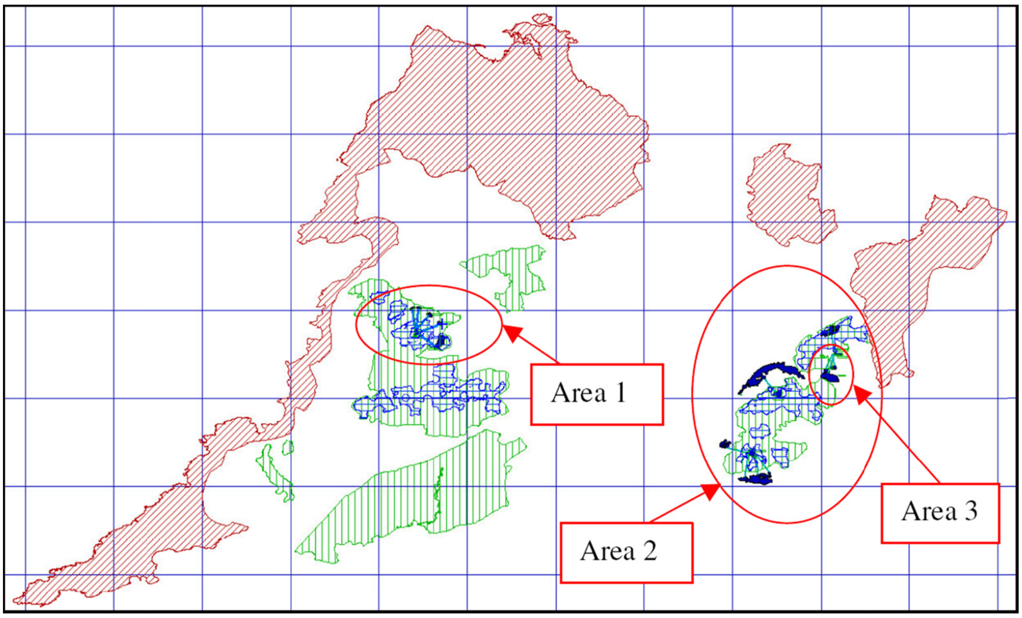

Figure 7: Potential PHES sites found within acceptable areas of County Clare with a head greater than 250 m.

The size and cost of a PHES facility is very difficult to predict as it is very site-specific. Therefore, a range of minimum and maximum values was created using the "Energy Storage Capacity & Cost Calculator".

For each site analysed below, four sets of parameters were chosen using the dropdown menus in the calculator (see Appendix for more details). The parameters for each scenario are outlined in Table 2. The first set of parameters, MinCAP, were chosen to calculate the minimum expected capacity at each site, while the second set of parameters, MaxCAP, were chosen to estimate a maximum capacity for the reservoirs. Hence, these two scenarios give the range of typical capacities one could install at the sites identified.

Table 2: Technical parameters assumed to identify the capacity of the energy storage facilities*.

Parameter	MinCAP	MaxCAP
Height of Reservoir (m)	20	50
Penstock Flow Rate (m^3/s)	50	150
Pump Efficiency (%)	82	92
Turbine Efficiency (%)	82	92

***These are indicative values only based on existing PHES facilities. Hence, new facilities could be different.**

An economic evaluation was also carried out while evaluating the MinCAP and MaxCAP scenarios. Therefore, a range of cost assumptions had to made, which are outlined in Table 3. Once again these assumptions are based on typical values which have previously been reported [6, 7], but they could vary considerably. If necessary, the calculator can be used to assess the sensitivity of any site to various financial parameters.

Table 3: Financial parameters assumed to identify the capacity of the energy storage facilities*.

Parameter	MinCAP	MaxCAP
Pump Cost (M€/MW)	0.25	0.25
Turbine Cost (M€/MW)	0.25	0.25
Storage Cost (M€/GWh)	15	15
Lifetime (years)	40	40
Real Interest Rate (%)	6	6

***These are indicative values only based on existing PHES facilities. Hence, new facilities could be different.**

5.1 TotalArea site

As mentioned earlier, the sites in area 1 of Figure 7 contained the only potential PHES location which was entirely located within the area of strategic interest. As outlined in Figure 8, there are a range of lower reservoirs which could be chosen at this location. Therefore, the sire parameters outlined in Table 4 were chosen for the analysis.

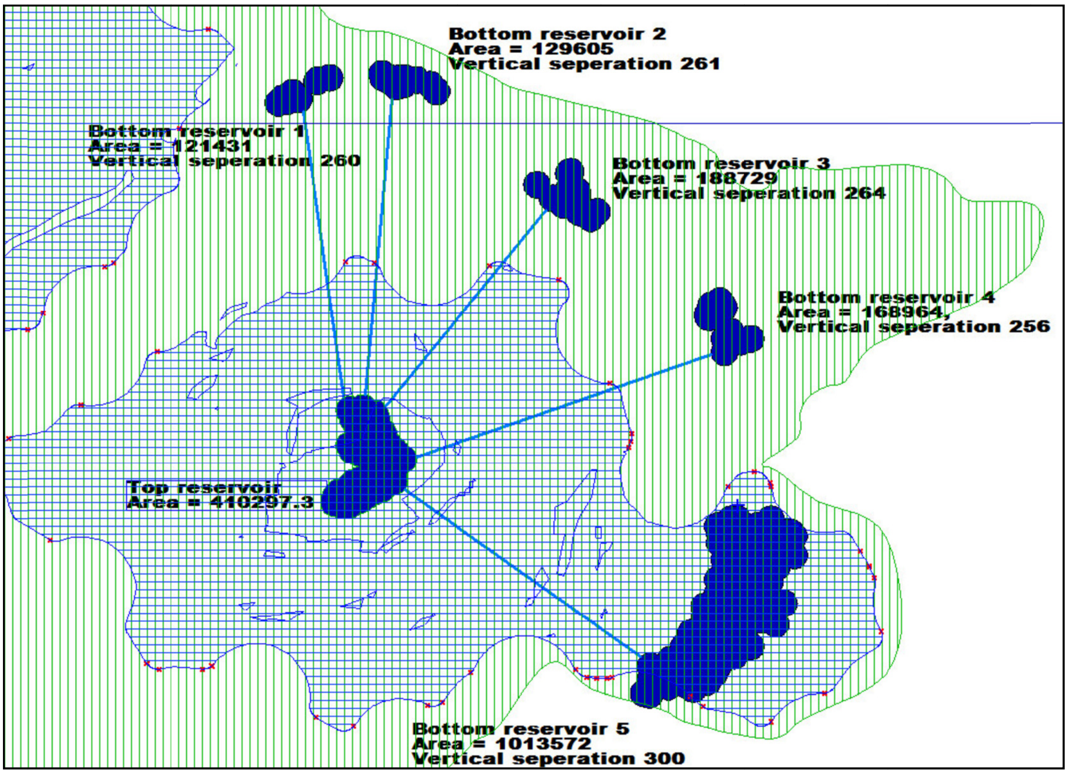

Figure 8: PHES facility located in Area 1: it is entirely within the area of strategic interest.

As displayed in Table 4, the size of the facility that could be constructed ranges from 121 MW to 406 MW, with corresponding storage capacities of approximately 5.5 GWh and 15 GWh respectively. Therefore, for this site the storage capacity feasible is much larger than would typically be required for the corresponding storage capacities. Therefore, the five lower reservoir alternatives displayed in Figure 8 would all be relevant for further analysis.

Table 4: Site parameters along with capacity and cost results from PHES facility in Area 1*.

Site Parameter	Value	Unit
Height between reservoirs	300	m
Area of smaller reservoir (upper)	410,297	m^2
Capacity Results	**MinCAP**	**MaxCAP**
Pump Capacity (MW)	120	405
Turbine Capacity (MW)	120	405
Storage Capacity (MWh)	5500	15430
Discharge Time (h)	45	38
Cost Results	**MinCAP**	**MaxCAP**
Total Annual Costs (M€/year)	12	35
Total Investment (M€)	143	435

***These are indicative values only based on existing PHES facilities. Hence, new facilities could be different.**

5.2 BigReservoir site

Area 2 of Figure 7 contained the largest potential reservoir area which was identified during the search. As outlined in Figure 9, the cumulative area of this reservoir was approximately 720,000 m^2. Once again, there was one primary upper reservoir which, but numerous alternatives for the location of the lower reservoir. Although the single upper reservoir location was located within the area of strategic interest, all of the lower reservoirs were outside, as displayed in Figure 9.

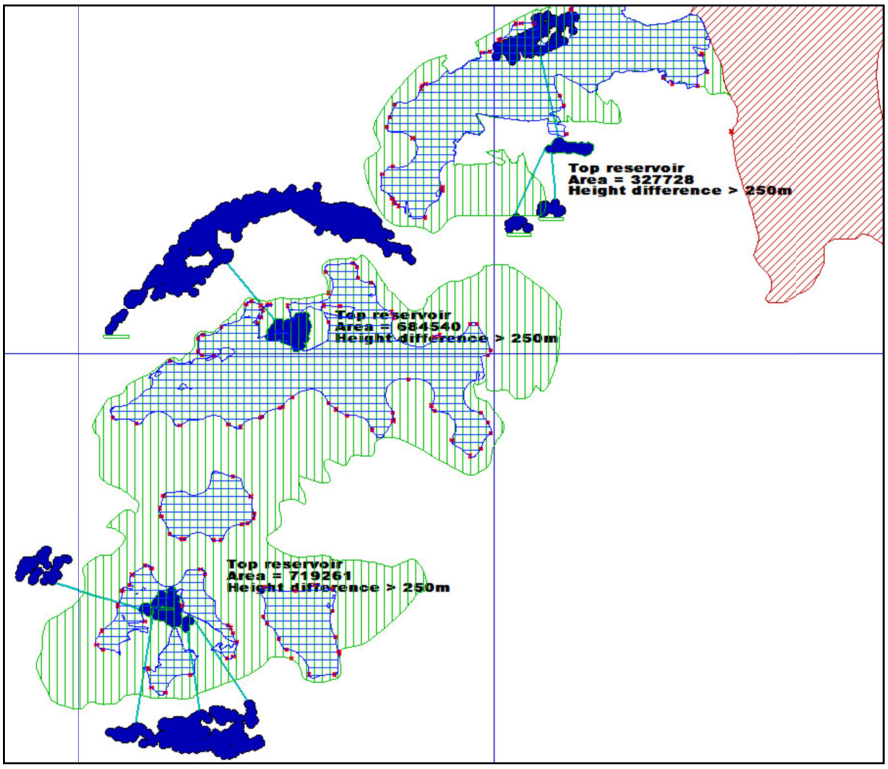

Figure 9: PHES facility located in Area 2: it has the largest reservoir area found.

Due to the large area of this site, the head varied at different locations between the upper and lower reservoirs, but overall the average head between them was greater than 250 m. Hence, the parameters defined in Table 5 were chosen. As expected, this location had an exceptionally large storage capacity, which could be as large as 22 GWh. Consequently, the costs of constructing the BigReservoir facility are higher than the TotalArea facility discussed previously.

Table 5: Site parameters along with capacity and cost results from PHES facility in Area 2*.

Site Parameter	Value	Unit
Height between reservoirs	250	m
Area of smaller reservoir (upper)	719,261	m^2
Capacity Results	**MinCAP**	**MaxCAP**
Pump Capacity (MW)	100	340
Turbine Capacity (MW)	100	340
Storage Capacity (MWh)	8040	22540
Discharge Time (h)	80	67
Cost Results	**MinCAP**	**MaxCAP**
Total Annual Costs (M€/year)	14	41
Total Investment (M€)	171	507

***These are indicative values only based on existing PHES facilities. Hence, new facilities could be different.**

5.3 BigHead site

The final site selected for analysis is located in area 3 of Figure 7. It was chosen because it had the largest vertical separation (i.e. head) of any potential site at 420 m. However, as displayed in Figure 10, both the upper and lower reservoirs were located outside the areas of strategic interest.

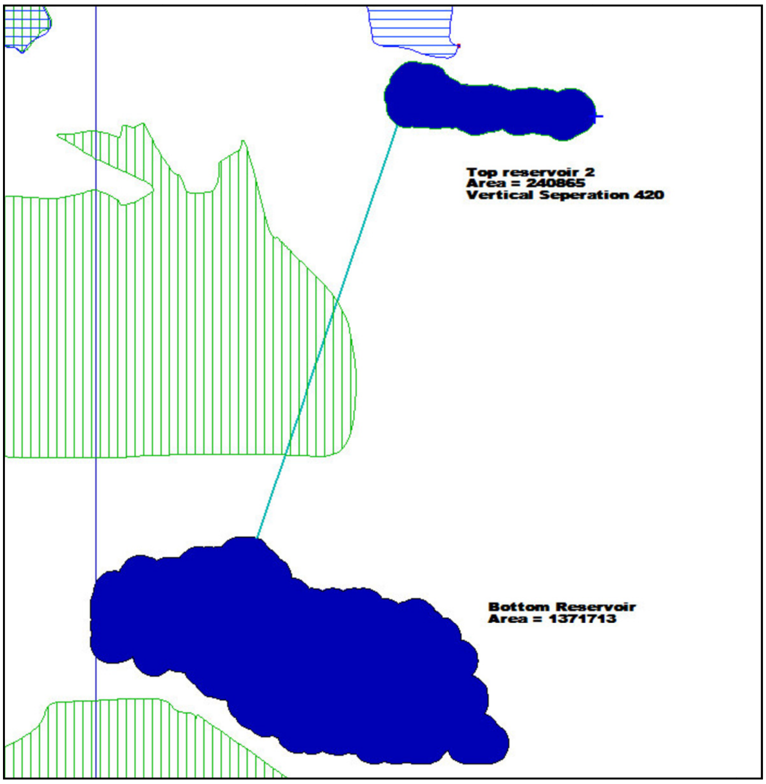

Figure 10: PHES facility located in Area 3: it has the largest vertical separation identified.

Based on the parameters defined for this potential site in Table 6, a power capacity ranging from 170 MW to 570 MW is feasible, which is large considering Turlough Hill[3] has a power capacity of 292 MW [8]. However, even with these relatively large power capacities, the discharge times for this site were still high at 27 and 22 hours for the MinCAP and MaxCAP parameters respectively. This is an important finding as it indicates that the upper reservoir area is relatively small compared to the TotalArea and BigReservoir sites. As the discharge time is still approximately double a conventional discharge time, the reservoir area could be halved to reduce the storage capacity while still retaining the large power capacity.

Table 6: Site parameters along with capacity and cost results from PHES facility in Area 3*

Site Parameter	Value	Unit
Height between reservoirs	420	m
Area of smaller reservoir (upper)	240,865	m^2
Capacity Results	**MinCAP**	**MaxCAP**
Pump Capacity (MW)	170	570
Turbine Capacity (MW)	170	570
Storage Capacity (MWh)	4520	12680
Discharge Time (h)	27	22
Cost Results	**MinCAP**	**MaxCAP**
Total Annual Costs (M€/year)	12	39
Total Investment (M€)	152	475

***These are indicative values only based on existing PHES facilities. Hence, new facilities could be different.**

[3] Turlough Hill is Ireland's only pumped hydroelectric energy storage facility. It has a pump capacity of 272 MW, a turbine capacity of 292 MW, and a storage capacity of approximately 1.7 GWh.

6 Discussion

Overall, the results indicate that based on typical technical parameters of existing PHES facilities, there is a lot of storage capacity available from freshwater PHES facilities in County Clare. In the three unique sites evaluated above, the discharge time was in the range of 27 to 80 hours. Although the topographical conditions at these sites would allow this, it is unlikely that a PHES facility would be designed with a discharge time greater than 12 hours. Consequently, the costs were recalculated using MaxCAP capacities, but with a discharge time of 12 hours instead of the maximum feasible storage capacity. As displayed in Table 7, the total annual investment costs for a PHES facility would be approximately 20-30 M€/year for a power capacity of approximately 300-600 MW respectively, which corresponds to a total investment over the lifetime of the facilities of 230-390 M€. It is worth stressing once again that these cost calculations are based on typical construction costs and borrowing costs as outlined in Table 3. Therefore, the actual costs could vary substantially depending on the site-specific construction costs and the financial parameters agreed for the construction of this facility.

Table 7: Cost of each storage facility based on MaxCAP capacities and a 12 hour discharge time*.

Capacity Results	TotalArea	BigReservoir	BigHead
Pump Capacity (MW)	405	340	570
Turbine Capacity (MW)	405	340	570
Storage Capacity (MWh)	4860	4080	6840
Discharge Time (h)	12	12	12
Cost Results	**TotalArea**	**BigReservoir**	**BigHead**
Total Annual Costs (M€/year)	23	19	32
Total Investment (M€)	276	230	387

***These are indicative values only based on existing PHES facilities. Hence, new facilities could be different.**

7 Conclusions

The following key conclusions can be drawn from the search completed:

1. County Clare has 14 distinct locations to construct freshwater PHES facilities with a head of at least 200 m: 5 are within excluded areas, 1 used the River Shannon as a lower reservoir[4], 7 are partially within areas open to consideration and partially within the areas of strategic interest, and 1 is located entirely within the area of strategic interest.
2. After applying the criteria specified in this study, there were 8 potential locations that could be used to build PHES in County Clare. Many of these locations contain numerous upper and lower reservoirs. Therefore, there are many more potential sites at each of these locations that could be chosen depending on their suitability.
3. Due to the large variety of potential sites available, an “Energy Storage Capacity and Cost Calculator” was developed during this study to extract the size and cost of the energy storage sites indentified. This will enable the Local Authority in County Clare to translate any of the results from the search into energy storage capacities and costs when relevant in the future.
4. The cost and capacity of three unique sites were evaluated here to assess the typical range of PHES sites available in County Clare. Based on typical parameters that are found at existing PHES facilities, the results indicate that the PHES sites analysed had very large storage capacities compared to their power capacities. Hence, the PHES facilities in County Clare will most likely be limited by their power capacity and not by their storage capacities[5].
5. Also, after evaluating the three unique sites identified, it became apparent that up to 570 MW of PHES is possible at one of these locations, while up to 405 MW and 340 MW is available at the remaining two. Considering Turlough Hill[6] has a power capacity of 292 MW, these are significantly large facilities for Ireland. Therefore, as the power capacity is the limiting factor at the PHES facilities found, this indicates that County Clare has a significant freshwater PHES resource.
6. Finally, the total annual investment costs for these three sites were calculated. Results indicate that a freshwater PHES facility in County Clare would cost approximately 20-30 M€/year for a power capacity of approximately 300-600 MW respectively, which

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[4] The site which used the River Shannon as a lower reservoir was excluded in the results as it is not a freshwater facility.

[5] Where economical viable, power capacities can be increased by constructing additional penstock connections between the upper and lower reservoirs, but this is site specific.

[6] Turlough Hill is Ireland’s only pumped hydroelectric energy storage facility. It has a pump capacity of 272 MW, a turbine capacity of 292 MW, and a storage capacity of approximately 1.7 GWh.

corresponds to a total investment over the lifetime of the facilities of 230-390 M€. However, it should be stressed that these costs are very sensitive to site-specific construction costs and also the cost of borrowing for the initial investment.

8 References

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9 Appendix: Energy Capacity and Cost Calculator

Due to the large quantity of potential sites identified during this analysis, it was difficult to identify a specific range of sites for evaluation. Consequently, three unique sites were chosen, which each met one very unique criterion. These were:

1. The entire site was included in the area of strategic interest.
2. The reservoir area was the largest identified.
3. The vertical head was the largest identified.

Consequently, for the remaining sites, an energy capacity and cost calculator was created, which is displayed in Figure 11 below. This will enable the Local Authority to translate the head and reservoir parameters identified in the search into energy storage capacities and investment costs.

As illustrated in Figure 11, the inputs highlighted in pink correspond to the parameters obtained during the PHES search of County Clare i.e. the head and reservoir area available. The cells highlighted in yellow are the primary results from the calculator which indicate the capacities and annual investment costs of the storage facility.

Each of the green inputs contains a dropdown menu of with three values: each value corresponds to either a low, medium, or high estimate for that parameter. The values of these are outlined in Table 8 for each parameter. This will enable the LCEA to evaluate the sensitivity of a site based on typical parameters found at existing PHES facilities. Note that the parameters are not related to one another in any way. A minimum value for the penstock flow rate could be combined with a maximum lifetime and a medium interest rate. Therefore, the user can specify the value for each parameter individually.

Table 8: Parameters available from the drop down menus in the calculator (see green cells in Figure 11)

Parameter	Min	Medium	Maximum
Height of Reservoir (m)	20	35	50
Penstock Flow Rate (m^3/s)	50	100	150
Pump Efficiency (%)	82	87	92
Turbine Efficiency (%)	82	87	92
Lifetime (years)	30	40	50
Real Interest Rate (%)	3	6	9

The orange inputs represent the cost parameters. These are fully editable as costs can vary substantially with each site and also over time. Therefore, as more detailed cost data becomes apparent, these inputs can be adjusted accordingly by the LCEA to carry out the calculations.

Finally, none of the blue inputs can be edited to ensure the validity of the results produced by the software. However, it is important that a user understands the accuracy of their inputs when using the calculator. A disclaimer and a full list of instructions is provided in the calculator software, which is saved as "**Energy Storage Capacity & Cost Calculator.xlsx**" or can be downloaded from [9].

Energy Storage Capacity & Cost Calculator		
Capacity and Cost of Energy Storage		
Pump Capacity	**213**	MW
Turbine Capacity	**213**	MW
Storage Capacity	**2489**	MWh
Total Annual Costs	**11.732**	M€/year
Geological Parameters of Energy Storage Facility		
Head	250	m
Area of Reservoir	120,000	m^2
Height of Reservoir	35	m
Volume of Reservoir	4,200,000	m^3
Density of Water	1000	kg/m^3
Acceleration Due to Gravity	9.81	m/s^2
Technical Parameters of the Technologies		
Penstock Flow Rate	100	m^3/s
Pump Efficiency	87%	%
Turbine Efficiency	87%	%
Financial Parameters		
Lifetime	40	years
Interest Rate	6%	(Fixed Repayment Loan)
Annual Fixed O&M Costs	1.5%	% of Annual Investment
Capital Cost of Pump	0.250	M€/MW
Capital Cost of Turbine	0.250	M€/MW
Capital Cost of Storage	15.000	M€/GWh
Total Investment		
Pump	53.342	M€
Turbine	53.342	M€
Storage	37.339	M€
Total	**144.023**	**M€**
Annual Loan Repayments (Million €/year)		
Pump	3.545	M€/year
Turbine	3.545	M€/year
Storage	2.482	M€/year
Total	**9.572**	**M€/year**
Annual Fixed Operation & Maintenance Costs (Million €/year)		
Pump	0.800	M€/year
Turbine	0.800	M€/year
Storage	0.560	M€/year
Total	**2.160**	**M€/year**

Figure 11: Interface of Energy Capacity and Cost Calculator.

Appendix D

Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Applied Energy 2010;87(4):1059-1082.

Applied Energy 87 (2010) 1059–1082

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A review of computer tools for analysing the integration of renewable energy into various energy systems

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ARTICLE INFO

Article history:
Received 25 July 2009
Received in revised form 21 September 2009
Accepted 21 September 2009
Available online 25 October 2009

Keywords:
Energy models
Energy tools
Energy systems
Renewable energy
Sustainable energy
Energy systems modelling

ABSTRACT

This paper includes a review of the different computer tools that can be used to analyse the integration of renewable energy. Initially 68 tools were considered, but 37 were included in the final analysis which was carried out in collaboration with the tool developers or recommended points of contact. The results in this paper provide the information necessary to identify a suitable energy tool for analysing the integration of renewable energy into various energy-systems under different objectives. It is evident from this paper that there is no energy tool that addresses all issues related to integrating renewable energy, but instead the 'ideal' energy tool is highly dependent on the specific objectives that must be fulfilled. The typical applications for the 37 tools reviewed (from analysing single-building systems to national energy-systems), combined with numerous other factors such as the energy-sectors considered, technologies accounted for, time parameters used, tool availability, and previous studies, will alter the perception of the 'ideal' energy tool. In conclusion, this paper provides the information necessary to direct the decision-maker towards a suitable energy tool for an analysis that must be completed.

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0306-2619/$ - see front matter
doi:10.1016/j.apenergy.2009.09.026

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1. Introduction

In recent times more diverse challenges have emerged in society such as climate change, security of energy supply, and economic recession. As a result, the energy sector, especially renewable energy, is being targeted to combat these issues. To be more precise, converting from an energy-system that is dependent on imported fossil-fuels to a renewable energy-system can play a significant role in solving these issues [1]. Therefore, identifying the potential of renewable energy has become a key area of interest within energy planning.

A crucial element in this transfer is often to show coherent technical analyses of how renewable energy can be implemented, and what effects renewable energy has on other parts of the energy-system. Such analyses require computer tools[1] that can create answers for these issues by modelling defined energy-systems. It is time-consuming to create new tools for each and every analysis, hence if feasible and accessible tools exist, these should be used. However, when beginning an investigation into the potential of renewable energy, it is difficult to identify which energy tool is the most suitable for the investigation, even with existing literature.

To date, a number of studies have been completed which analysed the potential of a single energy tool. To name a few, Cormio et al. [2] discussed the EFOM energy tool, Faraji-Zonooz et al. [3] provided a complete review of the MARKAL energy tool, Ball et al. [4] demonstrated the MOREHyS energy tool (which is based on the BALMOREL tool), Tsioliaridou et al. [5] assessed the In*vert* energy tool and finally, Cai et al. [6] discussed the UREM energy tool. However, these studies are primarily focused on the abilities of the energy tool in question and hence, they do not provide an extensive analysis of other energy tools. Other studies have been completed that do analyse more than one energy tool: Lund et al. [7] compared the two energy tools, EnergyPLAN and H_2RES, Morris et al. [8] compared results from NEMS and MARKAL-MACOR, Segurado et al. [9] compared the EMINENT energy tool with 5 other energy tools (CO2DB, MARKAL, IKARUS, E3database, and Synopsis), and Urban et al. [10] analysed the suitability of 12 energy tools for energy-systems in developing countries (including LEAP, MARKAL, MESSAGE, MiniCAM, and RETScreen). However, these are only a small selection of the energy tools that exist. The only study identified that does compare a large variety of energy tools was completed by Jebaraj and Iniyan [11]. However, this was a very broad study which accounted for supply–demand models, forecasting models, optimisation models, neural-network models, and emissions models. Therefore, the abilities and applications of the individual models were not discussed in detail.

Consequently, to aid the selection of a suitable energy tool, this review provides a detailed comparison of the energy tools used for analysing the integration of renewable energy in various energy-systems. The paper begins by outlining the methodology undertaken and subsequently the results are displayed. Afterwards, the paper contains an individual description about each of the energy tools reviewed and finally, a brief discussion outlines the context of the information provided. In addition, this paper provides a sample of the existing studies completed by each of the energy tools reviewed, with all information valid up to July 2009. The overall objective is to inform the reader about the computer tools available when embarking on a study, which analyses the integration of renewable energy into various energy-systems.

2. Methodology

To obtain a detailed understanding of the energy tools analysed, a survey was completed (using SurveyXact [12]) and distributed to a number of tool developers: a short summary of the survey can be seen in Appendix. Initially, the objective of this study was to identify energy tools that could simulate a 100% renewable energy-system. However, very early in the investigation it became apparent that most (90%) of the energy tools considered never simulated a 100%

[1] Energy tools are used to create energy models: therefore, the computer programs discussed in this paper are referred to as 'tools', which can be used to create various types of models.

Table 1
Tools considered for and their inclusion in the final analysis of this study.

Considered and included (website): description of a typical application		Considered but not included	
AEOLIUS [14]: power-plant dispatch simulation tool	BALMOREL [15]: open source electricity and district heating tool	BESOM	CEEM
BCHP Screening Tool [16]: assesses CHP* in buildings	COMPOSE [17]: techno-economic single-project assessments	CEPEL	CHP capacity optimizer
E_4cast [18]: tool for energy projection, production, and trade	EMCAS [19]: creates techno-economic models of the electricity sector	CHPSizer	CO2BD
EMINENT [20]: early stage technologies assessment	EMPS [21]: electricity systems with thermal/hydro generators	DER-CAM	DIMES
EnergyPLAN [22]: user friendly analysis of national energy-systems	energyPRO [23]: techno-economic single-project assessments	DREAM	E3database
ENPEP-BALANCE [24]: market-based energy-system tool	GTMax [25]: simulates electricity generation and flows	EFOM	Elfin
H_2RES [26]: energy balancing models for Island energy-systems	HOMER [27]: techno-economic optimisation for stand-alone systems	Endur	GmbH
HYDROGEMS [28]: renewable and H_2 stand-alone systems	IKARUS [29]: bottom-up cost-optimisation tool for national systems	GREET	H2A analysis
INFORSE [30]: energy balancing models for national energy-systems	In*vert* [31]: simulates promotion schemes for renewable energy	HUD CHP Screening Tool	HyDIVE
LEAP [32]: user friendly analysis for national energy-systems	MARKAL/TIMES [33]: energy–economic tools for national energy-systems	HYPRO	HyTrans
MESAP PlaNet [34] linear network models of national energy-systems	MESSAGE [35]: national or global energy-systems in medium/long-term	MENSA	MOREHyS
MiniCAM [36,37]: simulates long-term, large-scale global changes	NEMS [38]: simulates the US energy market	NESSIE	PSAT
ORCED [39]: simulates regional electricity-dispatch	PERSEUS [14]: family of energy and material flow tools	PSR	Ready Reckoner
PRIMES [40]: a market equilibrium tool for energy supply and demand	ProdRisk [41]: optimises operation of hydro power	Samplan	SEDS
RAMSES [42]: simulates the electricity and district heating sector	RETScreen [43]: renewable analysis for electricity/heat in any size system	SGM	TESOM
SimREN [44]: bottom-up supply and demand for national energy-systems	SIVAEL [45]: electricity and district heating sector tool	UREM	
STREAM [46]: overview of national energy-systems to create scenarios	TRNSYS16 [47]: modular structured models for community energy-systems		
UniSyD3.0 [48]: national energy-systems scenario tool	WASP [49]: identifies the least-cost expansion of power-plants		
WILMAR Planning Tool [50]: increasing wind in national energy-systems			

* CHP: combined heat and power.

Table 2
Tool information and the number of users in terms of downloads/sales.

Tool	Organisation (link)	Availability	Downloads/sales
	Very high number of users		
RETScreen	RETScreen International (http://www.retscreen.net/)	Free to Download	>200000
HOMER	National Renewable Energy Laboratory and HOMER Energy LLC (www.homerenergy.com)	Free to Download	>28000
LEAP	Stockholm Environment Institute (http://www.energycommunity.org/)	Commercial/free for developing countries and students	>5000
BCHP Screening Tool	Oak Ridge National Laboratory (http://www.ornl.gov/)	Free to Download	>2000
energyPRO	Energi-Og Mijødata (EMD) International A/S (http://www.emd.dk/)	Commercial	>1000
	High number of users		
EnergyPLAN	Aalborg University (http://www.energyplan.eu/)	Free to Download	100–1000
Invert	Energy Economics Group, Vienna University of Technology (http://www.invert.at/)	Free to Download	100–1000
MARKAL/TIMES	Energy Technology Systems Analysis Program, International Energy Agency (http://www.etsap.org/)	Commercial	100–1000
MESSAGE	International Institute for Applied Systems Analysis (http://www.iiasa.ac.at/)	Free/Simulators must be purchased	100–1000
ORCED	Oak Ridge National Laboratory (http://www.ornl.gov/)	Free to Download	100–1000
TRNSYS16	The University of Wisconsin Madison (http://sel.me.wisc.edu/trnsys/)	Commercial	100–1000
WASP	International Atomic Energy Agency (http://www.iaea.org/OurWork/ST/NE/Pess/PESSenergymodels.shtml)	Commercial/Free to IAEA member states	100–1000
	Medium number of users		
EMCAS	Argonne National Laboratory (http://www.dis.anl.gov/projects/emcas.html)	Commercial	20–50
EMPS	Stiftelsen for Industriell og Teknisk Forskning (SINTEF) (http://www.sintef.no/)	Commercial	20–50
ENPEP-BALANCE	Argonne National Laboratory (http://www.dis.anl.gov/projects/Enpepwin.html)	Free to Download	20–50
GTMax	Argonne National Laboratory (http://www.dis.anl.gov/projects/Gtmax.html)	Commercial	20–50
	Low number of users		
AEOLIUS	Institute for Industrial Production, Universität Karlsruhe (http://www-iip.wiwi.uni-karlsruhe.de/)	Commercial	1–20
COMPOSE	Aalborg University (http://www.socialtext.net/energyinteractivenet/index.cgi?compose)	Free to Download	1–20
IKARUS	Research Centre Jülich, Institute of Energy Research (http://www.fz-juelich.de/ief/ief-ste/index.php?index=3)	Commercial/Earlier versions are free	1–20
INFORSE	The International Network for Sustainable Energy (http://www.inforse.org/europe/Vision2050.htm)	Distributed to non-governmental organisations	1–20
Mesap PlaNet	seven2one (http://www.seven2one.de/de/technologie/mesap.html)	Commercial	1–20
NEMS	Office of Integrated Analysis and Forecasting, Energy Information Administration (http://www.eia.doe.gov/)	Free/Simulators must be purchased	1–20
PERSEUS	Institute for Industrial Production, Universität Karlsruhe (http://www-iip.wiwi.uni-karlsruhe.de/)	Commercial: only sold to large European utilities	1–20
ProdRisk	Stiftelsen for Industriell og Teknisk Forskning (SINTEF) (http://www.sintef.no/Home/)	Commercial	1–20
RAMSES	Danish Energy Agency (http://www.ens.dk/)	Projects completed for a fee	1–20
SIVAEL	Energinet.dk (http://www.energinet.dk/en/menu/Planning/Analysis+models/Sivael/SIVAEL.htm)	Free to Download	1–20
EMINENT	Instituto Superior Técnico, Technical University of Lisbon (http://carnot.ist.utl.pt/~eminent2/)	To be decided	0
PRIMES	National Technical University of Athens (http://www.e3mlab.ntua.gr/)	Projects completed for a fee	0
	Number of users is not specified as it is not monitored		
BALMOREL	Project Driven with a users network and forum around it (http://www.balmorel.com/)	Free to Download (Open Source)	Not specified
E4cast	Australian Bureau of Agricultural and Resource Economics (http://www.abare.gov.au/)	Commercial	Not specified
H2RES	Instituto Superior Técnico and the University of Zagreb (http://powerlab.fsb.hr/h2res/)	Internal use only	Not specified
HYDROGEMS	Institutt for energiteknikk (http://www.hydrogems.no/)	Commercial/free for TRNSYS Users	Not specified
MiniCAM	Pacific Northwest National Laboratory (http://www.globalchange.umd.edu/)	Free to Download Once Contacted	Not specified
SimREN	Institute of Sustainable Solutions and Innovations (http://www.isusi.de/theerjreport.html)	Projects completed for a fee	Not specified
STREAM	Ea Energy Analyses (http://www.ea-energianalyse.dk/)	Free to Download Once Contacted	Not specified
UniSyD3.0	Unitec New Zealand (http://www.unitec.ac.nz/)	Contact Prof. Jonathan Leaver: jleaver@unitec.ac.nz	Not specified
WILMAR Planning Tool	Risø DTU National Laboratory for Sustainable Energy (http://www.wilmar.risoe.dk/)	Commercial	Not specified

Table 3
Type of each tool reviewed.

Tool	Type						
	Simulation	Scenario	Equilibrium	Top-down	Bottom-up	Operation optimisation	Investment optimisation
AEOLIUS	Yes	–	–	–	Yes	–	–
BALMOREL	Yes	Yes	Partial	–	Yes	Yes	Yes
BCHP Screening Tool	Yes	–	–	–	Yes	Yes	–
COMPOSE	–	–	–	–	Yes	Yes	Yes
E4cast	–	Yes	Yes	–	Yes	–	Yes
EMCAS	Yes	Yes	–	–	Yes	–	Yes
EMINENT	–	Yes	–	–	Yes	–	–
EMPS	–	–	–	–	–	Yes	–
EnergyPLAN	Yes	Yes	–	–	Yes	Yes	Yes
energyPRO	Yes	Yes	–	–	–	Yes	Yes
ENPEP-BALANCE	–	Yes	Yes	Yes	–	–	–
GTMax	Yes	–	–	–	–	Yes	–
H2RES	Yes	Yes	–	–	Yes	Yes	–
HOMER	Yes	–	–	–	Yes	Yes	Yes
HYDROGEMS	–	Yes	–	–	–	–	–
IKARUS	–	Yes	–	–	Yes	–	Yes
INFORSE	–	Yes	–	–	–	–	–
In*vert*	Yes	Yes	–	–	Yes	–	Yes
LEAP	Yes	Yes	–	Yes	Yes	–	–
MARKAL/TIMES	–	Yes	Yes	Partly	Yes	–	Yes
Mesap PlaNet	–	Yes	–	–	Yes	–	–
MESSAGE	–	Yes	Partial	–	Yes	Yes	Yes
MiniCAM	Yes	Yes	Partial	Yes	Yes	–	–
NEMS	–	Yes	Yes	–	–	–	–
ORCED	Yes	Yes	Yes	–	Yes	Yes	Yes
PERSEUS	–	Yes	Yes	–	Yes	–	Yes
PRIMES	–	–	Yes	–	–	–	–
ProdRisk	Yes	–	–	–	–	Yes	Yes
RAMSES	Yes	–	–	–	Yes	Yes	–
RETScreen	–	Yes	–	–	Yes	–	Yes
SimREN	–	–	–	–	–	–	–
SIVAEL	–	–	–	–	–	–	–
STREAM	Yes	–	–	–	–	–	–
TRNSYS16	Yes	Yes	–	–	Yes	Yes	Yes
UniSyD3.0	–	Yes	Yes	–	Yes	–	–
WASP	Yes	–	–	–	–	–	Yes
WILMAR Planning Tool	Yes	–	–	–	–	Yes	–

renewable energy-system. Instead, the energy tools considered in this study were diverse in terms of their structure, operation, and applications. Consequently, the survey was designed with pre-defined answers and answers that the respondents could provide in their own words. This ensured that all relevant information was supplied by the respondent. In summary, the survey consisted of five sections:

A. Background information: an insight into the background of the respondent.
B. Users: who and how many people were using the tool, and how the tool could be obtained?
C. Tool properties: basic characteristics about the type of tool in question.
D. Applications: what applications *can* the tool be used for and what applications is it *typically* used for?
E. Case studies: how was the tool previously used with a specific focus on renewable energy?
F. Further information: the respondents provided a description of the tool in their own words, listed the tools they had previously known before this review, and answered general queries about the process of this study.

Included in the survey was the question "Please state what type of tool this is". However, from discussions with the tool developers, it became apparent that there is no common language shared amongst them that classifies different types of energy tools. Consequently, to ensure that the tools were described correctly, a common language was created and sent to the developers to distinguish between the different types of energy tools. Seven different tool types were defined, which can be used exclusively or collectively to describe an energy tool. The energy tool types are:

1. A simulation tool simulates the operation of a given energy-system to supply a given set of energy demands. Typically a simulation tool is operated in hourly time-steps over a one-year time-period.
2. A scenario tool usually combines a series of years into a long-term scenario. Typically scenario tools function in time-steps of 1 year and combine such annual results into a scenario of typically 20–50 years.
3. An equilibrium tool seeks to explain the behaviour of supply, demand, and prices in a whole economy or part of an economy (general or partial) with several or many markets. It is often assumed that agents are price takers and that equilibrium can be identified.
4. A top-down tool is a macroeconomic tool using general macroeconomic data to determine growth in energy prices and demands. Typically top-down tools are also equilibrium tools (see 3).
5. A bottom-up tool identifies and analyses the specific energy technologies and thereby identifies investment options and alternatives.
6. Operation optimisation tools optimise the operation of a given energy-system. Typically operation optimisation tools are also simulation tools (see 1) optimising the operation of a given system.

Table 4
Type of analysis conducted by each tool reviewed.

Tool	Geographical area	Scenario timeframe	Time-step	Specific focus
			1. National energy-system tools	
			1.1. Time-step simulation tools	
Mesap PlaNet	National/state/regional	No limit	Any	–
TRNSYS16	Local/community	Multiple years	Seconds	–
HOMER	Local/community	1 year[a]	Minutes	–
SimREN	National/state/regional	No limit	Minutes	–
EnergyPLAN	National/state/regional	1 year[a]	Hourly	–
SIVAEL	National/state/regional	1 year[a]	Hourly	–
STREAM	National/state/regional	1 year[a]	Hourly	–
WILMAR Planning Tool	International	1 year[a]	Hourly	–
RAMSES	International	30 years	Hourly	–
BALMOREL	International	Max 50 years	Hourly	–
GTMax	National/state/regional	No limit	Hourly	–
H2RES	Island	No limit	Hourly	–
MARKAL/TIMES	National/state/regional	Max 50 years	Hourly, daily, monthly using user-defined time slices	–
			1.2. Sample periods within a year	
PERSEUS	International	Max 50 years	Based on typical days with 36–72 slots for 1 year	–
UniSyD3.0	National/state/regional	Max 50 years	Bi-weekly	–
RETScreen	User-defined	Max 50 years	monthly	–
			1.3. Scenario tools	
E4cast	National/state/regional	Max 50 years	Yearly	–
EMINENT	National/state/regional	1 year[a]	None/yearly	–
IKARUS	National/state/regional	Max 50 years	Yearly	–
PRIMES	National/state/regional	Max 50 years	Years	–
INFORSE	National/state/regional	50+ years	Yearly	–
ENPEP-BALANCE	National/state/regional	75 years	Yearly	–
LEAP	National/state/regional	No limit	Yearly	–
MESSAGE	Global	50+ years	5 years	–
MiniCAM	Global and regional	50+ years	15 years	–
			2. Tools with a specific focus	
			2.1. Time-step simulation tools	
AEOLIUS	National/state/regional	1 year[a]	Minutes	Effects of fluctuating renewable energy on conventional generation
HYDROGEMS	Single-project investigation	1 year[a]	Minutes	Renewable energy and hydrogen stand-alone systems
energyPRO	Single-project investigation	Max 40 years	Minutes	Single power-plant analysis
BCHP Screening Tool	Single-project investigation	1 year[a]	Hourly	Combined heat and power
ORCED	National/state/regional	1 year[a]	Hourly	Dispatch of electricity
EMCAS	National/state/regional	No limit	Hourly	Electricity markets
ProdRisk	National/state/regional	Multiple years	Hourly	Hydro power
COMPOSE	Single-project investigation	No limit	Hourly	CHP with electric boilers or heat pumps
			2.2. Sample periods within a year	
EMPS	International	25 years	Weekly (with a load duration curve representing fluctuations within the week)	Hydro power
WASP	National/state/regional	Max 50 years	12 load duration curves for a year	Power-plant expansion on the electric grid
			2.3. Scenario tools	
In*vert*	National/state/regional	Max 50 years	Yearly	Heat sector
NEMS	National/state/regional	Max 50 years	Yearly	US energy markets

[a] Tools can only simulate 1 year at a time, but these can be combined to create a scenario of multiple years.

Table 5
Energy-sectors considered and renewable-energy penetrations simulated by each tool.

Tool	Energy-sectors considered			Renewable-energy penetrations simulated	
	Electricity sector	Heat sector	Transport sector	100% electricity simulated	100% renewable energy-system
Reports available detailing these renewable-energy penetrations					
EnergyPLAN	Yes	Yes	Yes	Yes	Yes
INFORSE	Yes	Yes	Yes	Yes	Yes
Mesap PlaNet	Yes	Yes	Yes	Yes	Yes
H2RES	Yes	Yes	Partly	Yes	Yes
SimREN	Yes	Yes	Partly	Yes	Yes
energyPRO	Yes	Partly	–	Yes	Partly[a]
HOMER	Yes	Yes	–	Yes	Partly[a]
TRNSYS16	Yes	Yes	–	Yes	Partly[a]
PERSEUS	Yes	Yes	Partly	Yes	–
MESSAGE	Yes	Yes	Yes	–	–
NEMS	Yes	Yes	Yes	–	–
Reports NOT available detailing these renewable-energy penetrations					
LEAP	Yes	Yes	Yes	Yes	Yes
In*vert*	Yes	Yes	Partly	Yes	Yes
EMPS	Yes	–	–	Yes	Partly[a]
ProdRisk	Yes	–	–	Yes	Partly[a]
RETScreen	Yes	Yes	–	Yes	Partly[a]
MiniCAM	Yes	Partly	Yes	Yes	–
SIVAEL	Yes	Partly	–	Yes	–
COMPOSE	Yes	Yes	Yes	–	–
ENPEP-BALANCE	Yes	Yes	Yes	–	–
IKARUS	Yes	Yes	Yes	–	–
MARKAL/TIMES	Yes	Yes	Yes	–	–
PRIMES	Yes	Yes	Yes	–	–
E4cast	Yes	Yes	Partly	–	–
STREAM	Yes	Yes	Partly	–	–
EMINENT	Yes	Yes	–	–	–
UniSyD3.0	Yes	Partly	Yes	–	–
WILMAR Planning Tool	Yes	Partly	Partly	–	–
BALMOREL	Yes	Partly	–	–	–
GTMax	Yes	Partly	–	–	–
RAMSES	Yes	Partly	–	–	–
HYDROGEMS	Yes	–	–	–	–
ORCED	Yes	–	Partly	–	–
EMCAS	Yes	–	Partly	–	–
WASP	Yes	–	–	–	–
AEOLIUS	Yes	–	–	–	–
BCHP Screening Tool	–	–	–	–	–

[a] Have simulated a 100% renewable-energy penetration in all the sectors they consider.

7. Investment optimisation tools optimise the investments in an energy-system. Typically optimisation tools are also scenario tools (see 2) optimising investments in new energy stations and technologies.

Once created, the survey was then distributed on four separate occasions:

1. The tools included in the first distribution of the survey were identified by the authors of this paper based on personal experience within the energy-planning field [13].
2. The second distribution included additional tools that were found after the first distribution was sent.
3. The third distribution consisted of tools that were recommended to the authors in the answers of the surveys from the first and second distributions.
4. The fourth distribution consisted of the tools discussed in a new journal paper completed by Segurado et al. [9], which had not already been included in this study.

After the surveys were answered and returned by the tool developers, the results were used to generate the tables displayed in Section 3 and the paragraphs completed in Section 4 of this paper. The tables act as a directory by providing a concise overview of each tool, while the paragraphs provide a more in-depth discussion where further information is required.

3. Results

Initially, 68 energy tools were considered for this review while 37 of these were included in the final analysis as displayed in Table 1. In addition, Table 1 also includes the most appropriate web-link available, along with a brief description of a typical application for each energy tool reviewed. The organisations responsible for each of the 37 tools reviewed, along with their availability and number of downloads/sales are displayed in Table 2. The different types of each tool reviewed are displayed in Table 3 (a detailed description of the various categories used in Table 3 has been provided in the Section 2), while the different types of analyses that can be completed with each of the tools are displayed in Table 4. Also, the energy-sectors considered by each tool along with the renewable-energy penetrations already simulated by each tool are shown in Table 5. The details contained within these tables can quickly reduce the number of tools that need to be considered for a specific investigation.

Finally, in Section 4 each of the energy tools reviewed are discussed separately to provide a greater level of detail. For conciseness, various categories of technologies and costs[2] have been grouped together throughout Section 4 as illustrated in Table 6. By combining the details in the tables with the descriptions in Section

[2] All currency conversions were made on the 11th July 2009.

Table 6
Different categories used in Section 4 of this study to discuss each of the tools.

	Category						
	Regions	Energy sectors	Costs	Thermal generation	Renewable generation	Storage/conversion	Transport
Incorporates	Global	Electricity generation	Fuel prices	Thermal power-plants	Hydro	Pumped-hydroelectric energy storage (PHES)	Internal-combustion vehicles (ICE)/conventional vehicles
	International	District heating	Fuel handling	Combined heat and power (CHP)	Solar thermal	Battery energy storage (BES)	Battery electric-vehicles (BEV)
	National/state/regional	Individual house heating	Investment	Nuclear power	Photovoltaic	Compressed-air energy storage (CAES)	Intelligent battery-electric-vehicles (SEV)
	Island	Industry	Fixed O and M[a]	Biomass power-plants	Geothermal	Hydrogen production	Vehicle-to-Grid electric-vehicles (V2G)
	Local/community	Transport	Variable O and M[a]		Wind	Hydrogen storage	Hydrogen vehicles
	Single-project		CO_2 Taxes		Wave Tidal	Hydrogen consumption	Hybrid vehicles Rail Aviation

[a] O and M: operation and maintenance.

4, a suitable tool can be identified for different investigations. These investigations vary from small renewable penetrations where they do not influence the energy-system significantly, to penetrations where renewables begin to complete with conventional production and even to penetrations where renewable technologies replace conventional technologies.

4. Energy tools

In this section, each of the 37 tools reviewed are discussed individually in detail. Each description has been completed in conjunction with the tool developer or the recommended contact for that tool. The information about the tool e.g., technologies, costs, analyses methodology, specification of the required training period, etc., has to be seen in this context. For each tool, three primary issues are discussed here: its background, its functionality, and its previous work. A more elaborate description of each tool is available online from [22].

4.1. AEOLIUS

AEOLIUS is a power-plant dispatch simulation tool developed by the Institute for Industrial Production at Universität Karlsruhe in Germany [14]. To date only one version of the tool has been created. The tool itself is not sold to external users. Instead a stakeholder can pay for the completion of a study, with prices available on request for a defined project.

The key focus of AEOLIUS is to analyse the impact of higher penetration rates of fluctuating energy carriers such as wind and PV, on conventional power-plant systems, especially the need for secured capacities and efficiency losses due to more frequent start-ups. The analysis is carried out using a 15 minute time-step over a maximum of 1 year and typically on a national energy-system. The tool simulates the electricity sector and accounts for all thermal-generation technologies as well as wind, photovoltaic, and geothermal power. In addition, pumped-hydroelectric and compressed-air energy storage can be simulated. Finally, AEOLIUS does not simulate the heat or transport sectors of an energy-system, and all costs except investment cost can be accounted for.

AEOLIUS has been used in conjunction with the PERSEUS-CERT (see Section 4.26) energy tool to analyse the effects from large-scale integration of wind [51], and it has also been used to analyse the future potential of renewable energy in the EU-15 [52].

4.2. BALMOREL

BALMOREL is a partial-equilibrium tool with an emphasis on the electricity sector and CHP. It is developed, maintained, and distributed under open source ideals since 2000, and can be freely downloaded from [15]. The tool is formulated in the GAMS modelling language [53] and approximately 10 different versions have been created (the number of users is not monitored). In addition to providing 100% documentation at code level, any user can modify the tool to suit specific requirements for a given application. The formulated model is solved in standard software so no new optimisation code needs to be written. To run a typical analysis using BALMOREL, one week of training is necessary.

Input data and calculation results are given in relation to a geographical subdivision. Time aspects are treated flexibly in relation to how many years are represented, and how many subdivisions of time are within the each year. Typical choices are 250 time segments per year over a 20 year time-horizon, or 8760 time segments per year over 1 year, depending on the purpose of the study. BALMOREL can simulate the electricity sector and some of the heat sector (district heating), but not the transport sector (transport technologies are not represented as standard, but some projects [54] have developed transport sector modules). The different types of units include electricity, district heating, CHP, short-term heat storages, hydro power, wind, and solar. Electricity storage can also be represented by hydrogen storage or pumped hydroelectric. Electricity transmission is described in relation to a number of nodes that are connected by transmission lines and allows for the identification of bottlenecks in the transmission system. In relation to generation capacity, the tool may invest optimally in electricity and CHP technologies. The investments respect specified restrictions e.g., in relation to maximum investment addition per year, or maximum fuel available. Also, BALMOREL considers all costs within the energy-system as well as SO_2 and NO_X penalties.

BALMOREL has been applied to projects in Denmark [55–57], Norway [58], Estonia [58], Latvia [59], Lithuania [60], Germany [4], and countries outside of Europe [61]. It has been used to analyse security of electricity supply [62,63], the role of demand response [55], wind power development [57,61], the role of natural gas [56], development of international electricity markets [64], market power [65], investigate the expansion of district heating in Copenhagen (an on-going project) [66], the expansion of electricity transmission [58], international markets for green certificates and emission trading as well as environmental policy evaluation [67], unit commitment [55–57], compressed-air energy storage [68], and learning curves [69]. To date the highest renewable-penetrations simulated by BALMOREL are 50% in the electricity sector [57] and 10% in the transport sector [54].

4.3. BCHP Screening Tool

The BCHP Screening Tool is a computer program for assessing the savings potential of combined cooling, heating, and power systems for commercial or institutional buildings. It was developed by the Oak Ridge National Laboratory in the USA [16]. Two versions have been completed so far, with releases in 2003 and 2007. The second version, which has been downloaded already over 2000 times, can be obtained for free from [16]. The training period varies between 2 and 7 days for a basic analysis depending on previous experience, while moving from a basic analysis to an advanced analysis would take approximately 1–2 weeks.

The BCHP Screening Tool is specifically designed for a single-project investigation in commercial-buildings, although commercial campuses can be handled by experts. It consists of databases for HVAC (heating, ventilating, and air-conditioning) equipment, electric generators, thermal-storage systems, prototypical commercial-buildings, climate data, and electric and gas utility rates. The tool is structured to perform parametric analyses between a baseline building, typically a conventional building without a CHP system, and up to 25 alternative CHP scenarios: these include varying selections for building mechanical systems and operating schedules. The economic analyses must be preformed separately to allow all factors to be handled correctly.

The BCHP Screening Tool has mainly been used for informal publications to US federal agencies. As it is focused on single-project investigations within the commercial and institutional sector, it does not model large sections of the electricity, heat, or transport sectors.

4.4. COMPOSE

COMPOSE (Compare Options for Sustainable Energy) is a techno-economic energy-project assessment tool developed by Aalborg University in Denmark in 2008 [17,70]. The aim of COMPOSE is to assess to which degree energy projects may support intermittency, while offering a realistic evaluation of the distribution of costs and benefits under uncertainty. COMPOSE is currently on version 1.06, and it can be freely downloaded from [17]. Presently four people have downloaded the tool and to complete a typical analysis using COMPOSE, three days of training are required.

The tool has a user-defined system which means that COMPOSE can simulate all financial aspects as well as all thermal generation, renewable energy, storage/conversion, and transport technologies in a single-project investigation. However, it does focus particularly on cogeneration with an electric boiler or compression heat pump. User-defined uncertainties may also be specified to allow for extensive risk analyses, such as specifying uncertainty ranges for wind production. The analysis is carried out using a one-hour time-step over a user-defined number of years. Special features currently include Monte Carlo risk assessments, integrated Wiki [17], import of projects from energyPRO (see Section 4.10), import/export of hourly distributions from/to EnergyPLAN (see Section 4.9), and import of climate data for localisation of distributions from RETScreen (see Section 4.30). The current functionality is focusing on the modelling framework design.

COMPOSE has been used in [70] to help identify options for dealing with intermittency, related to the large-scale penetration of wind power on the West Danish energy-system. It has also been used in [71] to analyse the benefits of energy storage and relocation options (such as the integration of heat pumps with CHP plants).

4.5. E_4cast

E_4cast is a partial-equilibrium tool for the Australian energy-system, which is used by the Australian Bureau of Agricultural and Resource Economics (ABARE) to project Australia's long-term energy production, consumption, and trade [18]. E_4cast has been regularly updated since 2000, but it is not for sale: instead customers pay to have their analysis completed at a rate of AU$1,500 (€838) per day. The exact number of users is not available.

E_4cast provides a detailed analysis of the energy sector by representing energy production, trade, and consumption in a comprehensive manner [72]. Typically, E_4cast is used to simulate future energy requirements and identify how these requirements can be met. The analysis is completed using an annual time-step for up to a maximum of 30 years. All costs are accounted for by the tool and energy consumption is projected by fuel, by industry, and by region, with all inputs based on annual amounts. This common structure of fuel is replicated in each of the tool's user-defined regions, while national figures are produced by summing these regional totals. In each region, conversion activities such as electricity generation and petroleum refining deliver energy to final end-users such as transport (includes conventional vehicles, and rail), manufacturing, mining, agriculture, residential, and commercial. The primary and final fuels consumed in each region can include crude oil and petroleum products, LPG, black and brown coal, coke and coal by-products, natural gas, electricity, and renewables (hydro, biomass, biogas, wind, and solar energy).

E_4cast is primarily used to predict future scenarios within the Australian energy-system [72]. It has also been used by the Australian Department of Climate Change (DCC) to evaluate the impact of various legislated and stipulated policies on emissions and renewable energy [73].

4.6. EMCAS

EMCAS (Electricity Market Complex Adaptive System) uses a novel agent-based modelling approach to simulate the operation of the power system [19]. It was developed in the USA in 2002 and is regularly updated by Argonne National Laboratory [74]. It is used by universities, transmission companies, system operators, and power companies in approximately 20 countries, but the exact number of users is not available. To complete a typical analysis using EMCAS requires approximately two weeks of training, but an additional week is necessary to complete an advanced analysis.

EMCAS is used to probe the possible operational and economic impacts of various external events on the electricity sector in an energy-system. The analysis is completed on an hourly basis over a user-specified period of time. Market participants are represented as 'agents' with their own set of objectives, decision-making rules, and behavioural patterns. Agents are modelled as independent entities that make decisions and take actions using limited and/or uncertain information available to them, similar to how organisations and individuals operate in the real world. EMCAS can simulate all costs (with the option of additional costs), thermal generation, and renewable generation technologies, as well as all energy storage/conversion technologies that do not involve hydrogen, and all electric vehicles. In early 2007, the capability to analyse power system investments and expansion issues was added using a multi-agent-based profit maximisation approach.

EMCAS has been used in a number reports which are listed on its homepage [74]. These include the analysis of plug-in-hybrids and their effects on the transmission grid [75], a study on the market competitiveness for the US Midwest Power Market [76], simulation of Central European electricity markets [77], short-term electricity market analysis of the Iberian system [78], system expansion planning for Iberian markets [79] and Korean markets [80], price-forecasting and unit commitment in UK electricity markets, and an analysis of the Croatian electricity market [79,81].

4.7. EMINENT

The EMINENT tool is designed to help introduce new energy technologies and new energy solutions into the market in a faster way. The tool was created in the Netherlands in 2005 by the Netherlands Organisation for Applied Scientific Research (TNO) during the EMINENT project [20]. It is still at the development stage so external users have limited access. To use EMINENT, approximately one month of training will be required and a cost has not been decided for purchasing the tool.

EMINENT consists of a database and an assessment tool. These provide the user with a general framework for the assessment and evaluation of new energy technologies and new energy solutions on national energy-systems. It evaluates the performance and potential impact of early stage technologies (ESTs) in a pre-defined energy supply chain over a one-year time-period. The tool is composed of two databases: a database of national energy infrastructures which contains information of the number of consumers per sector, type of demand, typical quality of the energy required, and the consumption and installed capacity per end-user; and a second database that contains key information on new thermal generation, heat, and renewable technologies that are currently under development. Furthermore, existing thermal generation, heat, and renewable technologies are also included, to enable the design of the most favourable energy chains. The tool is able to assess a technology at financial (including all costs except taxes), environmental, and energy level, comparing it with other technologies that already exist in the market.

An overview of the EMINENT tool is provided in [82], typical case studies are presented in [83], and a comparison between EMINENT and five other tools is made in [9].

4.8. EMPS

EMPS (EFI's Multi-Area Powermarket Simulator) has been developed and continually refined since 1975 by SINTEF (Stiftelsen for industriell og teknisk forskning) Energy Research (previously EFI) in Norway [21]. EMPS is a computer tool for the simulation and optimisation of the operation of power systems with a certain share of hydro power. Over ten versions of the software have been created and more than 30 users have bought it. It costs NOK 500,000 (€54,930) to purchase and it takes one month of training to use.

The EMPS tool simulates the electricity sector only, although parallel gas and CO_2 grids have been modelled experimentally. EMPS aims at optimal use of hydro resources and thermal generation in relation to uncertain inflows, power demand, thermal generation availability, and spot type transactions between areas. In addition to all thermal-generation technologies, wind power, and pumped-hydroelectric energy storage are also considered as well as four optional costs: fuel, variable O&M, CO_2 penalties, and taxes. EMPS consists of two parts: firstly, a strategy evaluation part computes regional decision tables in the form of expected incremental water capacity values. Secondly, a simulation part computes the optimal operational decision for a sequence of hydrological years. The time resolution in the tool is one week, with a duration curve to model variations in demand within the week (e.g., peak load, off-peak day, night, weekends), and the analysis can be carried out for up to a 25-year period. Results from EMPS comprise of detailed generation plans, consumption, rationing, exchange between areas, fuel costs, marginal costs (spot prices), marginal values of increased interconnection capacities, and others.

Previous case studies undertaken using EMPS include analysis of increased transmission capacity between the Nordic power market and continental Europe [84], planning for new hydro power production [85], price-forecasting by simulating the operation of the entire power system and electricity market [86,87], and identifying vulnerabilities in the Nordic power system [88]. An extended tool which includes a detailed load flow algorithm has also been used to study the effects of CO_2 quotas e.g., on transmission grid expansion [89].

4.9. EnergyPLAN

EnergyPLAN has been developed and expanded on a continuous basis since 1999 at Aalborg University, Denmark [90]. Approximately ten versions of EnergyPLAN have been created and it has been downloaded by more than 1200 people. The current version can be downloaded for free from [22] while the training period required can take a few days up to a month, depending on the level of complexity required.

EnergyPLAN is a user-friendly tool designed in a series of tab sheets and programmed in Delphi Pascal. The main purpose of the tool is to assist the design of national or regional energy planning strategies by simulating the entire energy-system: this includes heat and electricity supplies as well as the transport and industrial sectors. All thermal, renewable, storage/conversion, transport, and costs (with the option of additional costs) can be modelled by EnergyPLAN. It is a deterministic input/output tool and general inputs are demands, renewable energy sources, energy station capacities, costs, and a number of different regulation strategies for import/export and excess electricity production. Outputs are energy balances and resulting annual productions, fuel consumption, import/export of electricity, and total costs including income from the exchange of electricity. In the programming, any procedures which would increase the calculation time have been avoided, and the computation of 1 year requires only a few seconds on a normal computer. Finally, EnergyPLAN optimises the operation of a given system as opposed to tools which optimise investments in the system.

Previously, EnergyPLAN has been used to analyse the large-scale integration of wind [91] as well as optimal combinations of renewable energy sources [92], management of surplus electricity [93], the integration of wind power using Vehicle-to-Grid electric-vehicles [94], the implementation of small-scale CHP [95], integrated systems and local energy markets [96], renewable energy strategies for sustainable development [97], the use of waste for energy purposes [98], the potential of fuel cells and electrolysers in future energy-systems [99,100], the potential of thermoelectric generation (TEG) in thermal energy-systems [101], and the effect of energy storage [71], with specific work on compressed-air energy storage [102,103] and thermal energy storage [90,91,104]. In addition, EnergyPLAN was used to analyse the potential of CHP and renewable energy in Estonia, Germany, Poland, Spain, and the UK [105]. Other publications can be seen on the EnergyPLAN website [22], while an overview of the work completed using EnergyPLAN is available in [13]. Finally, EnergyPLAN has been used to simulate a 100% renewable energy-system for the island of Mljet in Croatia [7] as well as the countries of Ireland [106] and Denmark [1,107].

4.10. energyPRO

The energyPRO tool is a complete modelling software package for combined techno-economic design, analysis, and optimisation, of both fossil and bio-fuelled cogeneration and trigeneration projects, as well as wind power and other types of complex energy-projects. It is developed and maintained by the company EMD International A/S in Denmark [23], and over 50 versions have been released over the past 20 years. The tool can be bought for €2700 to €5600 depending on the modules chosen, and currently there are more than 1000 users in 16 countries. One day of training is necessary to use energyPRO.

The energyPRO tool is specifically designed for a single thermal or CHP power-plant investigation. It can model all types of thermal generation except nuclear, all renewable generation, and all energy storage units to complete the analysis. It only models district heating in the heating sector and does not include transport technologies. The analysis is carried out using a one-minute time-step for a maximum duration of 40 years (which represents the typical lifetime of a power-plant). In addition, energyPRO accounts for all system costs along with SO_2 and NO_X penalties.

To date energyPRO has been used to analyse CHP plants participating in the spot market or selling electricity at fixed tariffs [108], to simulate compressed-air energy storage in the spot market [103], to analyse CHP plants instead of boilers on district-heating networks [109], and to identify the optimal size of a CHP unit and thermal storage when a CHP plant is selling on the spot market [110]. Also, energyPRO has modelled single-projects where 100% of the demand was supplied by renewable resources (excluding transport) [111].

4.11. ENPEP-BALANCE

The non-linear, equilibrium ENPEP-BALANCE tool matches the demand for energy with available resources and technologies. It was developed by Argonne National Laboratory in the USA in 1999 and it is used in over 50 countries, but the exact number of users is not known. ENPEP-BALANCE can be downloaded for free from [24], and it takes approximately one week of training for basic applications or two weeks of training for advanced applications.

ENPEP-BALANCE uses a market-based simulation approach to determine the response of various segments of the energy-system to changes in energy prices and demand levels. The analysis is carried out on an annual basis for up to a maximum of 75 years, and typically on national energy-systems. The tool relies on a decentralised decision-making process in the energy sector and basic input parameters include information on the entire energy-system structure. All thermal and renewable generation can be simulated, but the only storage/conversion technology accounted for is hydrogen production. Also, all financial aspects are considered as well as the option of adding additional costs. ENPEP-BALANCE simultaneously finds the intersection of supply and demand curves for all energy supply forms and all energy uses included in the energy network. Equilibrium is reached when ENPEP-BALANCE finds a set of market clearing prices and quantities that satisfy all relevant equations and inequalities. The tool employs the Jacobi iterative technique to find the solution that is within a user-defined convergence tolerance.

Some of the case studies which ENPEP-BALANCE has been used for include analysing Mexico's future energy needs and estimating the associated environmental burdens [112], developing greenhouse-gas (GHG) emissions projections for Turkey [113], and a GHG mitigation analysis for Bulgaria [114]. A full range of other publications that ENPEP-BALANCE participated in is available at [115]. Finally, ENPEP-BALANCE has been used to simulate nearly 20% of the electricity production from renewable energy sources within an energy-system [116].

4.12. GTMax

GTMax (Generation and Transmission Maximisation Tool) simulates the dispatch of electric generating units and the economic trade of energy among utility companies, using a network representation of the power grid [25]. It was created by Argonne National Laboratory in 1995 [74] and is used by universities, consultants, and power companies in approximately 25 countries. Prices can only be obtained by contacting Argonne National Laboratory [25]. To use the basic functions of GTMax one week of training is required, and to use the advanced features an additional week is necessary.

In GTMax the generation and energy transactions serve electricity loads that are located at various locations throughout the simulated region, which is typically a national energy-system. GTMax can simulate both the electricity sector and district-heating networks. All thermal generation, renewable generation, and electric vehicles can be simulated by the tool as well as all storage/conversion technologies that do not involve hydrogen. In GTMax, links and transformers connect generation and energy delivery points to load centres. The objective is to maximise the net revenues of power systems by finding a solution that increases income while keeping expenses at a minimum. GTMax computes and tracks hourly energy transactions, market prices, and production costs (excluding investment and fixed O&M costs, but with the option of adding any additional costs), and it can be run for all 52-weeks in a year or for selected representative weeks.

GTMax has been used for a number of studies which are listed at [117]. Some examples are an investigation into a future regional electricity-market in South-Eastern Europe [118], an evaluation of a new transmission interconnection between Ethiopia and Kenya [119], and to evaluate the benefits of using high power flows from Glen Canyon Dam to improve natural, recreational, and cultural resources in Grand Canyon National Park [120].

4.13. H_2RES

H_2RES is a balancing tool that simulates the integration of renewable energy into energy-systems. The tool was developed in 2000 by the Instituto Superior Técnico in Lisbon, Portugal and the Faculty of Mechanical Engineering and Naval Architecture at the University of Zagreb, Croatia [26]. H_2RES is not yet sold to external users; instead it is supplied to internal users to complete their research. The training period required to use the tool is up to two months.

H_2RES balances the hourly time series of water, electricity, heat, and hydrogen demand, as well as appropriate storages and supply over any user-defined period. The tool has been specifically designed to increase the integration of renewable sources and hydrogen, into island energy-systems which operate as stand-alone systems. It can serve as a planning tool for single wind, hydro, or solar power systems, as well as for planning larger energy-systems. H_2RES considers all forms of thermal generation except nuclear power and all renewable technologies except tidal power. Also, all storage/conversion technologies are considered by H_2RES except compressed-air energy storage, but only hydrogen vehicles are simulated in the transport sector. The simulation of the electricity sector is based on criteria for the maximum acceptable proportion of intermittent and renewable-electricity in the power system. Using these criteria, H_2RES integrates as much renewable/intermittent energy as possible into the energy-system, while either storing or discarding the rest of the renewable/intermittent output. Excess renewable-electricity can be stored in a pumped-hydroelectric, battery or hydrogen energy storage facility, consumed by some non-time critical loads (deferrable loads), or used for desalination. Costs are currently not considered in H_2RES, but they will be added in the near future.

H_2RES has previously been used to create a methodology for the assessment of alternative scenarios in energy and resource planning on island energy-systems [121], to analyse different energy scenarios in Malta [122], to investigate the role of hydrogen in future island energy-systems [123], more specifically by aiding the integration of renewable energy [124], and to analyse the potential energy production from biomass for a wood processing factory [125]. Finally, H_2RES has previously simulated a 100% renewable energy-system for both the island of Mljet in Croatia [126] (the results obtained were compared to those obtained using the EnergyPLAN tool discussed in Section 4.9 [7]) and the island of Porto Santo in Portugal [127].

4.14. HOMER

HOMER is a user-friendly micropower design tool developed in 1992 by the National Renewable Energy Laboratory in the USA, who have released 42 versions of the program. It can be freely downloaded from [27], and to date 32,000 people have downloaded HOMER. A typical analysis can be run after one day of training.

HOMER simulates and optimises stand-alone and grid-connected power systems with any combination of wind turbines, PV arrays, run-of-river hydro power, biomass power, internal combustion engine generators, microturbines, fuel cells, batteries, and hydrogen storage, serving both electric and thermal loads (by individual or district-heating systems). Also, all costs (including any pollution penalties) except fuel handling costs and taxes are included. The simulation considers a one-year time-period using a minimum time-step of 1 min. It performs a sensitivity analysis which can help the analyst to do 'what-if' analyses and to investigate the effects of uncertainty or changes in input variables. The objective of the optimisation simulation is to evaluate the economic and technical feasibility for a large number of technology options, while considering variations in technology costs and energy resource availability.

A list of publications that involved HOMER is available from its homepage [27], but numerous others have been completed: HOMER has previously been used to assess the wind energy potential at individual locations in Ethiopia [128], to assess the feasibility of a stand-alone wind-diesel hybrid in Saudi Arabia [129], to assess the feasibility of zero-energy homes [130], and simulate a stand-alone system with hydrogen in Newfoundland, Canada [131]. Finally, HOMER has previously been used to simulate a system where 100% of the electricity and heat demand was met by renewable sources [132].

4.15. HYDROGEMS

HYDROGEMS is a set of hydrogen energy tools suitable for the simulation of integrated hydrogen energy-systems; particularly renewable energy based stand-alone power systems [28]. The tools have been developed at the Institute for Energy Technology since 1995, first as part of a PhD-study [133] and later in various projects [134–138]. HYDROGEMS were made publically available for TRNSYS15 users [139] in 2002, and in 2006 it was fully integrated into TRNSYS16 (see Section 4.34). To use HYDROGEMS requires about one month of training for TRNSYS users, or three months of training for others.

The HYDROGEMS-tools can be used to analyse the performance of hydrogen energy-systems down to one-minute time-steps. The tools are particularly designed to simulate hydrogen mass flows, electrical consumption, and electrical production, but can also be used to simulate the thermal performance of integrated hydrogen systems. The HYDROGEMS-library consists of the following component tools: wind energy conversion systems, photovoltaic systems, water electrolysis, fuel cells, hydrogen gas storage, metal hydride hydrogen storage, hydrogen compressor, secondary batteries (lead-acid), power conditioning equipment, and diesel engine generators (multi-fuels, including hydrogen). The HYDROGEMS component tools are based on thermodynamics, electrochemistry, and applied physics (e.g. electrical, mechanical, and heat and mass transfer engineering). The empirical parts of the tools are designed so that it is possible to find default parameters and/or calibrate coefficients based on data found in literature (e.g. product data sheets, journal papers and articles). Access to actual data from the hydrogen demonstration systems being modelled is essential to ensure the validity of the models created. From a financial viewpoint, fuel prices, investment, fixed O&M, and variable O&M costs can all be accounted for.

HYDROGEMS was initially used to analyse the operation of a stand-alone PV–hydrogen system [133,135,140,141], but more recently it has been used to investigate stand-alone wind–hydrogen systems [134,137,142]. It has also simulated renewable-based electrolytic hydrogen fuelling-stations [136,138].

4.16. IKARUS

IKARUS is a dynamic bottom-up linear cost-optimisation scenario tool for national energy-systems, which is maintained by the Institute of Energy Research at Jülich Research Centre, Germany [29]. To date 20 versions have been released, but the current version is not commercially available. However, earlier versions are sold for approximately €250 and to use IKARUS requires at least three months of training.

A time-step of five years is used by IKARUS and each one is optimised by itself using the heritage from all periods before. The tool can simulate a timeframe of approximately 40 years (usually up to 2050). Unlike perfect-foresight tools, IKARUS does not take into account future changes in each time-step during the optimisation to provide a realistic character of prognosis and projection. Therefore, aspects like reaction to sudden changes (e.g. of energy prices), flexibility of technical scenarios, lost opportunities, etc., can be examined. Interactions with macroeconomic input/output tools, dependencies on elasticities, and technological learning are also possible. The objective is normally to reduce total system costs, but numerous other objectives can be specified such as emissions reductions. IKARUS simulates all sectors of the energy-system and almost all generation, storage/conversion, and transport technologies: the only technologies not considered are wave, tidal, compressed-air energy storage, and intelligent battery-electric-vehicles.

Some investigations that IKARUS has contributed to are an investigation into the role of carbon capture and storage (CCS) in reducing carbon emissions [143], the effects of stochastic energy prices on long-term energy scenarios [144], the introduction of fuzzy constraints to provide a better representation of political decision-making processes in the energy economy and energy policy [145], and the implications of high energy prices [146].

4.17. INFORSE

INFORSE (International Network for Sustainable Energy) is an energy balancing tool for national energy-systems developed in 2002 by the network [30]. It is currently not for sale to external users, but instead is distributed to non-governmental organisations (NGOs). To use INFORSE requires 2–4 weeks of training.

The tool consists of linked spreadsheets which are used to input the details of the energy-system being modelled. These include details about energy production, energy demand, energy trends, and energy policies. All thermal generation, renewable generation, and hydrogen-based storage/conversion devices except tidal power are available. The transport technologies included are conventional, battery-electric, and hydrogen vehicles as well as rail. The results from INFORSE give an overview for the possible energy development in a country or region, by providing an energy balance for every decade simulated over a maximum timeframe of 100 years. This illustrates the potential use of renewable energy and identifies the trends in energy efficiency, energy services, and energy policies entered into INFORSE. The costs in INFORSE include an overall energy cost and CO_2 costs.

INFORSE has been used to simulate the potential utilisation of renewable energy by 2050 for a number of countries including Belarus, Bulgaria, Denmark, Latvia, Lithuania, Romania, Russia, Slovakia, Ukraine, and the UK, as well as simulating a 100% renewable energy-system for Denmark by 2030. These studies can be accessed via the INFORSE homepage [30].

4.18. Invert

The In*vert* simulation tool supports the design of efficient promotion schemes for renewable and efficient energy technologies [31]. It was developed by the Energy Economics Group (EEG) at Vienna University of Technology in 2003 (who regularly add new features), and the current version can be freely downloaded from [31]. To date there are 170 users, and it takes approximately one day to learn how to use the software.

In*vert* is primarily used to simulate national energy-systems. The simulation can be run for up to a 25-year period, using one-year time-steps, and it accounts for all sectors of the energy-system. All thermal generation except nuclear power and all renewable generation except wave and tidal can be modelled. However, no storage/conversion technologies and only biofuel transportation are simulated. In*vert* focuses specifically on the heat sector by analysing the utilisation of heat pumps, solar thermal, conventional heating systems etc. As the core objective of In*vert* is to evaluate the effects of different promotion schemes, all costs (except fuel handling and variable O&M costs) and feed-in tariffs, subsidies, soft loans, etc., can be defined in the tool. Outputs include costs, unit productions, fuel consumption, mix of energy carriers, energy demands, and installed capacities of units required.

In*vert* has been used previously to identify sustainable energy solutions for the town of Jordanów in Poland, the city of Vienna in Austria, the regions of Baden Württemberg in Germany and Cornwall in the United Kingdom, the island of Crete in Greece, and the entire country of Denmark: a full overview of these studies and their conclusions are available in [147], while detailed conclusions are available in [148,149]. Finally, In*vert* has been used to identify policies to support renewable energy in the heat sector [150] and also, to analyse the influence of different promotion schemes on the penetration of renewables in the electricity sector for the island of Crete [5].

4.19. LEAP

LEAP (Long-range Energy Alternatives Planning) is an integrated modelling tool that can be used to track energy consumption, production, and resource extraction in all sectors of an economy. LEAP was developed in 1980 in the USA and is currently maintained by the Stockholm Environment Institute [32]. It is free to qualified users in developing countries, but there is a cost for OECD (Organisation for Economic Co-operation and Development) based users. Currently LEAP has over 5000 users in 169 countries and to use LEAP typically requires three or four days of training (online training is available in English, French, Spanish, Portuguese, and Chinese).

LEAP is usually used to analyse national energy-systems. It functions using an annual time-step, and the time horizon can extend for an unlimited number of years (typically between 20 and 50). LEAP supports a number of different modelling methodologies: on the demand-side these range from bottom-up, end-use accounting techniques to top-down macroeconomic modelling. On the supply side, it provides a range of accounting and simulation methodologies for modelling electricity generation and capacity expansion planning. LEAP does not currently support optimisation modelling, although this capability is currently being developed in conjunction with the IAEA (International Atomic Energy Agency) in Vienna. Overall, LEAP can simulate all sectors, all technologies, and all costs within an energy-system, as well as externalities for any pollutants, decommissioning costs, and unmet demand costs. LEAP also includes a scenario manager that can be used to describe individual policy measures. The resulting scenarios are self-consistent storylines of how an energy-system might evolve over time. LEAP displays its results as charts, tables, and maps which are user-defined and can be exported to Excel or PowerPoint. The results include fuel demands, costs, unit productions, GHG emissions, air-pollutants, and more. Usually, these results are then used to compare an active policy scenario versus a policy neutral business-as-usual scenario.

A list of 34 reports involving LEAP can be obtained from [151]. In addition, LEAP has been used for over 70 peer-reviewed journal papers including, an analysis of the potential reductions in energy demand and GHG emissions within road transport in China [152], identifying the feasible penetration of sustainable energy on the Greek island of Crete [153], and an investigation into the benefits of improved building energy-efficiencies in China [154].

4.20. MARKAL/TIMES

The MARKAL/TIMES family are energy/economic/environmental tools developed in a collaborative effort under the auspices of the International Energy Agency's "Energy Technology Systems Analysis Programme", which started in 1978 [155]. At the moment, MARKAL/TIMES is used in 70 countries by 250 institutions (of which 75% are active users). The source code is distributed free-of-charge by signing a Letter of Agreement. However, the code is written in GAMS, which is a commercial language and therefore has to be purchased. In addition, both an interface and a solver must also be purchased to use the source code effectively: as a result the total cost is approximately US$1780–US$4420 (€1275–

€3170) for an educational license and approximately US$13,700–US$21,200 (€9825–15,200) for a commercial license [156]. The most demanding part of MARKAL/TIMES is training which takes some months.

MARKAL/TIMES are general purpose model generators tailored by the input data to represent the evolution over a period of usually 20–50 or 100 years, of a specific energy–environment system at the global, multi-regional, national, state/province, or community level. Each annual load duration curve, hence each annual variable can be detailed by as many user-defined time slices as desired at three levels: seasonal (or monthly), weekdays/weekends, hour of the day. All thermal, renewable, storage/conversion, and transportation technologies can be simulated by MARKAL/TIMES. Also, many different energy networks or reference energy-systems are feasible for each time period simulated. Therefore, MARKAL/TIMES finds the 'best' reference energy-system for each time period, by selecting the set of options that minimises total discounted system cost or the total discounted surplus over the entire planning horizon. This is done within the limits of all imposed policy and physical constraints. All costs as well as externalities can be accounted for in the analysis.

The MARKAL/TIMES tools have been used for countless studies [157], which include an investigation into the future prospects of hydrogen and fuel cells [158–160], as well as hydrogen vehicles [161,162], examinations into the future role of nuclear power [163] and nuclear fusion [164–166], and the impacts of wind power on the future use of fuels [167]. Also, MARKAL/TIMES has been used to simulate European Commission integrated policies on the use of renewable sources, climate change mitigation and energy efficiency improvement, the so called 20–20–20 targets, and far more stringent targets in the longer term at the national and pan EU level [168].

4.21. Mesap PlaNet

Mesap (Modular Energy-System Analysis and Planning Environment) is an energy-system analysis toolbox, and PlaNet (Planning Network) is a linear network module for Mesap. It was originally developed by the Institute for Energy Economics and the Rational Use of Energy (IER) at the University of Stuttgart in 1997 [169–171], but it is now maintained by the German company Seven2one Informationssysteme GmbH [34]. In total 15 versions of Mesap PlaNet have been released and it has approximately 20 users. To purchase Mesap PlaNet costs at least €11,500, but there is a discount for research groups. It takes five days of training to learn how to use Mesap PlaNet.

Mesap PlaNet is designed to analyse and simulate energy supply, demand, costs, and environmental impacts for local, regional, national, and global energy-systems. A detailed cost calculation determines the specific production cost of all commodities in the reference energy-system, based on the investment, fixed O&M, and variable O&M costs. The tool uses a technology-oriented modelling approach, where several competitive technologies that supply energy services are represented by parallel processes. All thermal generation, renewable, storage/conversion, and transport technologies are considered in the simulation. The simulation is carried out in a user-specified time-step which ranges from 1 min to multiple years, while the total time-period is unlimited.

Mesap PlaNet has previously been used to simulate global energy supply strategies [172,173] and to compare energy-efficiency strategies in Slovenia [174]. It has also simulated a 100% renewable energy-system [173].

4.22. MESSAGE

MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) has been developed by the International Institute for Applied Systems Analysis (IIASA) in Austria since the 1980s [35,175]. Depending on the scope and research question, various different versions of MESSAGE have been created with several hundred users. It is free for academic purposes, and a special agreement between the IIASA and IAEA (International Atomic Energy Agency) permits its use within the IAEA and its member states. The latter has facilitated a number of in-depth training courses for energy experts in the IAEA member countries: usually taking approximately 2 weeks of training to be able complete basic applications.

MESSAGE is a systems engineering optimisation tool used for the planning of medium to long-term energy-systems, analysing climate change policies, and developing scenarios for national or global regions. The tool uses a 5 or 10 year time-step to simulate a maximum of 120 years. All thermal generation, renewable, storage/conversion, transport technologies, and costs (including SO_2 and NO_X costs) can be simulated by MESSAGE as well as carbon sequestration. The tool's principal results are the estimation of global and regional multi-sector mitigation strategies instead of climate targets. MESSAGE determines cost-effective portfolios of GHG emission limitation and reduction measures. It has recently been extended to cover the full suite of GHGs and other radiative substances, for the development of multi-gas scenarios that try to stabilise future CO_2-equivalent concentrations [176].

MESSAGE has previously been used to develop global energy transition pathways for the World Energy Council [177] and GHG emission scenarios for the Intergovernmental Panel on Climate Change [178]. Other studies include scenario assessment with a focus on climate stabilization [179,180], national studies of innovation programs on the Iranian electricity sector [181], policy options for increasing the use of renewable energy [182], energy supply options in the Baltic states [183], and designing a sustainable energy plan for Cuba [184]. MESSAGE has been used to simulate renewable-energy penetrations of 70% in the electricity sector, 60% in the heat sector, and 55% in the transport sector, in the GGI B1 scenario of [180] (all the quantitative data for this study is available at [185]).

4.23. MiniCAM

MiniCAM is a fast and flexible partial-equilibrium tool designed to examine long-term, large-scale changes in global and regional energy and agriculture systems. It was originally developed by the Pacific Northwest National Laboratory in the USA in the 1980s, and it continues to evolve in its capability and detail [36]. A user version of MiniCAM is available for free upon request from [37], and it currently has several hundred users. It takes several months to learn the complete functionality of the tool.

MiniCAM has global coverage in the form of 14 distinct regions. It simulates economic activity, energy consumption, and emissions, in 15-year time-steps from 1990 to 2095. Markets are defined for oil (conventional and unconventional), gas, coal, biomass, uranium, carbon, and agricultural products. All energy-system costs are also included in the tool. MiniCAM has a strong focus on energy supply technologies including electricity generation (from all thermal and renewable technologies except CHP plants, wave, and tidal), hydrogen production, synthetic fuel production, and geological carbon sequestration from fossil-fuels (during electricity generation, hydrogen production, and synthetic fuel production). However, district heating as well as pumped-hydroelectric, battery, hydrogen, and compressed-air energy storage are not considered. MiniCAM is specifically designed to address issues associated with global change.

MiniCAM has been used to evaluate the impact of oil and nuclear power in the past and future [186], analyse the feasibility of GHG stabilisation by 2100 [187], investigate the future contribution of the transport sector to GHG reductions [188], and to study the economic and technological requirements for various stabilisation levels of GHG [189]. Finally, MiniCAM has been used to simulate a suite of advanced technology including renewable energy and energy efficiency [190].

4.24. NEMS

The National Energy Modelling System (NEMS) is a large, regional, energy–economy–environmental tool for US energy markets [38]. It was originally developed by the Energy Information Administration (EIA) (part of the United States government) in 1993, and it has approximately 20 users. NEMS is free but it requires FORTRAN, EViews, IHS Global Insight model, and OML (a linear-programming package) to run which must be purchased. The training required to use NEMS is very diverse depending on the user's requirements.

Overall, NEMS represents the behaviour of energy markets and their interactions with the US economy on an annual basis up to the year 2030. NEMS balances the quantities that producers are willing to supply at different energy prices, with the quantities that consumers wish to consume. The system reflects market economics, industry structure, and existing energy policies and regulations that influence market behaviour. NEMS consists of four supply modules (oil and gas, natural gas transmission and distribution, coal, and renewable fuels); two conversion modules (electricity and petroleum refineries); four end-use demand modules (residential, commercial, transportation, and industrial); one module to simulate energy/economy interactions (macroeconomic activity); one module to simulate world oil markets (international energy activity); and one module that provides the mechanism to achieve a general market equilibrium. The only notable technologies that are not considered in NEMS are wave, tidal, compressed-air energy storage, and all hydrogen technologies except hydrogen vehicles. The results from NEMS project the energy, economic (includes all costs as well as SO_2 and NO_X penalties), environmental, and security impacts on the United States, for alternative energy policies and for different assumptions about energy markets.

NEMS is used every year to create the US Annual Energy Outlook [191]. It has also been used to evaluate the future options for coal-fired power-plants in the US [192], the impact of carbon reduction policies on the electricity sector [193], to analyse more energy-efficient technologies in the US building sector [194], and renewables on the US energy markets [195]. NEMS has simulated a renewable-energy penetration of 25% in the electricity sector and 12% in the transport sector [196]. A full list of reports using NEMS is available at [197], and the accuracy of previous projections from NEMS are discussed in [198].

4.25. ORCED

The ORCED (Oak Ridge Competitive Electricity Dispatch) tool dispatches power-plants in a region to meet the electricity demands for any given year up to 2030. The Oak Ridge National Laboratory (ORNL) in the USA have developed three versions of the software since the first edition in 1996, and the latest can be freely downloaded from [39]. The number of existing users is unknown, and it will take approximately one week of training to learn how to use ORCED.

ORCED uses public sources of data describing electric power units such as those from the National Energy Modelling System (see Section 4.24), and hourly demands from utility submittals to the Federal Energy Regulatory Commission (FERC). These are projected forward to simulate a single region of the US for a given year. The simulation matches generation to demands on an hourly basis, by assuming no transmission constraints within the region as well as limited transmission in and out of the region. By running the tool with and without demand changes, such as recharging plug-in hybrids or operating distributed generation, the marginal impact of these technologies can be found. However, only the electricity sector is simulated using ORCED. It accounts for all costs considered in this study except fuel handling costs, but includes additional costs such as SO_2, NO_X, and market electricity costs. All thermal and renewable generation except wave and tidal power are also incorporated, but the only storage/conversion device considered by ORCED is pumped-hydroelectric energy storage.

ORCED has been used to assess the impacts of plug-in hybrid electric-vehicles [199] (simulated electric vehicles as additional electric load), to identify the contribution of hydropower in reducing GHG [200], and to design mechanisms for policy makers to recover transition costs from a regulated to a restructured market [201]. Additional studies (e.g., restructured power prices in the Pacific Northwest, restructuring electricity markets in Oklahoma, carbon tax impacts, biomass resources in the southeast) that have been competed are discussed on the ORCED website [39].

4.26. PERSEUS

PERSEUS (Programme-package for Emission Reduction Strategies in Energy Use and Supply-Certificate Trading) is a tool family with several different applications. It is maintained by the Institute for Industrial Production at Universität Karlsruhe in Germany and the Chair for Energy Economics at the Brandenburgische Universität Cottbus (BTU), where in total about 25 PhD theses have developed and advanced the tool [14]. It is sold in general to energy utilities and existing users include six of the largest European energy utilities. To use PERSEUS usually requires two weeks of intensive training.

PERSEUS is an energy and material flow tool applying a multi-periodic linear-programming approach. The target function demands a minimisation of all decision-relevant expenditure within the entire energy supply system, by considering all possible costs within the energy-system (including carbon trading). The relevant techno-economic characteristics of the real supply system have been considered by implementing further equations covering technical, ecological, and political restrictions. The time structure is constructed using load curves which represent typical days. There are 36–72 time slots for 1 year, and the longest timeframe that can be simulated is 50 years. PERSEUS can simulate all thermal generation, renewable, and storage/conversion technologies. However, only electric vehicles can be simulated within transport. A detailed description of the entire tool can be found in [52].

PERSEUS has been used previously to analyse the benefits of international mechanisms to combat climate change [202], the effects of the emissions trading scheme on the European electricity sector [203], and in conjunction with the AEOLIUS energy tool to analyse the effects of large-scale wind integration [51]. The largest renewable-energy penetrations simulated by PERSEUS are 100% in the electricity sector and 50% in the heat sector [52], but it has never been used to simulate renewable energy in the transport sector.

4.27. PRIMES

PRIMES simulates a market equilibrium solution for energy supply and demand [40]. It has been developed by the National Technical University of Athens (NTUA) since 1994, but it is not sold to third parties. Instead, the tool is used within consultancy projects undertaken by NTUA and partners.

The equilibrium used in PRIMES is static (within each time period) but repeated in a time-forward path, under dynamic relationships. All thermal, renewable, storage/conversion, and transport technologies can be simulated except battery energy storage, compressed-air energy storage, intelligent battery-electric-vehicles, and hybrid vehicles. PRIMES is organised in sub-tools, each one representing the behaviour of a specific 'demander' and/or a 'supplier' of energy. The tool can support policy analysis in the following fields: (1) standard energy policy issues: security of supply, strategy, costs (includes all costs), etc., (2) environmental issues, (3) pricing policy and taxation, standards on technologies, (4) new technologies and renewable sources, (5) energy efficiency in the demand-side, (6) alternative fuels, (7) conversion to decentralisation and electricity-market liberalisation, (8) policy issues regarding electricity generation, gas distribution, and new energy forms. PRIMES is organised by an energy production sub-system for supply consisting of oil products, natural gas, coal, electricity and heat production, biomass supply, and others, and by end-use sectors for demand consisting of residential, commercial, transport, and nine industrial sectors. Some demanders may also be suppliers, as for example industrial co-generators of electricity and steam.

PRIMES has previously been used to create energy outlooks for the EU [204], develop a climate change action and renewable energy policy package for the EU [205] and also, to analyse a number of different policies to reduce GHG in the EU25 by 2030 [206,207]. Finally, PRIMES has been used for several EU governments as well as private companies.

4.28. ProdRisk

ProdRisk is used for the optimisation and simulation of hydro-thermal systems with one bus bar, which has been developed by SINTEF (stiftelsen for industriell og teknisk forskning) since 1994 [41]. In total about ten versions of the software have been released, and it is used by five utilities. The cost of ProdRisk varies considerably depending on the required functionality, and one week of training is necessary to use the software.

ProdRisk uses stochastic dual dynamic programming to solve the optimisation problem. It is mainly used for medium and long-term hydro scheduling on local or regional energy-systems over a 2–5 year time horizon: the time-step used for the analysis is user-defined as hourly, daily or weekly. Only the electricity sector is modelled by ProdRisk and it simulates four technologies: thermal power-plants, wind power, hydro power, and pumped-hydroelectric energy storage. The main stochastic inputs for ProdRisk are inflows to the reservoirs and market prices for electricity (based on fuel prices, fixed O&M costs and taxes), if market prices are modelled externally. The outputs are scenarios for reservoir operation, hydro production, marginal value of water in different reservoirs, and a profit distribution. ProdRisk can also be used as a market simulator for a one price area system.

Previous case studies include assessing various operation strategies for an 11 reservoir, 7 hydro plant system [208], scheduling hydro systems in an electrical spot market [209], and assessing the optimal utilisation of flexible power contracts combined with financial hedging [210].

4.29. RAMSES

RAMSES is a simulation tool of electricity and district heat production for any number of electricity and district-heating areas, which is used by the Danish Energy Agency [42]. Six major releases have been developed and it is not sold to external users, although it has previously been used as part of a research project [211]. To use RAMSES takes one week of training.

RAMSES can simulate a 30-year time-horizon with a user-defined time-step: the time-step options are 1–4, 6, 8, 12, and 24 hours. RAMSES is primarily used to analyse the Nordic electricity market. It considers the operation of the existing plants, as well as reinvestment in new plants if required from year to year. The results are the primary energy consumption, renewable-energy penetrations, CO_2 emissions, and more. It considers all costs and thermal-generation technologies within a national energy-system, as well as wind, hydro, PV, geothermal, heat pumps, pumped-hydroelectric energy storage, compressed-air energy storage, and battery energy storage. However, RAMSES can only simulate heating requirements that are on a district heating network and no transport technologies are considered. To carry out the simulation, it uses datasets such as a plant database, information on electrical energy consumption, district heating consumption, fuel prices, fuel properties, exchange capacity, taxes, quota prices, grants, environmental costs (i.e. CO_2, SO_2, NO_X costs), etc.

RAMSES has been used for most governmental national energy forecasts in Denmark since the 90s, including "Energy 21" in 1996 [212] and "A visionary Danish energy policy 2025" in 2007 [213], as well as numerous other policy publications and baseline calculations of the Danish energy-system.

4.30. RETScreen

The RETScreen 'Clean Energy Project Analysis Software' is a decision support tool developed with contributions from government, industry, and academia by Natural Resources Canada in 1996. The software is provided free-of-charge from [43] and can be used worldwide to evaluate the energy production and savings, costs, emission reductions, financial viability, and risk for various types of 'Renewable-energy and Energy-efficient Technologies' (RETs). Approximately 1000 people download the tool every week with a total so far of more than 200,000 downloads.

Fundamental to RETScreen is a comparison between a 'base case', typically the conventional technology, and a 'proposed case' which is typically the clean energy technology. The comparison includes all costs and a number of economic indices i.e. internal rate of return (IRR) and net present value (NPV). RETScreen is ultimately not concerned with the absolute costs, but rather the costs of the proposed case that are in excess of those for the base case. If, for example, a proposed on-grid wind farm generates 50,000 MWh per year, then this is compared to 50,000 MWh of electricity from conventional sources available through the grid. Typically, the costs will not be the same for the base case and the proposed case: the proposed case will have higher initial costs and lower annual costs (i.e. savings). The software can be applied to any energy-system, ranging from individual projects to global applications. All thermal generation and renewable technologies can be accounted for using RETScreen and it can incorporate energy efficiency measures relatively easily. However, the only storage/conversion device considered is battery energy storage, and it cannot model any transport technologies.

Previously RETScreen has been used to assess the feasibility of wind farm development in Algeria [214], the feasibility of solar water heating in Lebanon [215], the viability of solar PV in Egypt [216], as well as identifying the potential of a building-integrated PV system [217] and GHG reductions in the residential sector [218]. A detailed assessment of the projects and results completed using RETScreen is available in [219].

4.31. SimREN

The SimREN (Simulation of Renewable Energy Networks) software designs 'close to reality' models of energy supply and demand systems following a bottom-up approach [44]. It was developed in 1999 by the Institute for Sustainable Solutions and Innovations (iSUSI) [220]. SimREN is not sold to third parties, but it is possible to pay for projects to be completed with price varying considerably depending on the project.

SimREN uses independent and detailed tools for energy demand, energy management, adapted distribution systems, and energy supply. It is primarily used to study different energy-systems relying on renewable sources. A national or island energy-system can be divided into N regions, with each region subdivided in up to M sub-regions, each consisting of many different suppliers and consumers. The simulation uses real measured weather data with a typical time resolution of 15 min for one simulation step (smaller and bigger steps can be chosen), over a one-year timeframe. Both supply and demand can be simulated with their dependence from the actual time and weather. All thermal generation and renewables can be simulated using SimREN except wave and tidal power. Pumped-hydroelectric energy storage, battery energy storage, and hydrogen production can also be modelled, but no transport technologies are considered (although hydrogen production can be used to simulate a demand for hydrogen vehicles). Costs are not currently included, but these will be added in the next version. A detailed overview of SimREN is available in [221].

Finally, SimREN has been used to simulate a 100% renewable energy electricity sector for the region of Catalonia in Spain [222] and a 100% renewable energy-system for Japan [221].

4.32. SIVAEL

SIVAEL is a simulation program for the electricity sector and district-heating systems developed by the Danish transmission system operator (TSO), Energinet.dk [45]. There is one external version of SIVAEL which is freely available from [223]. Currently there are four users of the software and it takes 1–2 weeks of training to complete a typical application.

SIVAEL makes a simulation with start/stop and load distribution on an hourly basis, while the maximum scenario-timeframe can range from one day to 1 year. The program can handle condensing plants, CHP plants (both back pressure and extraction), as well as wind power, battery energy storage, and trade with foreign countries. In SIVAEL wind forecast errors can be simulated using a stochastic process to replicate real-life. This enables SIVAEL to simulate the need for upward and downward regulation in the day of operation as a consequence of unreliable wind-forecasting. However, SIVAEL does not simulate heating demands outside of district-heating networks or transport technologies. The program optimises the energy-system to produce the most economical fuel combination by considering all costs except investment and fixed O&M costs. The results are a standard report for the whole simulation period and the possibility of analysing various different data down to an hourly level.

A full list of publications involving SIVAEL can be found at [45]. Previously SIVAEL has been used to analyse the impacts of CHP and large-scale wind energy on the Danish energy-system [224], to examine the environmental impacts of Danish electricity and CHP generation [225], and to project the consumption of natural gas in Denmark [226].

4.33. STREAM

STREAM is a scenario building tool that produces results for decision-making in national energy-systems, by providing a good overview of the complete energy-system on both the demand and supply side. It is maintained by the Danish company Ea Energy Analyses [227] who distribute STREAM for free [46], while all datasets used by STREAM are from other publicly available sources. So far three versions have been created and it only takes a few hours to learn how to use the tool.

STREAM consists of three spreadsheet tools: (1) the energy flow tool, (2) the energy savings tool, and (3) the duration curve tool, which are all based on a bottom-up approach. Financial calculations are calculated based on the inputs to the model and therefore, STREAM does not perform an economic optimisation of the energy-system. Instead, the purpose of the STREAM is to create an overview of GHG emissions, energy resources, fuel consumption, and fuel conversion in the energy-system using the energy flow tool, and to project the demand for energy services in the given year using the energy savings tool. The duration curve tool forms the basis for (1) the overall energy flows and (2) the economic calculations, used in the energy flow tool: for example, the expected number of operation hours at the various energy production facilities. All thermal and renewable technologies can be simulated by STREAM, but only one storage/conversion device is considered in the form of pumped-hydroelectric energy storage. In addition, the transport technologies included are conventional vehicles, battery electric-vehicles, rail, and aviation, while all costs are included except taxes.

Previous studies that have been completed using STREAM include a study on the potential of GHG and demand reductions in the Baltic Sea region (including all or part of ten countries in total) [228], as well as developing scenarios for GHG [229] and fossil-fuel [230] reductions in Denmark.

4.34. TRNSYS16

TRNSYS is a transient systems simulation program that has been commercially available since 1975. The tool is currently maintained by an international collaboration from the United States (Thermal Energy System Specialists and the University of Wisconsin-Solar Energy Laboratory), France (Centre Scientifique et Technique du Bâtiment), and Germany (TRANSSOLAR Energietechnik) [47]. 16 versions of the software have been developed to date. The latest version costs US$2100 (€1506) for an educational license and US$4200 (€3012) for a commercial license. About 1143 users bought the TRNSYS tool between 2000 and 2008, and it takes approximately one day of training to begin using TRNSYS16.

TRNSYS16 has an open modular structure with open source code which simulates the electricity and heat sectors of an energy-system. TRNSYS16 simulates the performance of the entire energy-system by breaking it down into individual components, and it is primarily used for analysing single-project, local community, or island energy-systems. It can simulate all thermal and renewable generation except nuclear, wave, tidal, and hydro power. The only electrical energy storage considered by TRNSYS16 is battery energy storage, while hydrogen systems are simulated in detail using the formally independent tool, HYDROGEMS (see Section 4.15) [28]. The tool uses a user-defined time-step, which ranges from 0.01 seconds to 1 hour, and it can analyse a time-horizon of multiple years. Also, it facilitates the addition of mathematical tools, available add-on components, and the ability to interface with other simulation programs if necessary. System costs are analysed external to TRNSYS16 in a spreadsheet tool.

TRNSYS has been used extensively to simulate solar energy applications, conventional buildings, and even biological processes. Studies include prototype solar-thermal systems [231,232], analysing the thermal performance of buildings [233], and modelling a hybrid PV–thermal solar system in Cyprus [234]. TRNSYS has been used to simulate a renewable-energy penetration of 110% in the electricity sector [235] and 90% of the heat sector [236].

4.35. UniSyD3.0

UniSyD3.0 is a multi-regional partial-equilibrium tool for national energy and economic systems. It was developed with system dynamics software by the Unitec Institute of Technology in New Zealand and Stanford University in the USA. While the tool was originally developed for New Zealand it can be readily applied to any national economy. Three versions of the software have been created since the first in 2003, and UniSyD3.0 is available for use under negotiated terms with Unitec [48] (by contacting Prof. Jonathan Leaver: jleaver@unitec.ac.nz).

UniSyD3.0 is constructed with modules that incorporate key sectors of the energy economy. The analysis is normally run using a fortnightly time-step with a maximum time-horizon of 50 years. All costs including air and water pollution costs, and all energy-system sectors except district heating are considered in the tool. The electricity sector is driven by a statically defined demand growth. All thermal generation except nuclear and all renewable technologies except wave and tidal can be simulated using UniSyD3.0. Energy conversion is considered using a hydrogen-electricity cogeneration option, but no energy storage is simulated. However, UniSyD3.0 does incorporate four separate vehicle technologies: conventional vehicles, hydrogen internal-combustion vehicles, hydrogen fuel-cell vehicles, and battery electric-vehicles. The principal outputs of the tool are profiles for electricity and hydrogen generation, vehicle fleet numbers, electricity and hydrogen production prices, GHG volumes, primary energy use, and water and air pollution costs.

Previously UniSyD has been used to analyse the potential of a hydrogen economy in New Zealand [237] and also, to assess the impact of four alternative vehicle fleets in terms of GHG emissions [238] and economic impacts [239] in New Zealand. The structure of UniSyD3.0 is described in [237] and typical results are discussed in [240].

4.36. WASP

The WASP (Wien Automatic System Planning Package) tool permits the user to find an optimal expansion plan for a power generating system over a long period, within the constraints defined by the planner. It is maintained by the IAEA (International Atomic Energy Agency) [49], who have developed four versions of the program and distributed it to several hundred users. WASP is freely available to IAEA member states and requires 4–6 weeks of training.

In WASP the optimum expansion plan is defined in terms of minimum discounted total costs. The entire simulation is carried out using 12 load duration curves to represent each year, for up to a maximum duration of 30 years. Conventional fossil-fuel, nuclear, and biomass power-plants can be simulated along with wind, wave, tidal, hydro power, and pumped-hydroelectric energy storage. Using the electricity demand for the future year, WASP explores all possible sequences of capacity additions that could be added to the system within the required constraints. These constraints can be based on achieving a certain level of system reliability, availability of certain fuels, build-up of various technologies, or environmental emissions. The different alternatives are then compared with one another using a cost function which is composed of capital investment costs, fuel costs, operation and maintenance costs, fuel inventory costs, salvage value of investments, and cost of energy demand not served.

WASP has previously been used to evaluate the potential of biomass power generation [241], to examine the future role of nuclear power in Korea [242], and to evaluate Thailand‘s dependence on natural gas and imported fuels [243].

4.37. WILMAR Planning Tool

The WILMAR Planning Tool was developed by an international consortium in the EU-funded WILMAR project [50]. It is used to analyse the optimal operation of a power system, while treating wind power production forecasts and load forecasts as stochastic input parameters. The first version was created in 2006 and although the tool will be commercially available in the future, a price has not yet been decided. To use the WILMAR Planning Tool, 2–3 months of training is necessary as well as GAMS software.

The WILMAR Planning Tool has a number of sub-tools and databases, while its functionality is embedded in a Scenario Tree Tool (STT) and a Scheduling Model (SM). The main input data for the Scenario Tree Tool is wind speed and/or wind power production data, historical electricity demand data, assumptions about wind production and load forecast accuracies for different forecast horizons, data in relation to outages, and details about the mean time to repair power-plants. The Scenario Tree Tool generates stochastic scenario trees containing three input parameters for the Scheduling Model: (1) the demand for positive reserves with activation times longer than 5 min and the need for replacement reserve with forecast horizons from 5 min to 36 h ahead, (2) wind power production forecasts, and (3) load forecasts. The Scheduling Model is a mixed integer, stochastic, optimisation model, which tries to minimise the expected value of the system operation costs: the costs consist of fuel costs, start-up costs, emission costs (i.e. CO_2 permits and SO_2 costs), variable O&M costs, and taxes. WILMAR is typically used to simulate international energy-systems over a 1-year time-horizon using an hourly time-step. All thermal and renewable generation are considered by WILMAR except solar thermal and geothermal, while energy storage can be accounted for using pumped-hydroelectric, battery or compressed-air energy storage. Heat demands are accounted for on district-heating networks, and all electric vehicles can be simulated.

WILMAR has previously been used to analyse the change in operation costs within the electricity sector due to increased wind-penetrations [244], to simulate the integration of wind power onto the Nordic energy-system [245], to evaluate how electric boilers and heat pumps can improve the feasibility of large wind-penetrations [246], to identify the consequences of increased wind power on the island of Ireland [247], and to analyse the effects of stochastic wind and load on the dispatch of power systems with high wind-penetrations [248].

5. Discussion and conclusions

From this review it is evident that there is a wide range of different energy tools available which are diverse in terms of the regions they analyse, the technologies they consider, and the objectives they fulfil. Therefore, without going into detail, a good overview of the tools can be achieved by looking at their typical applications.

The BCHP Screening Tool, HOMER, HYDROGEMS, and TRNSYS16 tools primarily focus on stand-alone applications of renewable energy such as single-building, local community, or single-project applications.

In relation to the electricity sector, the energyPRO tool can analyse the feasibility of a new power-plant or CHP facility, and the WASP tool can analyse the need for new power capacities. ProdRisk and EMPS optimise the operation of hydro power, while the AEOLIUS tool analyses the effects of fluctuating renewable-energy on conventional generation. ORCED simulates the dispatch of electricity, and EMCAS simulates electricity markets. Therefore, while all of these tools are primarily concerned with the electricity sector, the objectives of each tool vary considerably.

All other tools include the heat or transport sector in addition to the electricity sector in their analyses, but with various considerations. BALMOREL, GTMax, RAMSES, and SIVAEL account for district heating as well as the electricity sector, while E_4cast, EMINENT, and RETScreen include all aspects of the heat sector as well as the electricity sector: this improves the integration of fluctuating renewable-energy through the use of CHP and thermal storage. In addition to the heat sector, PERSEUS, STREAM, and WILMAR Planning Tool also include the transport sector in the form of electric vehicles. By doing so, each of the tools can encompass a larger part of the energy-system. This introduces more options for increasing flexibility within the energy-system, which in turn increases the renewable-energy penetrations that are feasible. MiniCAM and UniSyD3.0 go one step more by introducing hydrogen and electric vehicles into the transport sector, which increases the number of options for increasing the energy-system flexibility once again. In contrast, In*vert*, H_2RES, and SimREN include one transport technology only, in the form of biofuels for In*vert* and hydrogen vehicles for H_2RES and SimREN. However, unlike previous tools that had transport technologies, H_2RES, In*vert*, and SimREN also model all aspects of the heat sector. This has enabled H_2RES, In*vert*, and SimREN to simulate 100% renewable energy-systems.

The remaining tools (COMPOSE, EnergyPLAN, ENPEP-BALANCE, IKARUS, INFORSE, LEAP, MARKAL/TIMES, Mesap PlaNet, MESSAGE, NEMS, and PRIMES) can account for all technologies in the electricity, heat, and transport sectors. However, only four of these, EnergyPLAN, Mesap PlaNet, INFORSE, and LEAP have previously simulated 100% renewable energy-systems.

It is worth mentioning at this point that although the typical application of each tool has been outlined briefly here, it is also imperative to consider numerous other factors when choosing an energy tool. For example, if the objective is to simulate a 100% renewable energy-system, then there are seven tools that have done this: EnergyPLAN, H_2RES, In*vert*, Mesap PlaNet, INFORSE, LEAP, and SimREN. Four of these, EnergyPLAN, Mesap PlaNet, H_2RES, and SimREN used time-steps of 1 h or less, whereas the other three, In*vert*, INFORSE, and LEAP, used annual time-steps. As a result, if the objective is to optimise the energy-system to accommodate the fluctuations of renewable energy, EnergyPLAN, Mesap PlaNet, H_2RES, and SimREN would be more beneficial than In*vert*, INFORSE, and LEAP, although both sets of energy tools can analyse 100% renewable energy-systems. Conversely, if the objective is generate a long-term 'storyline' for implementing 100% renewable energy-systems, In*vert*, INFORSE, and LEAP would be more suitable due to their lengthy scenario-timeframe. In addition, there are a number of other factors illustrated in the results of this paper that could alter the perception of the 'ideal' energy tool, such as the technologies and sectors considered, economic capabilities, accessibility to the tool (e.g. cost), existing users, type of tool, future support, and previous studies. However, the goal of this study was not to identify the ideal energy tool, but to provide the details required so that the decision-maker can pick the most suitable energy tool based on specific objectives. Therefore, from objectives such as analysing the feasibility of a community district-heating system to investigating the potential of a 100% national energy-system, this paper illustrates that there is an energy tool available to aid the transition from a fossil-fuel to a renewable energy world.

Acknowledgements

We would like to thank all the energy tool developers who participated in this review. Also, the findings in this article result from a research project at the University of Limerick, which has been supported financially by the Irish Research Council for Science, Engineering & Technology (IRCSET).

Appendix A. Survey sent to tool developers

A number of the questions below had a list of pre-defined answers for the respondents to choose from, but these have not been included here due to the large amount of space required to display them.

A.1. Section A: Background information

A1. Please enter your name below.
A2. Please enter a contact number (optional).
A3. What is the name of the energy-system-analysis tool being discussed?
A4. Are you the developer or a primary user of the energy tool in question?
A4.1. If no, could you please provide the contact details for the developer or a primary user of the energy tool so that we can contact them also?

A.2. Section B: Users

B1. How many versions of the software have been released to date?
B2. How many people have downloaded/bought the tool?
B3. How much does the tool cost?
B4. What is the required training period in order to use the tool for a typical application?

A.3. Section C: Tool properties

C1. Please state what type of tool this is:
C2. What is the longest duration that can be analysed using the tool?
C3. What time-step is used for the analysis?
C4. Are any of the following financial aspects considered in the tool?

A.4. Section D: Applications

D1. What area can the tool be used for?
D2. What area is the tool primarily used for?
D3. Which of the following energy sectors are considered in the tool?
D4. What kinds of generation technologies are considered in the tool?
D5. What kinds of renewable energy technologies are included in the tool?
D6. What kinds of storage and conversion technologies are included in the tool?
D7. What kinds of transport technologies are included in the tool?
D8. Does the tool focus particularly on any of the technologies or groups of technologies mentioned above?
D9. Does the tool simulate grid dynamics i.e. voltage and frequency?
D9.1. If no, what assumptions are used to account for grid dynamics?

A.5. Section E: Case studies

E1. Can the tool be used to simulate a 100% renewable energy-system i.e. electricity, heat, and transport demands all supplied by renewable energy sources?
E2. To date, what is the highest renewable-energy penetration simulated by the energy tool?

E3. Can you provide a brief description of the three most diverse case studies undertaken using the tool i.e. diverse in terms of region, technologies considered, problems identified by the tool?
E4. Has the energy tool been used for any publications?
E4.1. If yes, could you please provide a title/link to the publications that the tool was used in?

A.6. Section F: Further information

F1. Can you give an overview of the tool in your own words?
F2. Which of the following tools have you heard of previously?
F3. If there is any energy-systems-analysis tool(s) NOT included above that you feel should be included in the review paper, please provide the name(s) below (a contact or reference for the tool would also be appreciated).
F4. Can we contact you in the future if we have any further questions?
F5. Would you like to review a copy of the paragraph completed to define your energy tool before it is published in the review paper (We would appreciate if you would review the paragraph prior to publication)?
F6. Would you like a copy of the final "Energy-Systems-Analysis Tools" review paper?

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Appendix E

Connolly D, Lund H, Mathiesen BV. A User's Guide to EnergyPLAN. Aalborg University, University of Limerick, 2009. Available from: http://www.EnergyPLAN.eu.

A User's Guide to EnergyPLAN

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10 December 2010
Version 4.1

I would like to thank Prof. Henrik Lund and Assistant Prof. Brian Vad Mathiesen for all their help during my time at Aalborg University.

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1 Introduction

This is a brief description of my experience when I learned how to use the energy tool EnergyPLAN [1]. It is a short description of why I chose EnergyPLAN for my particular study, followed by a brief account of the sources I used to gather the data for the model.

When I was carrying out my work using EnergyPLAN, I did not know where to begin looking for a lot of the data I needed. As a result, the primary aim of this document is to share with others where and how I found the required data for my model. I hope that this brief overview of my experience will enable the reader to use EnergyPLAN quicker and more effectively. Finally, I welcome any contributions that could be made to improve the content of this document, such as new sources of data or suggestions for new content. If you have any further questions or contributions regarding any of the material in this document, you can contact me at david.connolly@ul.ie.

Nomenclature

Symbols

CF_W	Average capacity factor for an offshore wind farm
E_{Annual}	Annual output from a wind farm
E_{OUT}	Total electricity produced from a generating facility
E_{IN}	Total electricity consumed by a PHES
GridStab	Percentage of electricity production from grid stabilising units
F_{IN}	Total fuel input, Wh
MGSPS	Minimum Grid Stabilisation Production Share
P_W	Installed wind capacity
d_{Stab}	Minimum grid stabilisation production share in EnergyPLAN
e_{Stab}	Total electricity production from grid stabilising units
stab.-load	Percentage of grid stabilisation criteria which have been met during each hour
η_{COND}	Efficiency of all the condensing plant
η_{TH}	Round-trip efficiency of a PHES

Abbreviations

BEV	Battery Electric Vehicle
CDD	Cooling degree days
CEEP	Critical excess electricity production
CHP	Combined Heat and Power
CSO	Central Statistics Office, Ireland
DH	District heating
EEEP	Exportable Excess Electricity Production
ENTSO-E	European Network of Transmission System Operators for Electricity
GJ	Gigajoule
GE	The General Electric Company
HDD	Heat degree days
IEA	International Energy Agency
kW	Kilowatt
kWh	Kilowatt hour
kg	Kilogram
M€	Million Euro
M2	Data buoy number 2 around the Irish coast
M4	Data buoy number 4 around the Irish coast
MW	Megawatt
OECD	Organisation for Economic Co-Operation and Development
PES	Primary Energy Supply
PHES	Pumped hydroelectric energy storage
PP	Power Plant
SEAI	Sustainable Energy Authority of Ireland
TSO	Transmission System Operator
TWh	Terawatt hour
VAT	Value added tax
Wh	Watt-hour
bbl	Barrel
m	metre
s	second

2 Why EnergyPLAN?

It is difficult to choose a suitable energy tool at the beginning of a study due to the wide range of different energy tools available, which are diverse in terms of the regions they analyse, the technologies they consider, and the objectives they fulfil. In addition, it can be very difficult to define what exactly the primary focus of any research will become. Therefore, the first step which I would advise, is defining an overall objective for any modelling work which you intend to do. For example, the underlying objective in my work was:

"To identify how Ireland could integrate the most renewable energy into its energy system".

After establishing a core objective, it is then possible to rate various different energy tools against one another based on their capabilities of fulfilling this objective. To aid this comparison, an overview of all the energy tools I considered, as well as many others can be found in [2, 3]. Hence, these will not be discussed in detail here, but instead the only reasons I chose EnergyPLAN are outlined below:

1. EnergyPLAN is a user-friendly tool designed in a series of tab sheets and hence the training period required usually varies from a few days up to a month, depending on the level of complexity required. Also in relation to this point, there is online training available from the EnergyPLAN website so it is relatively straight forward to experience a typical application of the software [1].
2. The EnergyPLAN software is free to download [1].
3. EnergyPLAN considers the three primary sectors of any national energy system, which includes that electricity, heat, and transport sectors. As fluctuating renewable energy such as wind power becomes more prominent within energy systems, flexibility will become a vital consideration. One of the most accessible methods of creating flexibility is the integration of the electricity, heat, and transport sectors using technologies such as combined heat and power (CHP) plants, heat pumps, electric vehicles, and hydrogen. Therefore, for certain objectives, this can be an essential issue for a study.
4. EnergyPLAN was previously used to simulate a 100% renewable energy system for Denmark [4-8].
5. The results developed using EnergyPLAN are constantly being published within academic journals. A number of energy tool developers publish their results in private reports for those who fund their investigations. However, in order to obtain my PhD qualification I needed to publish my work in academic journals. Therefore, it was fortunate and important that EnergyPLAN was being used for this purpose.
6. The quality of journal papers being produced using EnergyPLAN was a key attraction. Below are a few examples of the titles I recorded before contacting Prof. Henrik Lund about EnergyPLAN:
    a. Energy system analysis of 100% renewable energy systems – The case of Denmark in years 2030 and 2050 [7].
    b. The effectiveness of storage and relocation options in renewable energy systems [9].
    c. Large-scale integration of optimal combinations of PV, wind and wave power into electricity supply [10].
    d. Large-scale integration of wind power into different energy systems [11].

   After reading these journal papers and observing the contribution that the results made to the Danish energy system, it was evident that similar research would benefit the Irish energy system.
7. Finally and possibly the most important reason for using EnergyPLAN, was Prof. Henrik Lund's supportive attitude when I approached him about using EnergyPLAN. My progress has been accelerated beyond expectation due to the support and guidance from both Prof. Henrik Lund and Associate Prof. Brian Vad Mathiesen. This is an essential aid when embarking on research, especially when learning new skills and meeting deadlines at the same time.

These are only some of reasons for using the EnergyPLAN tool. A more detailed overview of EnergyPLAN can be found in [1], while a more thorough comparison with other energy tools can be found here [2, 3].

3 Collecting the Required Data

After choosing any energy tool for a study, it is crucial that you ensure that the tool is capable of accurately modelling your particular application. Therefore, the first step is to create a reference model of an historical year. In my first study, I chose the 2007 Irish energy system as my reference and hence this report is primarily based on this application. However as I was making the reference model, I felt that a lot of questions could have been answered if I simply knew where to begin looking for the data required. Therefore, this document simply discusses where I found the information I needed to complete my reference model of the 2007 Irish energy system. I hope that this will enable future EnergyPLAN users to collect their data more effectively.

Important: There are important points below that need to be considered when reading the following chapters:

1. I have discussed a number of inputs in great detail and others only briefly. This reflects the effort required and the assumptions made in order to get the data and **not** the importance of the data.
2. When you download the EnergyPLAN model, a number of distributions are included with it. In a lot of studies these distributions will suffice as the results from the EnergyPLAN model may not be greatly improved by a more accurate distribution. Therefore, it is worth analysing the effects of various distributions on your results before allocating large periods of time to creating distributions.

This chapter is divided into **two** primary sections:

1. Technical Data
2. Economic Data

The order is used as this is a typical modelling sequence that can be used when simulating an energy system. Firstly, a reference model is created to ensure that EnergyPLAN can simulate the energy system correctly. The reference model does not require economic inputs, as it is usually only the technical performance that is compared. After creating the reference model using the technical inputs, then the fuel, investment, and O&M costs can be added to carry out a socio-economic analysis of the energy system. Therefore, alternatives can now be created and compared in relation to their technical performance and annual operating costs. Finally, the external electricity market costs can be added so a market optimisation can be completed in EnergyPLAN: this enables you to identify the optimum performance of the energy system from a business-economic perspective, rather than a technical perspective. However, typically the aim when creating future alternatives is to identify how the optimum business-economic scenario, can be altered to represent the optimum socio-economic scenario (i.e. by adjusting taxes) as this is the most beneficial for society.

Finally, before discussing the data that was collected, it is important to be aware of the type of data that EnergyPLAN typical requires. Usually, the EnergyPLAN model requires two primary parameters:

1. The total annual production/demand.
2. The hourly distribution of the total annual production/demand, which have the following criteria:
    a. There must be 8784 data points, one for each hour.
    b. The data points are usually between 0 and 1, representing 0-100% of production/demand as shown in Figure 1[1]. However, if a distribution is entered with values greater than 1, EnergyPLAN will index the distribution: This is done by dividing each entry in the distribution by the maximum value in the distribution. This means that historical hourly data can be used in EnergyPLAN for a distribution. An example, displaying how an index is created, and also how an index is used is shown in Table 3-1.
    c. The distribution is inputted as a text file and stored in the "Distributions" folder.

[1] This does not apply to the price distributions. For the price distribution, the actual values provided in the distribution are used.

The distribution is simply adjusted to reflect the total annual production/demand. For example, in Figure 2, the distributions for three separate demands are shown, which show how the distribution in Figure 1 is manipulated to model the total demand.

Table 3-1
How a distribution is indexed and subsequently used in EnergyPLAN (Note: 8784 hours in total are required).

Time (h)	Output from a 100 MW Wind Farm (MW)	Index Data		Using Indexed Data to Simulate a 400 MW Wind Farm	
		Fraction	Decimal		
1	20	20/100	0.2	0.2*400	80
2	30	30/100	0.3	0.3*400	120
3	60	60/100	0.6	0.6*400	240
4	100	100/100	1.0	1.0*400	400
5	80	80/100	0.8	0.8*400	320
6	40	40/100	0.4	0.4*400	160

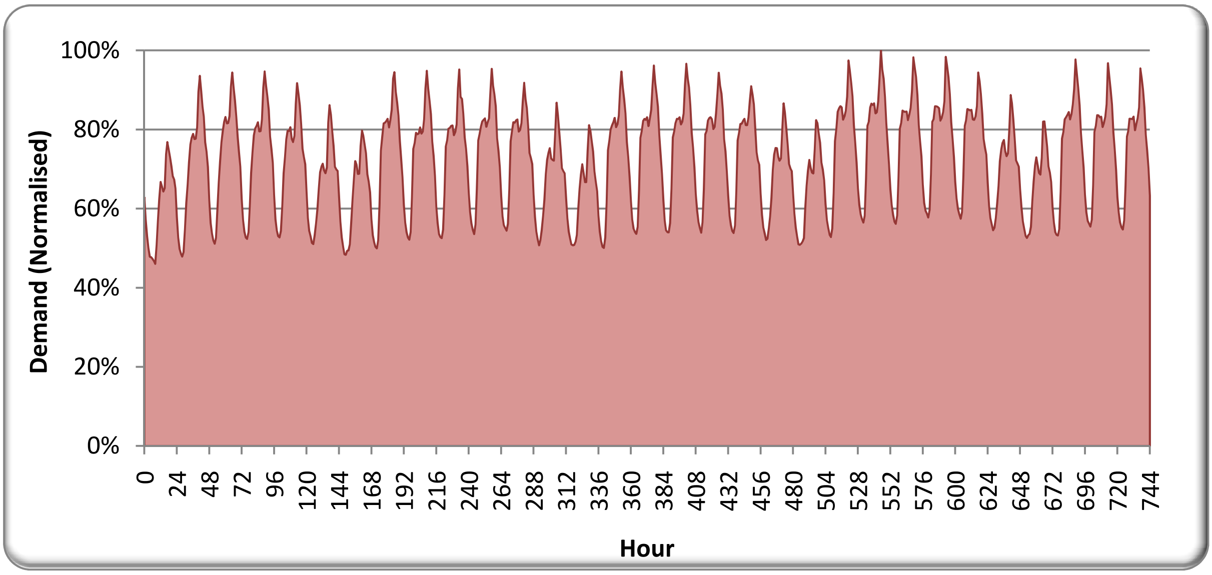


Figure 1: Distribution of Irish electricity demand for January 2007 [12].

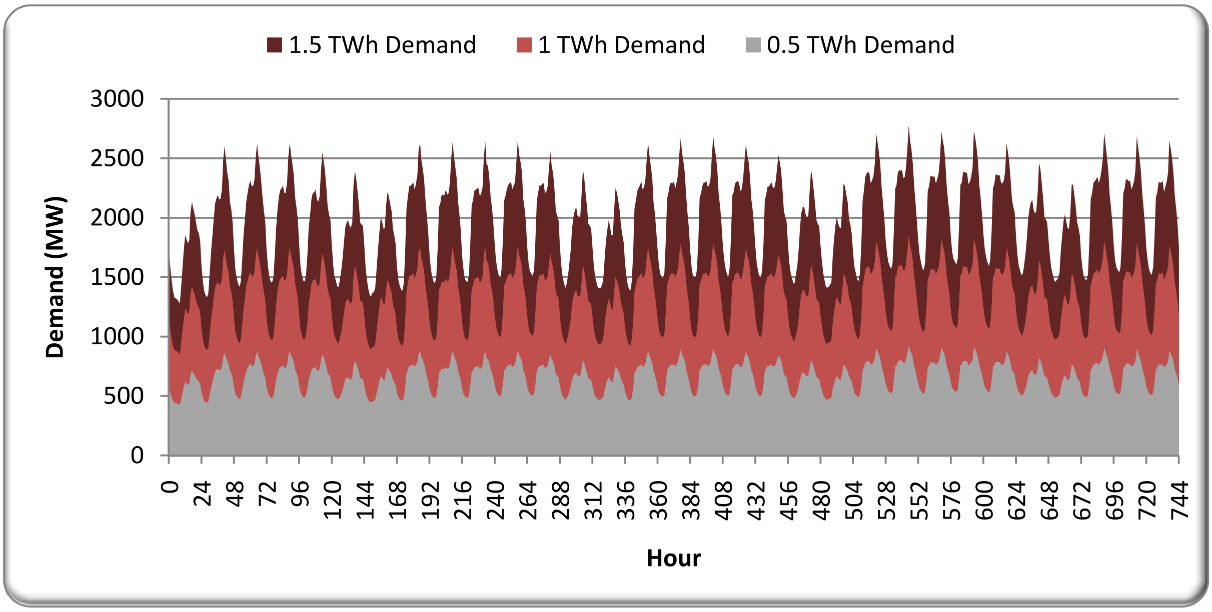


Figure 2: Distribution modified by the total Irish electricity demand required for January 2007 [12].

3.1 Technical Data Required

EnergyPLAN simulates a single year in hourly time-steps. To create an initial model, I picked the year 2007 as it was the most recent when I started gathering my data.

To explain where I got my data, I will discuss each tab within the EnergyPLAN model separately. The 'Frontpage' tab displayed in Figure 3 illustrates a flow diagram of the EnergyPLAN model, indicating how all the various components of the energy system interact with one another. The 'Input' tab is used to describe the parameters of the energy system in question. The 'Cost' tab is used to input the costs associated with the energy system being investigated and the 'Output' tab is used to analyse the results of your investigation. Finally, the 'Settings' tab enables the user to change the scale of the units in the program.

Below I will discuss in detail where I got the information for the 'Input' tab and the 'Cost' tab, as these account for the majority of data required.

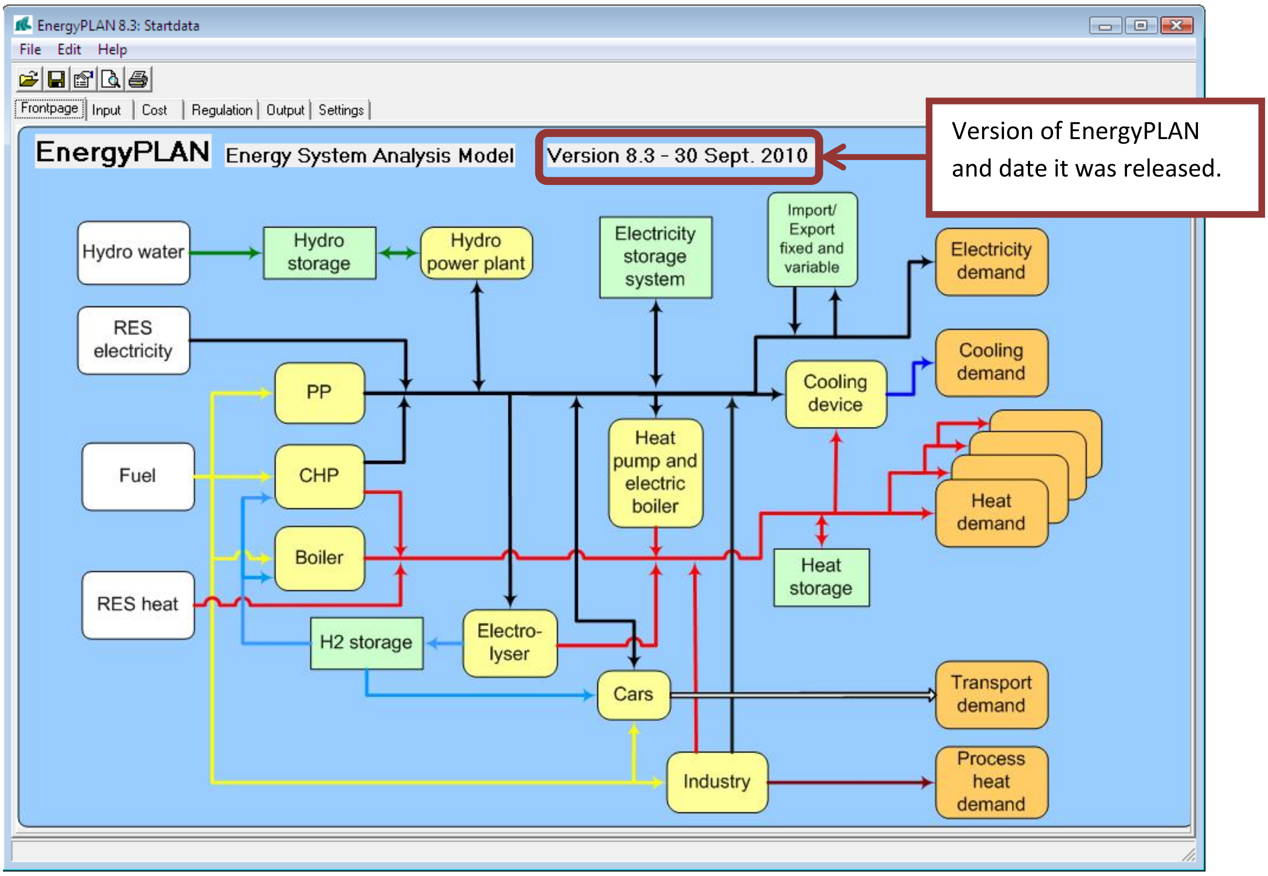


Figure 3: Frontpage of the EnergyPLAN tool.

3.1.1 Input Tab

Below is a brief description of the data I used under the 'Input' tab in my model. It is worth noting that the data required for EnergyPLAN is usually generic data that can be obtained in most OECD[2] countries. Therefore, if I was able to obtain the data for the Irish energy system, it is likely to be available in other countries also. Also note that each sub-heading in this section represents data required for a different tab in EnergyPLAN.

The first piece of information that you should try to source is the 'Energy Balance' for your country or region. The Irish Energy Balance was completed by the Irish energy agency called the Sustainable Energy Authority of

[2] Organisation for Economic Co-Operation and Development: http://www.oecd.org.

Ireland (SEAI) [13]. The Energy Balance indicates the energy consumed within each sector of the energy system as displayed Figure 4 and Appendix 8.1. The International Energy Agency (IEA) completed two reports on energy balances in 2008: one with the Energy Balances for each of the OECD countries [14] and one with the Energy Balances for a number of non-OECD countries [15]. These documents must be purchased so I have not obtained a copy. However, this is one possible source for an energy balance of your energy system.

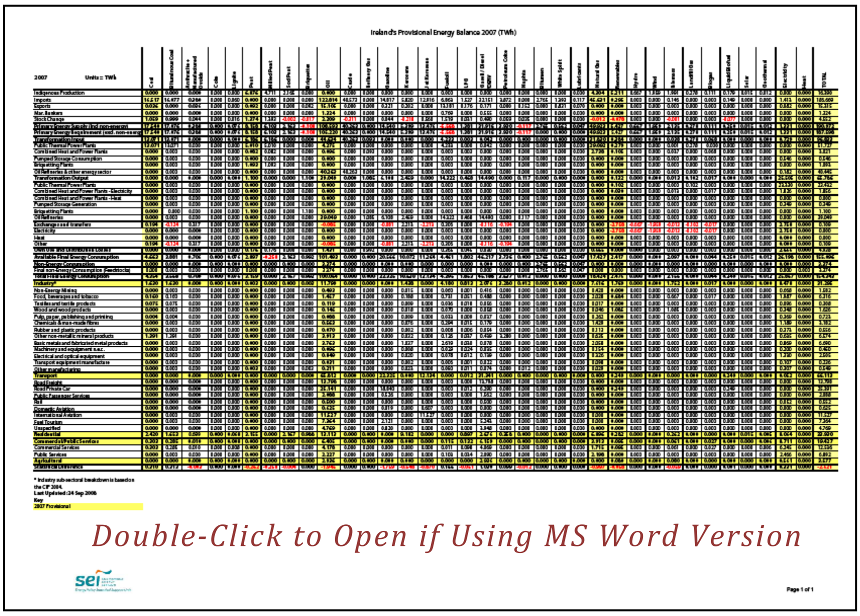


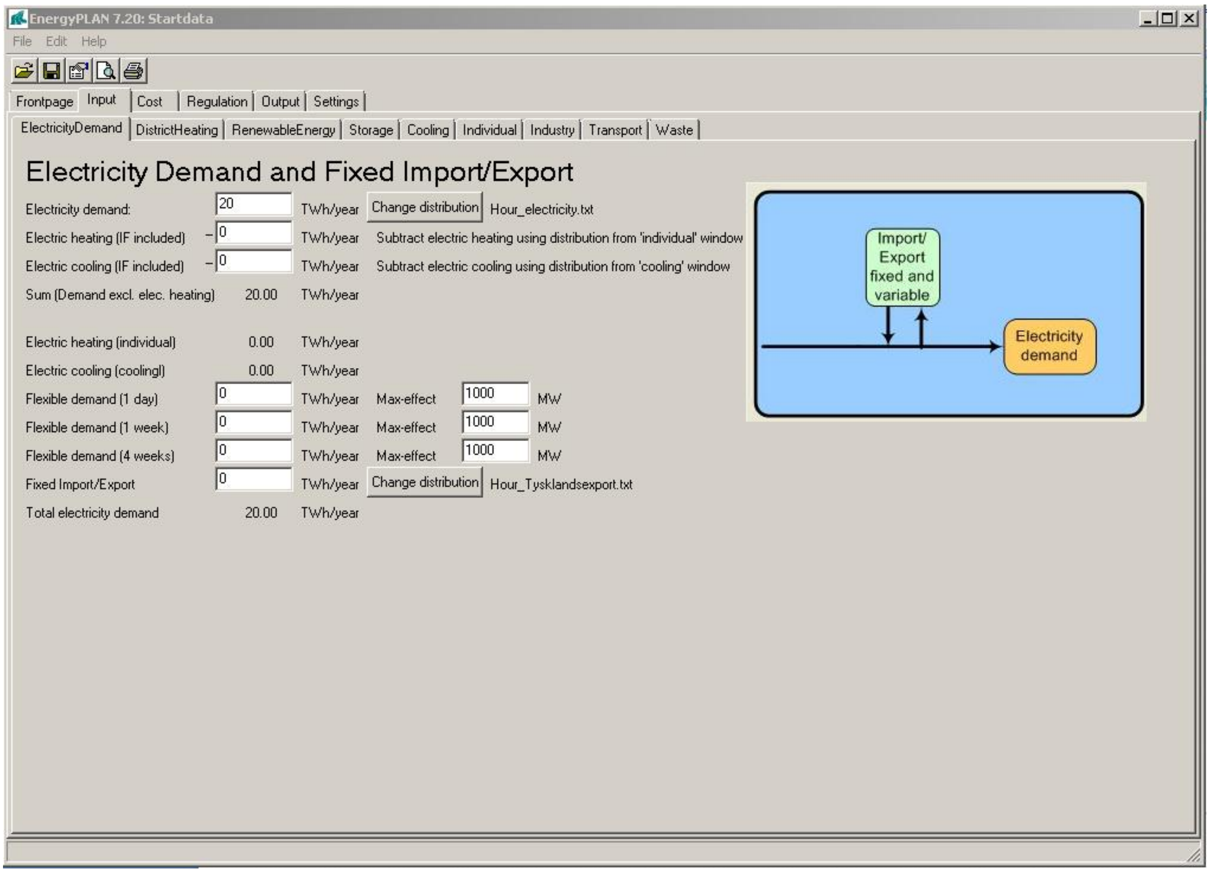
Figure 4: Irish energy balance for 2007: see Appendix 8.1 and reference [16].

The Energy Balance document proved to be the most useful source of information for my investigation. However, it is important to check the accuracy of the data in this document, as the figures can sometimes be based on estimates.

Secondly, meteorological data also proved very important when predicting renewable energy production. Meteorological data can usually be obtained from a national meteorological association. However, another option is to use a program called 'Meteonorm' [17]. This program has gathered data from a number of meteorological stations around the world, which can be accessed using a very intuitive user-interface. However, the program is not free so you will need to decide how important meteorological data will be before purchasing it[3]. Even if you use this program, it could also be useful to compare the data in the software to actual measurements from a weather station to ensure that the program is providing accurate data.

[3] Data from meteorological stations may or may not be free so it is worth enquiring about this also.

3.1.1.1 Electricity Demand



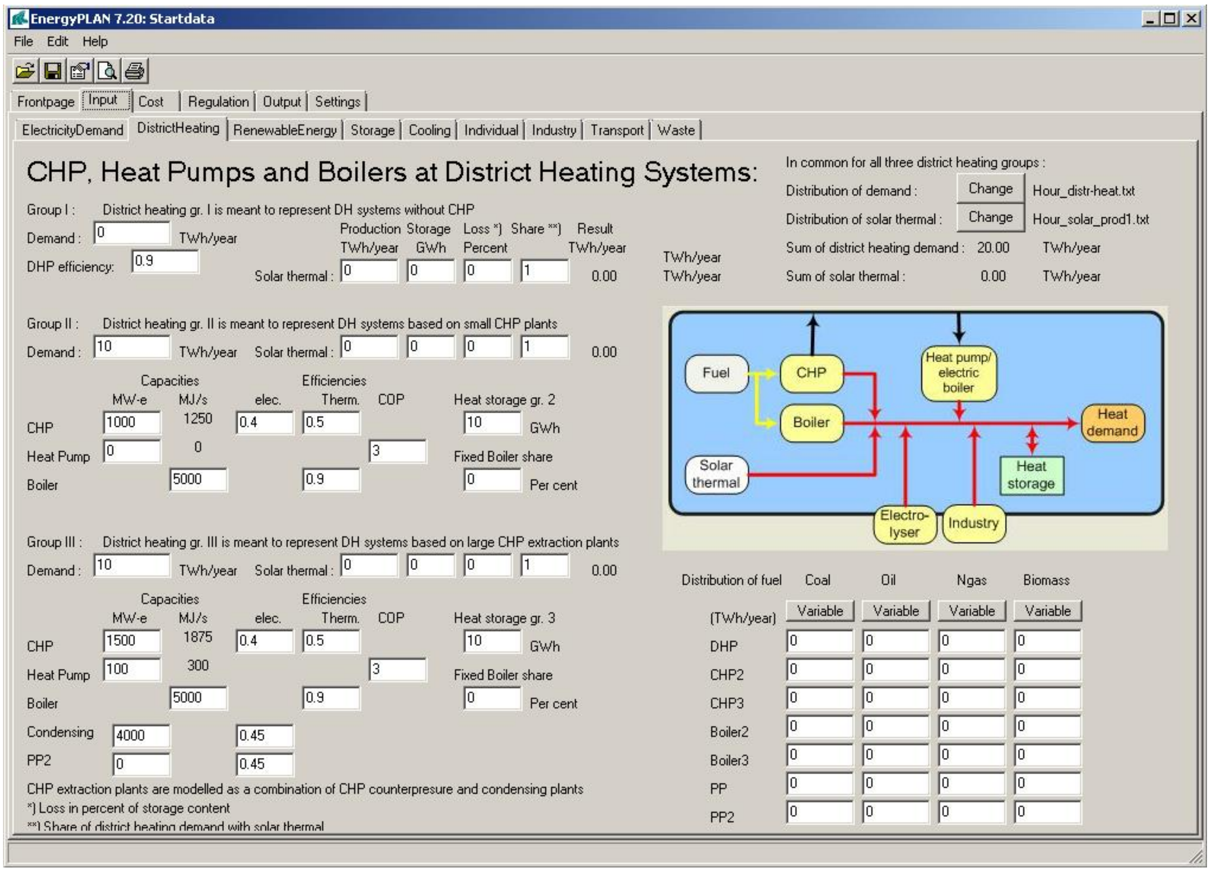
Total electricity demand was obtained from the Irish transmission system operator (TSO), EirGrid [13], and the Energy Balance document. Imported and Exported electricity was also obtained from the TSO in Ireland.

Twenty-four European countries are involved in the "European Network of Transmission System Operators for Electricity" (ENTSO-E), which provides a lot of detailed data about the production and consumption of electricity. A list of the countries in the ENTSO-E is available from [18], and the data can be obtained from [19]. The data includes the following:

- Statistics
- Production Data
- Consumption Data
- Exchange Data
- Miscellaneous Data
- Country Data Packages

Therefore, this is a useful source of information if you are modelling a European region.

3.1.1.2 District Heating



For my initial energy model I did not have to include any district heating or CHP as there are currently no large-scale installations in Ireland. For power plants, the first parameter required is the total capacity installed, which I got from the Irish TSO [13]. If necessary, it is possible to divide the power plants into two categories: condensing and PP2. The PP2 category is usually used if there is a highly contrasting plant mix on the system i.e. if there is one group of plants with a low efficiency and are expensive, but another group of plants which have a high efficiency and are cheap. Therefore, the PP2 can be suitable for some energy systems.

In addition to the PP capacity, you also need to find the total fuel consumed by the power plants, which is usually available in the energy balance. For example, in the Irish energy balance, you can see that there is a category titled "Public thermal power plants", which can be broken down by coal, oil, gas, and biomass. These values are entered into the "Distribution of Fuel" grid. If you put all of the PP capacity into the "condensing" section, then all of the fuel consumption needs to be in the PP row of the grid. However, if you put some plants in PP and some other plants in PP2, then the fuel will need to be split across these rows, in a way that reflects this divide.

Finally, you will also need the efficiency of the power plants. As mentioned, the total fuel consumption for each type of power plant can be obtained from the energy balance. Using the energy balance document I could calculate the efficiency of all the condensing plant, η_{COND}, using the total fuel input, F_{IN} (Wh), and total electricity generated, E_{OUT} (Wh),

$$\eta_{COND} = \frac{E_{OUT}}{F_{IN}} \qquad (1)$$

It was difficult to obtain the efficiencies of the individual condensing plant as it was "commercially sensitive information". However, I obtained a breakdown of fuel inputted into the Irish condensing plants, see Figure 5, once again from the Irish energy agency SEAI, and used this to calculate the efficiencies for the condensing plant of different fuel type (using formula 1). For the reference model you will not need to know this: instead all you need to find out is the total fuel consumed by all the power plants, and the total electricity generated by all the power plants (then you can calculate the condensing efficiency). However, the efficiency of the power plants under each fuel type will be necessary when simulating future alternatives: for example, if you wanted to simulate coal power plants being replaced by natural gas power plants as illustrated in Table 3-2.

Table 3-2
How individual power plant efficiencies alter the overall "Condensing" power plant efficiency.

	Coal PP (MW)	Natural Gas PP (MW)	Coal PP Efficiency	Natural Gas PP Efficiency	Total Capacity (MW)	Overall Efficiency
Reference	1000	2000	0.4	0.5	3000	0.466
Alternative 1	500	2500	0.4	0.5	3000	0.484
Alternative 2	0	3000	0.4	0.5	3000	0.500

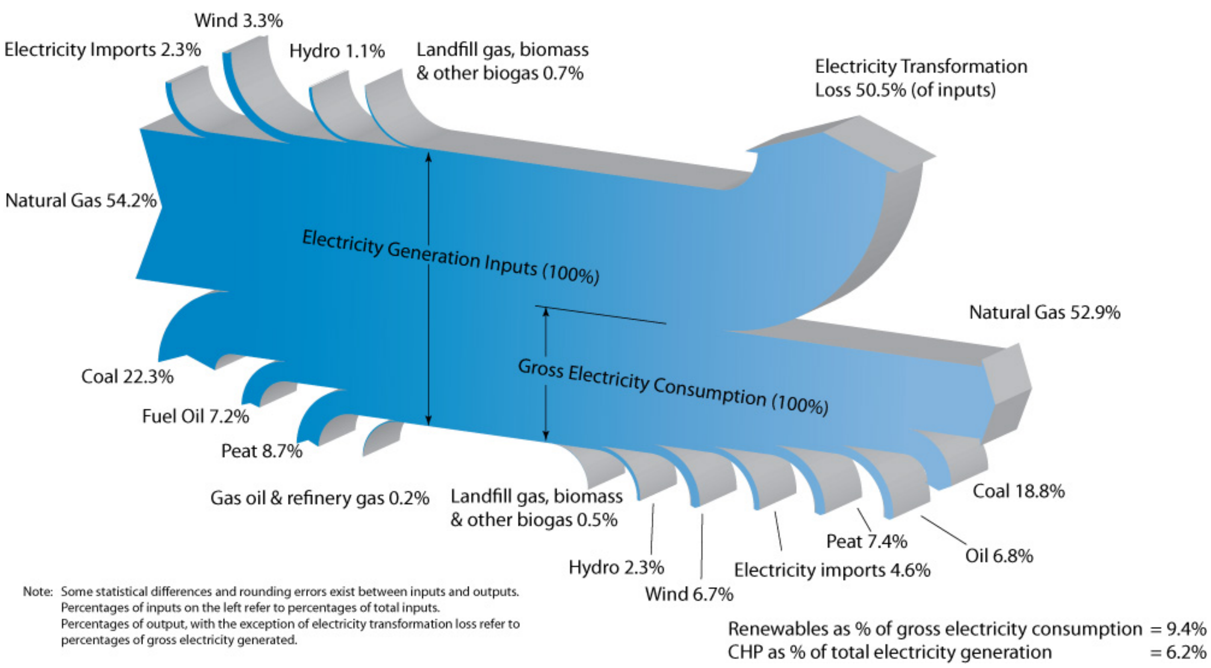
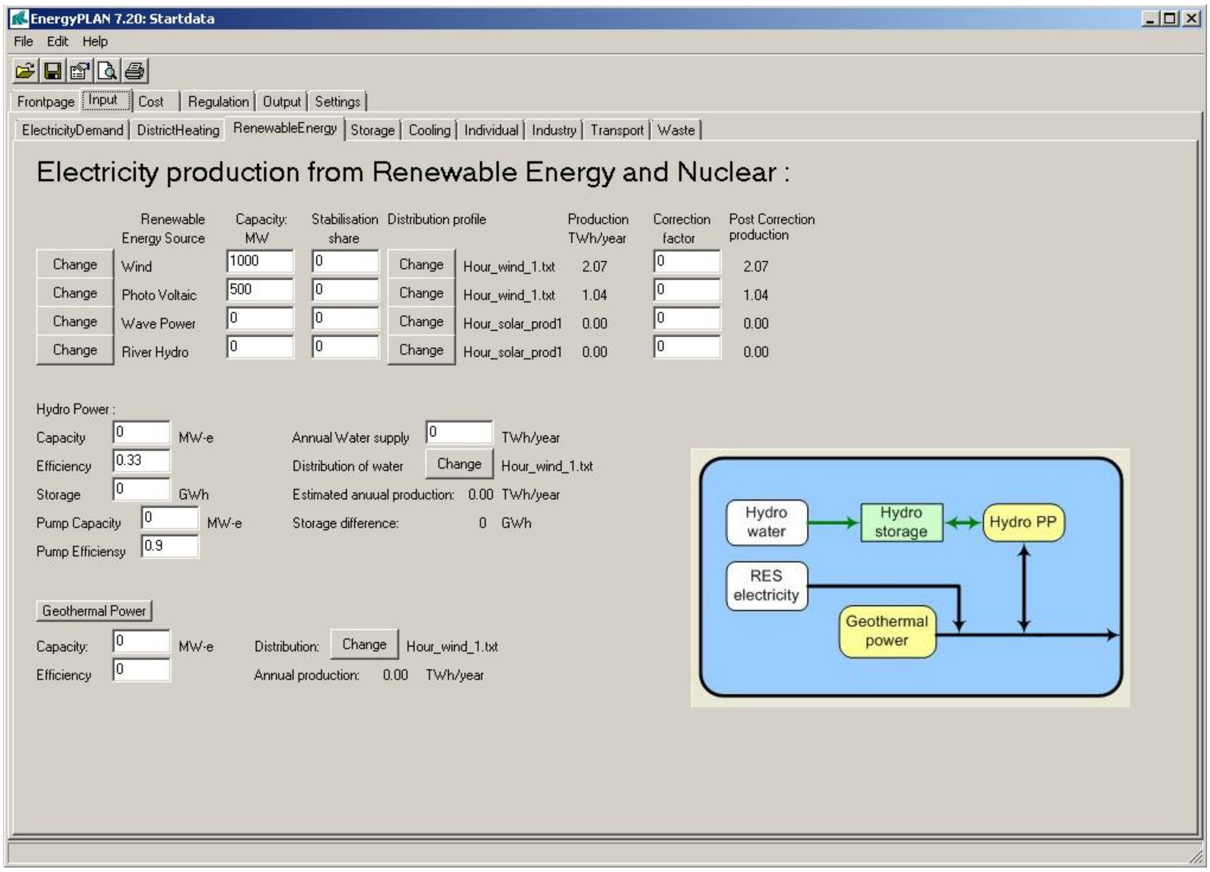


Figure 5: Breakdown of fuel consumption and electricity generated in Irish electricity system [20].

3.1.1.3 Renewable Energy



In order to define the energy available from a renewable energy resource in your energy system, you need to define five major features:

1. The type of renewable energy in question.
2. The installed capacity of the renewable resource.
3. The distribution profile (hourly for one year).
4. The stabilisation share.
5. The correction factor.

Parameters 1-3 are reasonably intuitive and have been discussed in detail in at the start of section 3. Therefore, I will only recap on the 'stabilisation share' and the 'correction factor' here. So, just to repeat from the EnergyPLAN user manual [1], the stabilisation share is the percentage (between 0 and 1) of the installed capacity of the renewable resource that can contribute to grid stability i.e. provide ancillary services such as voltage and frequency regulation on the electric grid. At present renewable energy technologies, with the exception of hydro plants with storage, cannot help regulate the grid. Therefore, the stabilisation share will be set to 0 unless this changes in the future.

Also from the EnergyPLAN user manual [1], the correction factor adjusts the hourly distribution inputted for the renewable resource. It does not change the power output at full-load hours or hours of zero output. However, it does increase the output at all other times. This can be used for a number of different reasons. For example, future wind turbines may have higher capacity factors, and thus the same installed wind capacity will produce more power.

Onshore Wind

I obtained the installed wind capacity and the hourly wind output for 2007 from the Irish TSO. The stabilisation factor was inputted as 0 because wind power does not contribute to grid stabilisation. Also, the correction factor was inputted as 0 because the installed wind capacity and the distribution used generated the expected annual wind energy. Otherwise, the correction factor would need to be adjusted until the wind production calculated by the model was the same as the actual annual production.

Offshore Wind

There was very little historical data available for offshore wind in Ireland. There is currently only one offshore wind farm constructed, which is located at Arklow Banks near County Wicklow. This wind farm is using a new wind turbine developed by GE Energy (The General Electric Company), hence they will not release any information in relation to the power generated from the turbines. The only information I had was the installed capacity of the wind turbines, which was 25.2 MW (7 x 3.6 MW turbines). As a result I used the onshore wind distribution that I had obtained from the Irish TSO, combined with the correction factor in EnergyPLAN. The reason the onshore wind distribution is a good source of data, is because it accounts for the variations in wind speed over the island of Ireland. The only difference between onshore and offshore wind distributions is the higher capacity factor for offshore. This is accounted for by the correction factor in EnergyPLAN. However, after deciding to use the onshore wind distribution, I then had to identify the annual wind energy produced by the 25.2 MW of offshore wind. I calculated this in two different ways.

For the first method I began by obtaining the average annual wind speed at the location of the offshore wind farm (8.75 m/s), using the Irish wind atlas [21]. Then I got an annual offshore wind distribution from a data buoy located close to the offshore wind farm (data buoy M2 from [22]). This data had an average annual wind speed of 7.82 m/s over the year 2007. Therefore, I scaled up this distribution curve until the average annual wind speed was 8.75 m/s (the same as the average wind speed at the offshore wind farm). Finally, I got the power curve for a Vestas V90 wind turbine as seen in Figure 6, and calculated the expected output for a single year from the offshore wind farm. I did not want to use the power curve for the GE Energy wind turbines which were installed at the offshore wind farm, as these are still at the testing stage. At this point I had calculated an expected offshore wind production of 0.11 TWh: using the power curve and wind speed distribution with average annual wind speed of 8.75 m/s. Using the onshore wind distribution, the annual electricity generated from the 25.2 MW offshore wind farm was 0.07 TWh. However, from my calculations, the total electricity that should have been generated was 0.11 TWh. Consequently, I adjusted the 'Correction Factor' (to 0.65) until the total offshore wind output was 0.11 TWh. This accounted for the higher capacity factor of the offshore wind turbines in comparison to the onshore wind turbines. However, if 25.2 MW of wind power produced an annual output of 0.11 TWh, this would give the wind farm a capacity factor of 49.8% which is very high and hence I used a second method also.

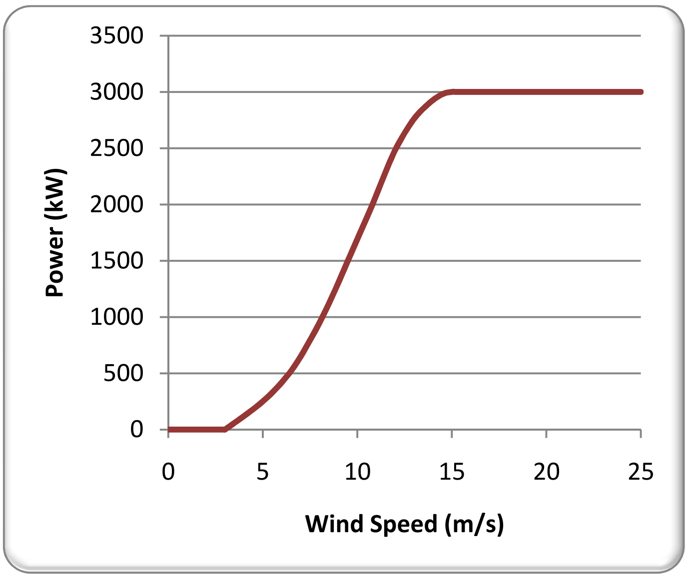


Figure 6: Power curve for a Vestas V90 wind turbine [23].

For the second method, I simply found the average capacity factor for an offshore wind farm in Ireland, which was 40% [24]. I then calculated the annual output from the wind farm, E_{Annual}, using the installed wind capacity, PW, and the average capacity factor for an offshore wind farm, CF_W, as displayed below:

$$E_{Annual} = 8760 P_W CF_W \qquad (2)$$

The result was 0.088 TWh from an installed wind capacity of 25.2 MW with a capacity factor of 40%. Therefore, after the offshore wind capacity and onshore wind distribution were inputted into EnergyPLAN, and the correction factor was adjusted (to 0.36) until the annual output was 0.088 GWh. In my opinion, this method is better when simulating alternatives which introduce new large-scale wind capacities, as it uses the average capacity factor. In comparison, the first method is better if you are simulating a specific wind farm as it takes into account the specific wind speeds at that site. As Ireland has very little offshore wind at the moment, but my future alternatives will most likely simulate large-scale offshore wind capacities, I used the second method for my model.

Photovoltaic

As I could not obtain PV output from Ireland, I used the results obtained from a Danish project called Sol300, as the solar radiation in Denmark is very similar to the solar radiation in Ireland, which is displayed in Figure 7. To ensure the Danish solar resource was similar to the Irish solar resource, global solar radiation data was compared between Denmark and Ireland as seen in Table 3-3. It clearly verifies the similarity and therefore it was considered reasonable to assume that the solar thermal output would be very similar for both Denmark and Ireland.

This Sol300 project involved the installation of grid-connected PV panels on 300 homes in Denmark and the corresponding output was recorded. This output is discussed in [10], and is available in the Distributions folder that comes with the EnergyPLAN model. The name of the distribution is hour_PV_eltra2001 and hour_PV_eltra2002, for the years 2001 and 2002 respectively.

Work is currently underway to find a relationship between PV output and global solar radiation (as global solar radiation is the most common form of measuring solar radiation at meteorological stations). This section will be updated when this work is completed.

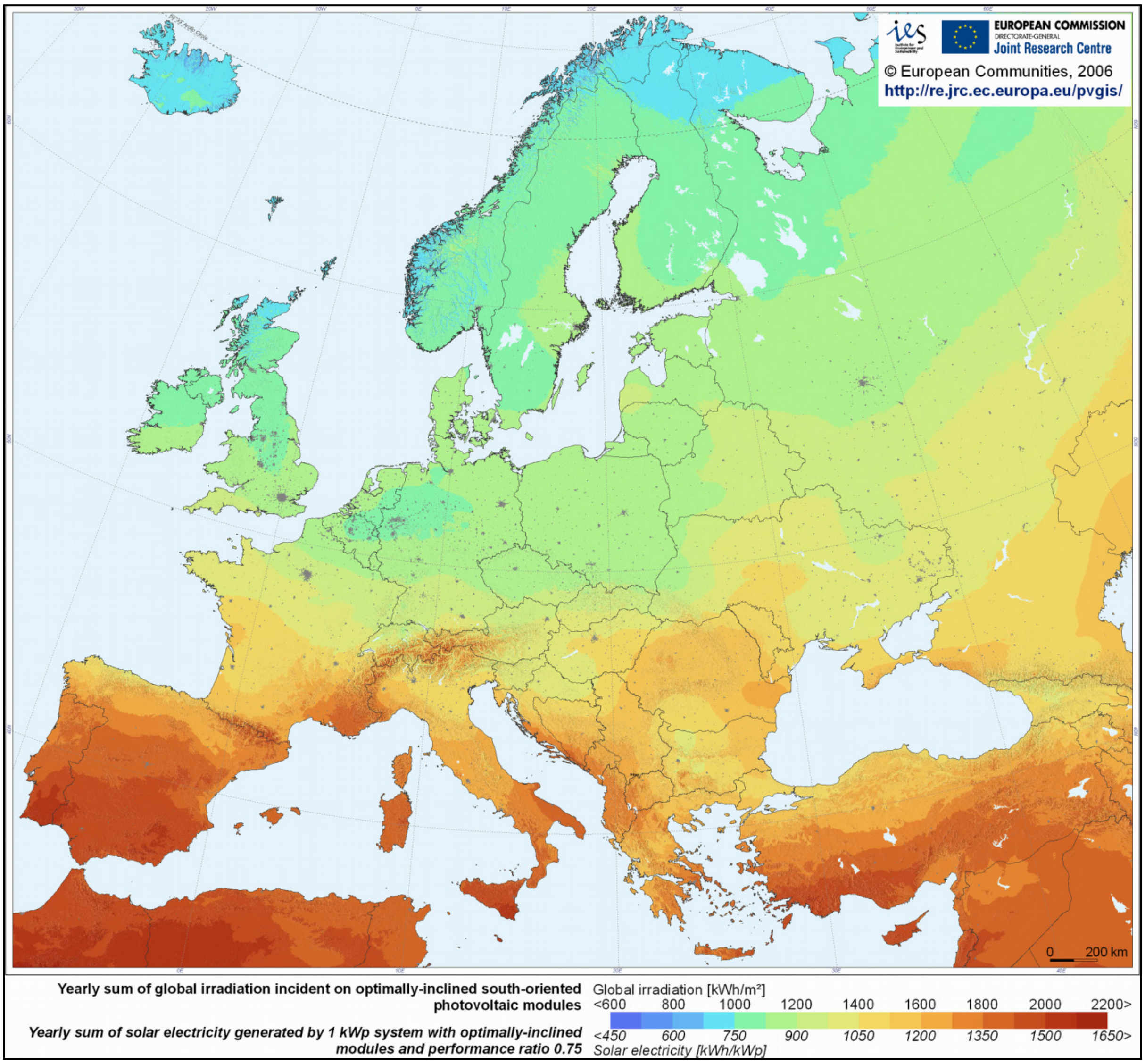


Figure 7: Yearly global irradiation data in Europe [25].

Table 3-3
Global solar radiation in Denmark and Ireland for 2007 [26, 27].

Country	Number of Stations That Provided Data	Average Annual Global Solar Radiation (kWh/m^2)
Denmark	4	976
Ireland	7	989

Tidal

Tidal power is developing rapidly at present. It is very similar to most renewable energy as it must be used at the time of generation. However, the unique characteristic of tidal power is the fact that it can be predicted in on a minute resolution at least three years in advance, if not more. In order to simulate tidal power, I sourced two studies completed in Ireland: one by SEAI (the Irish Energy Authority), titled "Tidal and Current Energy Resources in Ireland" [28], and one by the Department of Communications, Energy and Natural Resources called the "All-Island Grid Study: Renewable Energy Resource Assessment (Workstream 1)" [29]. The first study [28] identified viable tidal energy resource available in Ireland from tidal power (0.92 TWh), and the second study [29] created a power output curve for tidal devices as seen in Figure 8. Using these two inputs it was possible to simulate tidal energy in EnergyPLAN. It is worth noting that these figures were based on 'first-generation tidal devices', so the area investigated came under the following restrictions:

1. Water depth between 20m and 40m.
2. Sites outside major shipping lanes.
3. Sites outside military zones and restricted areas.
4. Sites which do not interfere with existing pipelines and cables.
5. 12 nautical mile limit offshore.
6. Peak tidal velocity greater than 1.5 m/s.

'Second-generation tidal devices' are expected to be developed that can be placed in areas without some of these restrictions (see Figure 9). However, these devices are not expected until 2015 [29].

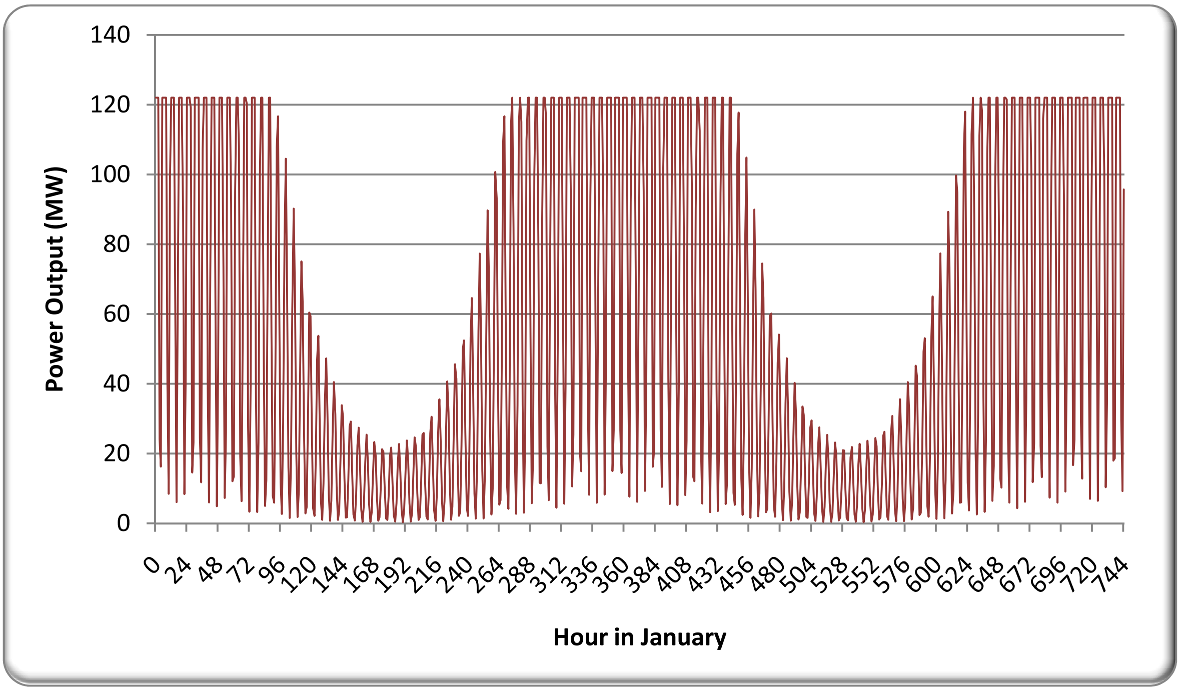


Figure 8: Tidal power output expected in Ireland for the month of January from a 122 MW Tidal Farm [29].

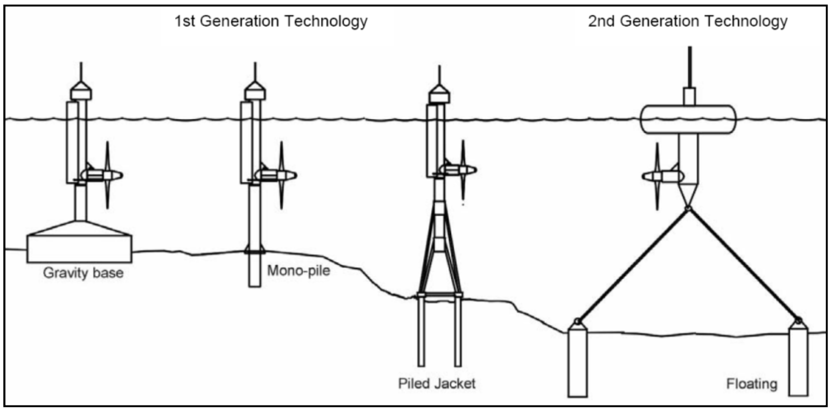


Figure 9: First and Second generation tidal technology [30].

Wave Power

I consulted with Jens Peter Kofoed from Aalborg University in order to generate the expected wave power data for my model. During our discussion, it became apparent that the future of wave power is very unclear.

Unlike wind power where the three-bladed turbine has become the primary technology, there will be no standard design for future wave generators. This is due to the fact that wave power depends on two parameters: wave height and wave period. Different wave generators will be used depending on the specific wave height and period characteristics at a site and hence, it is unlikely that any single wave generator will be the most efficient at all sites.

The most convincing way to predict the wave power contribution for an energy system in the future is to use the output from a wave generator device that is publicly providing a power matrix, such as the Pelamis in Figure 10, the Wave Dragon in Figure 11, and the Archimedes in Figure 12. These power matrices are available to the public and hence can be used in conjunction with wave height and wave period data to predict future wave power.

Significant wave height (H_{sig}, m) \ Power period (T_{pow}, s)	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0
0.5	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle
1.0	idle	22	29	34	37	38	38	37	35	32	29	26	23	21	idle	idle	idle
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
2.0	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
3.0	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
3.5	-	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
4.0	-	-	462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
4.5	-	-	544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
5.0	-	-	-	739	726	731	707	687	670	607	557	521	472	417	369	348	328
5.5	-	-	-	750	750	750	750	750	737	667	658	586	530	496	446	395	355
6.0	-	-	-	-	750	750	750	750	750	750	711	633	619	558	512	470	415
6.5	-	-	-	-	750	750	750	750	750	750	750	743	658	621	579	512	481
7.0	-	-	-	-	-	750	750	750	750	750	750	750	750	676	613	584	525
7.5	-	-	-	-	-	-	750	750	750	750	750	750	750	750	686	622	593
8.0	-	-	-	-	-	-	-	750	750	750	750	750	750	750	750	690	625

(a) (b)

Figure 10: Pelamis wave generator (a) and power matrix: output in kW (b).

Wave Period – Tz (s)

Significant Wave Height - m	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.0	203	276	348	432	516	608	699	798	896	925	953	958	962	941	919	870	820	742	663	555	446
1.5	412	448	485	617	750	899	1049	1212	1375	1433	1491	1509	1527	1502	1477	1404	1332	1209	1086	912	737
2.0	621	621	621	802	983	1191	1398	1626	1853	1941	2029	2061	2092	2063	2034	1939	1844	1677	1509	1269	1028
2.5	1123	1123	1123	1213	1304	1609	1914	2258	2602	2752	2903	2972	3041	3017	2993	2868	2743	2504	2266	1910	1555
3.0	1624	1624	1624	1624	1624	2027	2430	2890	3350	3563	3776	3883	3989	3970	3951	3796	3641	3332	3022	2552	2082
3.5	2581	2581	2581	2581	2581	2783	2984	3588	4191	4494	4796	4870	4945	4935	4926	4845	4765	4374	3983	3372	2761
4.0	3538	3538	3538	3538	3538	3538	3538	4285	5032	5424	5816	5858	5900	5900	5900	5895	5889	5416	4943	4191	3439
4.5	4719	4719	4719	4719	4719	4719	4719	5093	5466	5662	5858	5879	5900	5900	5900	5897	5895	5658	5422	4822	4222
5.0	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5452	5004
5.5	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5676	5452
6.0	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900
6.5	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900
7.0	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900
7.5	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900
8.0	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900

Figure 11: Wave Dragon power matrix (optimised for high average wave conditions): output in kW [31].

Wave Period – Tpow (s)

Significant Wave Height Hsig - m	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5	18.0
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.0	2	7	13	19	26	34	41	48	58	68	81	93	105	118	131	144	153	163	183	203	213	223	223	223	223	225	227
1.5	4	15	28	41	56	72	85	99	121	143	173	203	226	248	266	285	309	334	357	380	389	398	398	398	398	403	409
2.0	8	26	49	73	100	127	150	172	210	247	292	337	366	395	418	442	482	523	543	563	579	596	596	596	596	597	598
2.5	15	43	78	113	159	205	234	263	320	376	438	499	531	563	603	643	675	708	741	774	785	797	797	797	797	800	804
3.0	25	61	111	161	227	293	339	386	453	521	600	680	722	765	827	888	897	906	945	984	996	1009	1009	1009	1009	1003	998
3.5	35	92	155	218	305	391	454	517	605	694	772	851	913	975	1036	1096	1119	1141	1163	1185	1198	1211	1211	1211	1211	1208	1206
4.0	35	114	194	273	380	486	572	659	776	894	961	1027	1103	1179	1227	1275	1316	1357	1365	1374	1394	1414	1414	1414	1414	1415	1416
4.5	0	0	235	332	479	626	722	819	957	1096	1168	1240	1320	1401	1449	1497	1547	1598	1590	1583	1610	1637	1637	1637	1637	1616	1595
5.0	0	0	280	400	592	784	899	1014	1144	1274	1380	1487	1569	1651	1691	1731	1785	1838	1807	1777	1806	1836	1836	1836	1836	1806	1777
5.5	0	0	320	432	641	849	1033	1216	1331	1446	1568	1690	1778	1867	1919	1970	1977	1984	1994	2005	2017	2030	2030	2030	2030	1990	1951
6.0	0	0	0	0	680	944	1155	1367	1495	1623	1759	1895	1983	2072	2137	2202	2205	2207	2226	2246	2240	2234	2234	2234	2234	2194	2154
6.5	0	0	0	0	720	1123	1335	1547	1678	1809	1963	2116	2200	2284	2332	2380	2425	2470	2452	2434	2403	2373	2373	2373	2373	2354	2336

Figure 12: Archimedes Wave Swing power matrix (unrestricted): output in kW [31].

When multiple power matrices are available, the suitability of the device for a particular site can be evaluated by completing a scatter diagram. The wave height and wave period recorded at the site in question should be plotted against one another as illustrated in Figure 13. If the power matrix and recorded data from the site in question overlap each other significantly on the scatter diagram, then the wave energy generator being investigated is a good choice for that particular location. As seen in Figure 13, the Pelamis is a very good match for the sample site analysed.

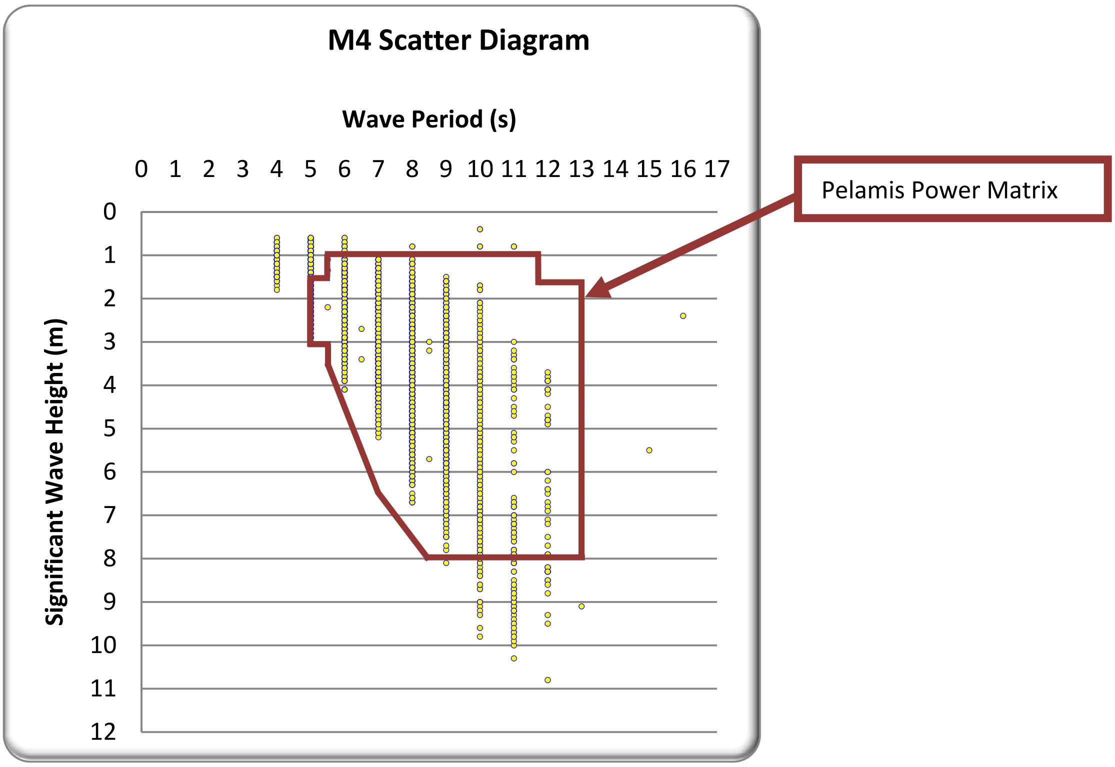


Figure 13: Scatter diagram for M4 data buoy off the coast of Ireland.

Once the most suitable wave power device has been chosen, and the power matrix obtained, the wave height and wave period data recorded at the site must be converted into power output. To do this, I created a program in MATLAB [32] and I used wave height and wave period data from four different sites around the coast of Ireland. The data was gathered by the Marine Institute in Ireland using data buoys (see Figure 14) distributed around the Irish coast [33]. Obtaining data from four different locations spread around the island ensured that wave energy fluctuations were minimised. A list of data buoys can be seen at [34].

Figure 14: A Data Buoy.

River Hydro

River hydro refers to hydroelectric dams with no storage facility i.e. they must operate as water passes through them. Although there is no river hydro in Ireland at the moment, it was used to simulate the Irish reference model. I found that if hydro power was simulated under the "Hydro" option, which is discussed after this section, EnergyPLAN would optimise the dispatch of hydro itself. However, the optimal dispatch of hydro according to EnergyPLAN was different to the actual dispatch of hydro power in Ireland in the year 2007. In contrast, the river hydro power did not optimise the dispatch of hydro, but instead it replicated the historical hourly values that were inputted as the distribution. These hourly outputs were obtained from the Irish TSO, but note that it took four months to obtain this data so long waiting periods may need to be accounted for. When modelling future alternatives for Ireland, I will use the Hydro Power option in EnergyPLAN, as this will enable EnergyPLAN to optimise the dispatch of hydro itself, which is desirable in the future.

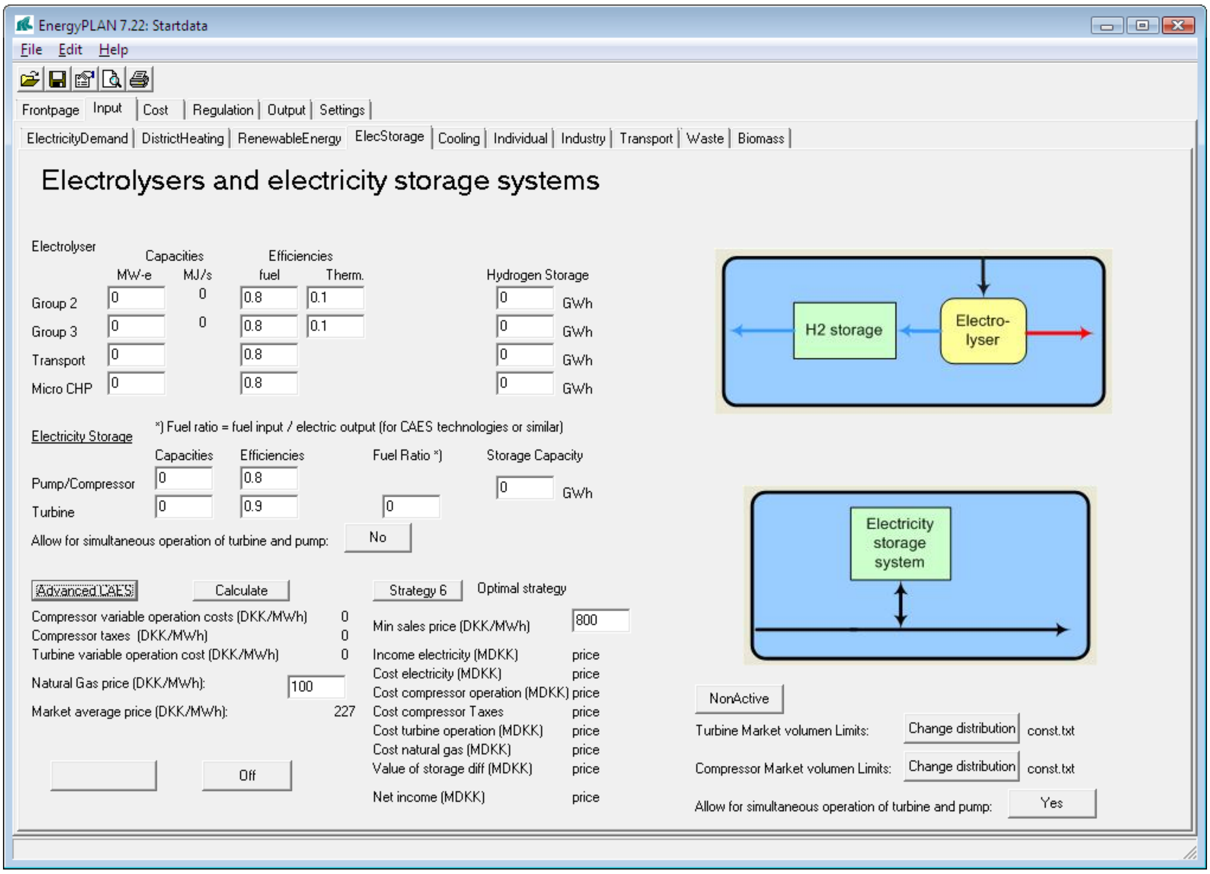
Hydro Power

I found that hydro data was quite difficult to gather i.e. power capacity and storage capacity. As indicated in Figure 5, hydro only provides 2.3% of Ireland's electricity demands, and therefore there is not a lot of detailed information which is easily accessible for the hydro plants. As a result, I found that the most productive approach was to contact the hydro plants directly, and request the data required from the operator in the control room. For the distribution of the hydro production, I used annual output data for the hydro plants which was recorded by the Irish TSO's, EirGrid [35] and SEMO [36]. As stated previously, hydro power was only simulated using this option when modelling future alternatives for Ireland, and not when modelling the reference model in 2007.

Geothermal / Nuclear

There is currently no geothermal or nuclear power plants installed in Ireland so no data has been gathered for them.

3.1.1.4 Electricity Storage

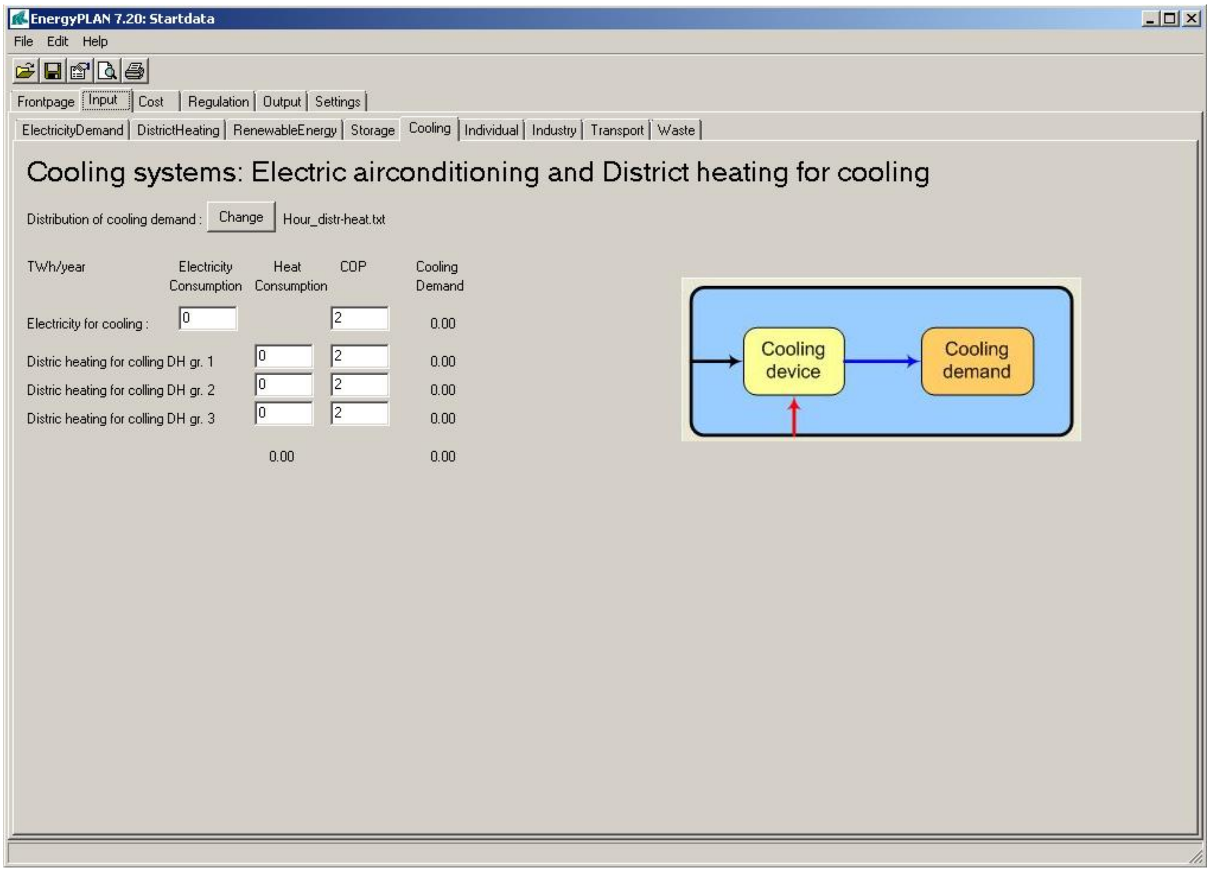


Only pumped hydroelectric energy storage (PHES) is in use in Ireland so I did not have to gather any data on electrolysers or compressed air energy storage (CAES). For the PHES parameters I simply contacted the plant control rooms and they provided information of pump/turbine and storage capacities. However, plant efficiencies could not be revealed as it was "commercially sensitive". Therefore, from the Energy Balance, I calculated the overall PHES efficiency using

$$\eta_{TH} = \frac{E_{OUT}}{E_{IN}} \tag{3}$$

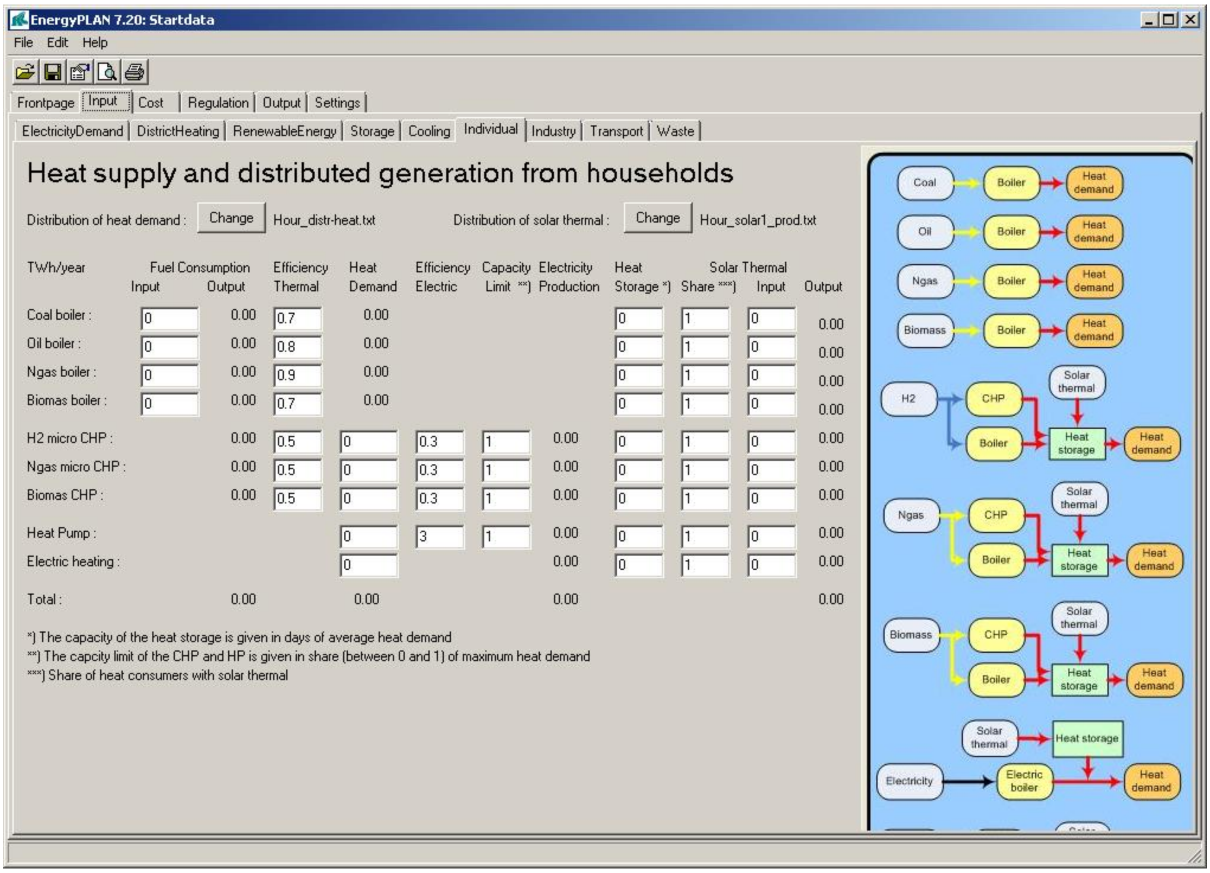
where E_{OUT} was the total electricity produced from Turlough Hill in 2007 (0.349 TWh) and E_{IN} is the total electricity consumed by Turlough Hill in 2007 (0.546 TWh). The resulting round-trip efficiency, η_{TH}, was 63.9%. Therefore, I inserted the a pump efficiency of 79.9% and a turbine efficiency of 79.9%, so that the round-trip efficiency was 0.799*0.799 = 0.639. Note that the same efficiency was used for the pump and turbine as this is typically the situation within a PHES facility [37].

3.1.1.5 Cooling



There is currently no cooling load in Ireland so no data was required for the Irish reference model. Note that the heat demand under the cooling tab is for absorption cooling.

3.1.1.6 Individual



Heat Distribution

It was very difficult to predict the annual heat distribution for the entire population of Ireland. In order to estimate it, I used 'Degree Day' data from Met Éireann, the Irish meteorological service [26].

There are Heating Degree Days (HDD) and Cooling Degree Days (CDD). As their title suggest, the HDD indicate the level of heating required on a given day, and the CDD indicate the level of cooling required on a given day. In Ireland, cooling is not usually necessary due to the climate and therefore, the HDD was used to estimate the amount of heat required.

Heating Degree Days work as follows: The temperature within a building is usually 2-3°C more than outside, so when the outside temperature is 15.5°C, the inside of a building is usually 17.5°C to 18.5°C. Therefore, once the temperature drops below this 15.5°C outside-temperature setpoint, the inside temperature drops below 17.5/18.5°C and the space heating within a building is usually turned on. Note that this 15.5°C setpoint is specifically for Ireland and it can change depending on a number of factors such as the climate and the typical level of house insulation [38]. A full explanation about the calculation and application of degree data can be obtained from [38, 39].

For the heat demand, an annual distribution with a resolution of 1 day is required, but the Degree Day data obtained from various weather stations around Ireland is only recorded on a daily basis, as seen in Figure 15. Therefore, this 1 day data had to be converted into hourly readings. To do this, I took a daily cycle from a similar study completed on Denmark in [7] and applied it to the Irish distribution with a program I developed in MATLAB [32], which is displayed in Figure 16. As district heating is common in Denmark, hourly data could be easily obtained over a 24 hour period and it was assumed that Ireland would have a similar daily distribution in its heat demands as Denmark.

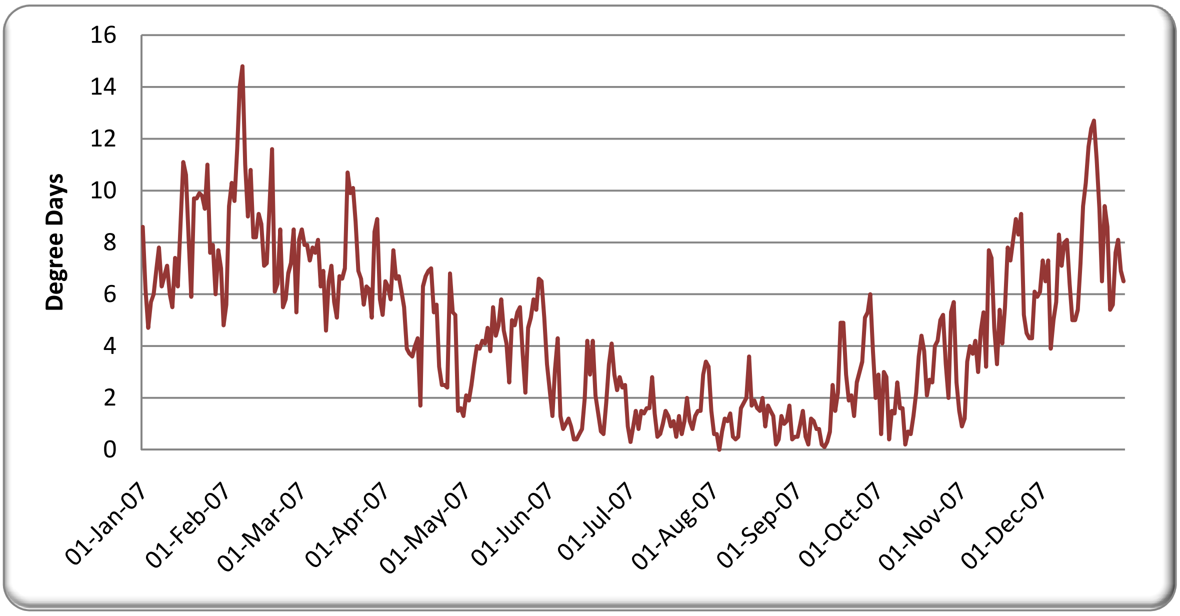


Figure 15: Degree Day data from Belmullet meteorological station in Mayo, Ireland [26].

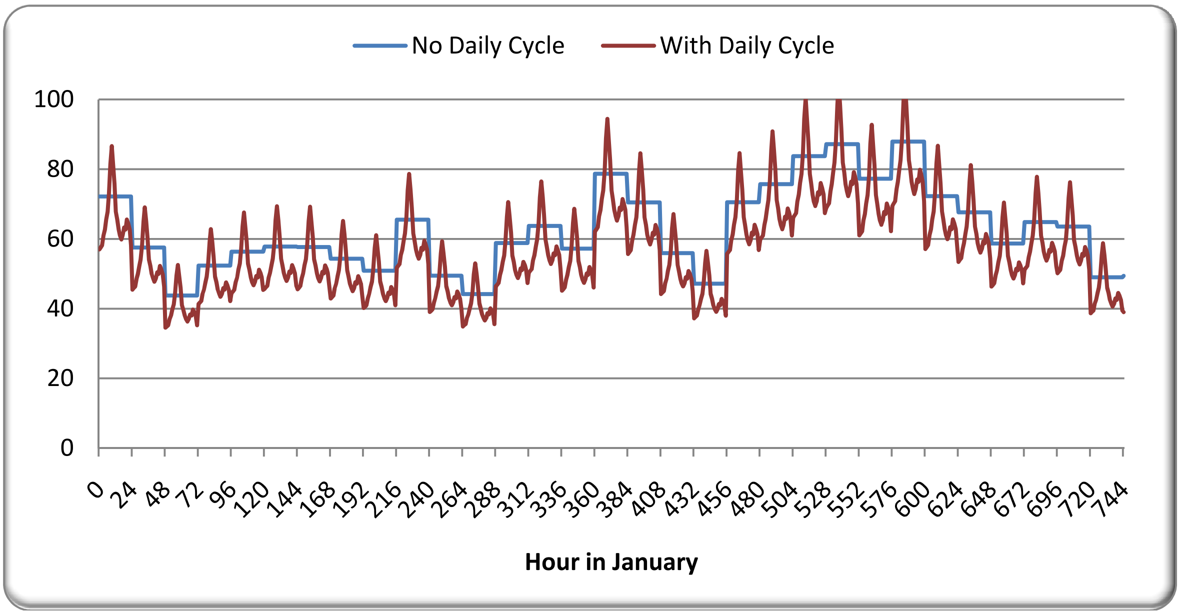


Figure 16: Individual heat distribution for January 2007 in Ireland (Hourly).

Finally, by obtaining the HDD data, the level of heat required each day within a building can be estimated. However, this only considered the space heating distribution and not the hot water distribution. Therefore, a heat distribution which accounted for both space heating and hot water demand had to be constructed. For the summer months, it was assumed that space heating would not be required: it was assumed that the heat absorbed by the building during warm temperatures, and also the building's occupants, would keep the building warm during colder temperatures. Therefore, during the summer hot water is the only heating demand. It was also assumed that hot water is a constant demand each day for the entire year, as people tend to use a consistent amount of water regardless of temperature or time of year. The BERR in the UK completed a report in relation to domestic hot water and space heating, which indicated that the ratio of space heating to hot water heating in the home is 7:3 [40]. Therefore, as seen in Figure 17, for the heat distribution a 30% constant bandwidth was placed at the base representing hot water demand, and a 70% demand was placed on top (based on Degree Day data) representing the space heating requirements. Figure 17 represents the heat distribution constructed for modelling the heat demand within the Irish energy system.

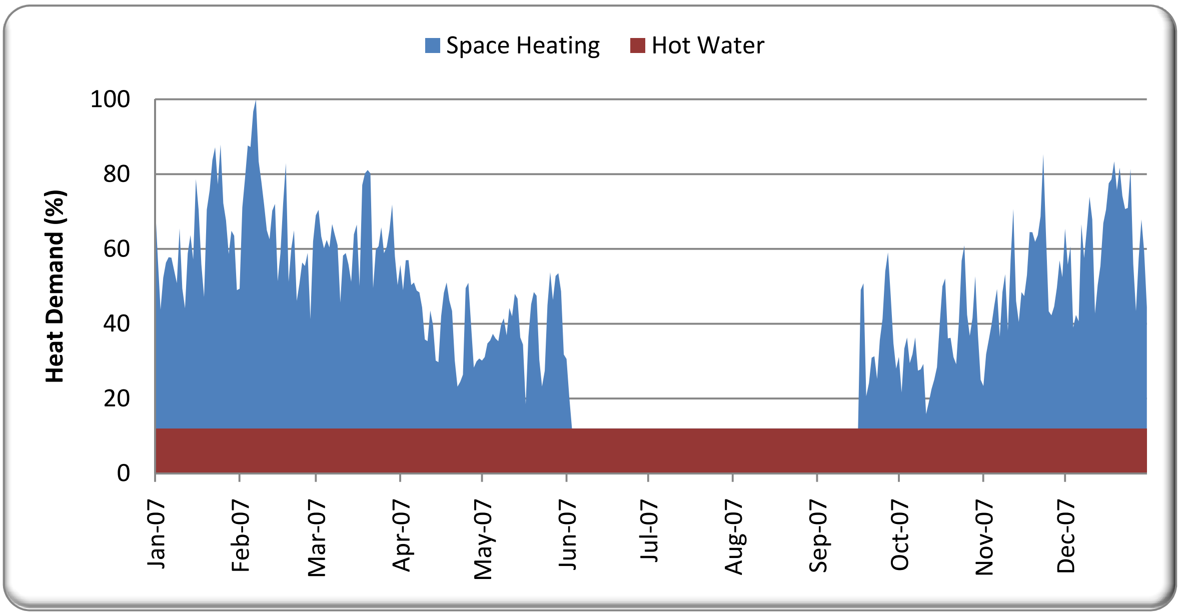


Figure 17: Individual heat distribution for Ireland.

Fuel Consumption and Efficiency of Boilers

The fuel consumed for residential heating can be obtained from the Energy Balance. For the boiler efficiencies, I consulted the Building Energy Rating documentation provided by the Irish energy agency, SEAI [41]. This documentation is used by assessors to complete energy ratings for homes in Ireland. Therefore, the documentation gave the typical type and efficiency of different domestic boilers used in Ireland. This could be available in other countries also, or if not, the efficiencies within this documentation could be applied to other applications.

Electric Heating

Electric heating demand can also be difficult to quantify as it is usually documented in conjunction with the heating demand and not as a separate entity. From a report completed by the Irish energy agency, SEAI, it was found that 14% of all domestic electricity is used for space heating and 23% for hot water [42]. In a separate report by SEAI, it was found that 12% of commercial electricity was used for heating purposes [43]. Therefore, I used these figures to calculate the electric heating demand in Ireland i.e. (37% of domestic electricity plus 12% of commercial electricity).

Solar Distribution

There are two types of solar thermal in the EnergyPLAN model: solar thermal that contributes to district heating and solar thermal for individual households. At present, only individual solar thermal energy is used in Ireland and hence it is discussed here under the individual's heating demands. The inputs required for the EnergyPLAN model are the:

1. The total annual solar thermal production.
2. Hourly distribution of the solar thermal production over the year.
3. Solar thermal share.

The total solar production in Ireland for 2007 was got from the 2007 Energy Balance [16]. For the distribution, an attempt was made to obtain the hourly power output from a solar panel for an existing installation[4] in Ireland, but this could not be obtained. As discussed previously, the solar radiation available in Ireland and Denmark is very similar (see Table 3-3) and hence, a solar thermal output curve which was constructed for Denmark was used. This solar thermal distribution was created by a Danish energy consultancy firm,

[4] Solar-thermal output can be found by measuring the inlet and outlet temperatures of the collector, and also the flow rate.

PlanEnergi [44], for the 2030 Danish Energy Plan [7, 8]. The distribution gives the production from an individual solar thermal installation of 4.4 m^2 during a typical Danish year. The energy produced from the solar panel is based on a daily consumption demand of 150 litres, which needs to be heated from 10°C to 55°C in combination with a 200 litre storage tank. The 4.4 m^2 represents a solar thermal installation designed for hot water and some contribution to space heating.

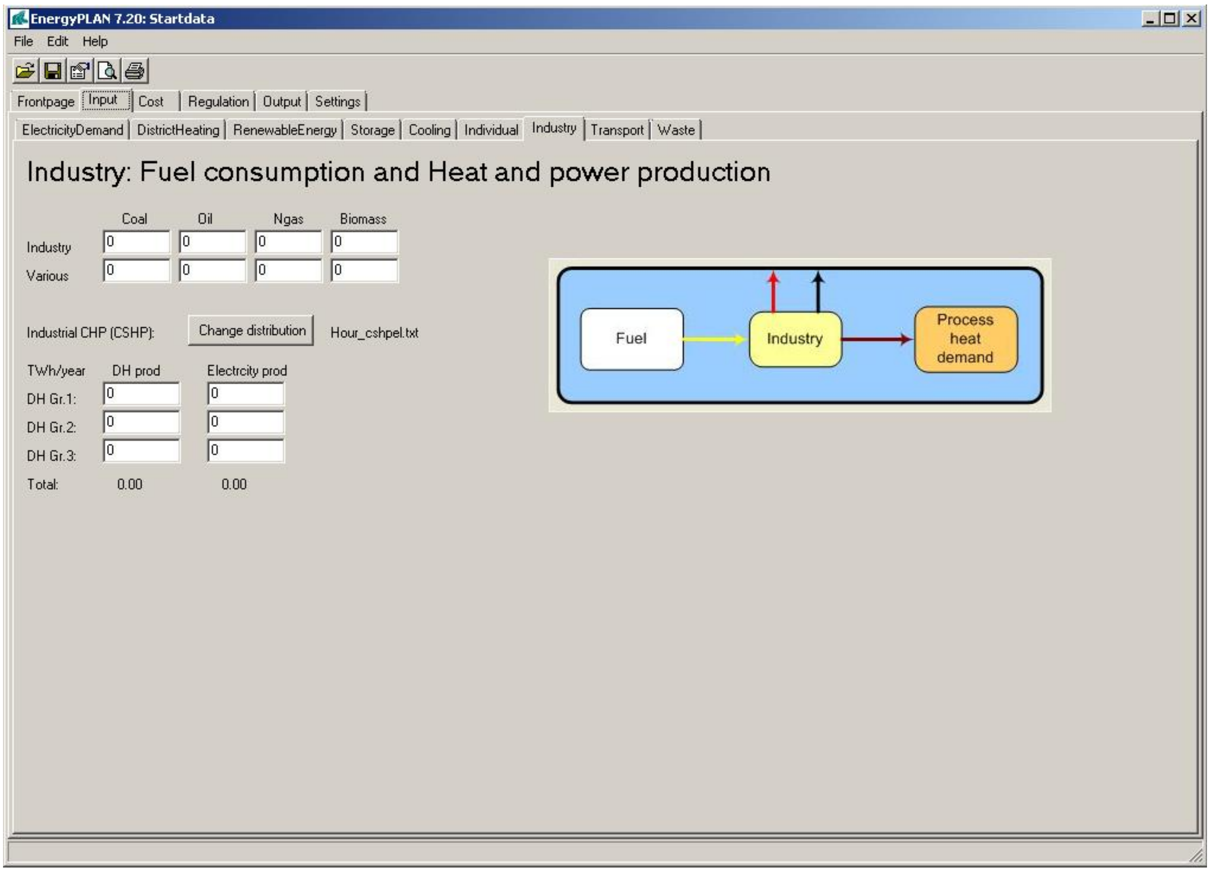
Solar Share

The solar share is the percentage of houses that have a solar panel installed: To estimate this in Ireland, I contacted the Irish energy agency, SEAI [13], who told me that there was 33,600 m^2 of solar thermal panels installed in Ireland. A typical solar installation in Ireland uses 5 m^2, therefore it was assumed that there are approximately 6,720 solar installations in Ireland. From the 2006 census in Ireland, it was stated that there are 1,469,521 homes in Ireland [45]. Therefore, it was concluded that there is a solar thermal installation in 0.45% (6720/1469521) of Irish houses.

Solar Input

As stated above, I found the total solar energy utilised from the Irish Energy Balance [16]. The solar input and solar share can be adjusted if necessary to match the solar production with the value stated in the Energy Balance.

3.1.1.7 Industry



Fuel Consumption

The quantity of each fuel-type consumed within industry can be found in the Energy Balance [16]. The 'Various' input is only used when a consumption cannot be specified anywhere else or may need to be analysed on its own i.e. gas consumption for offshore drilling.

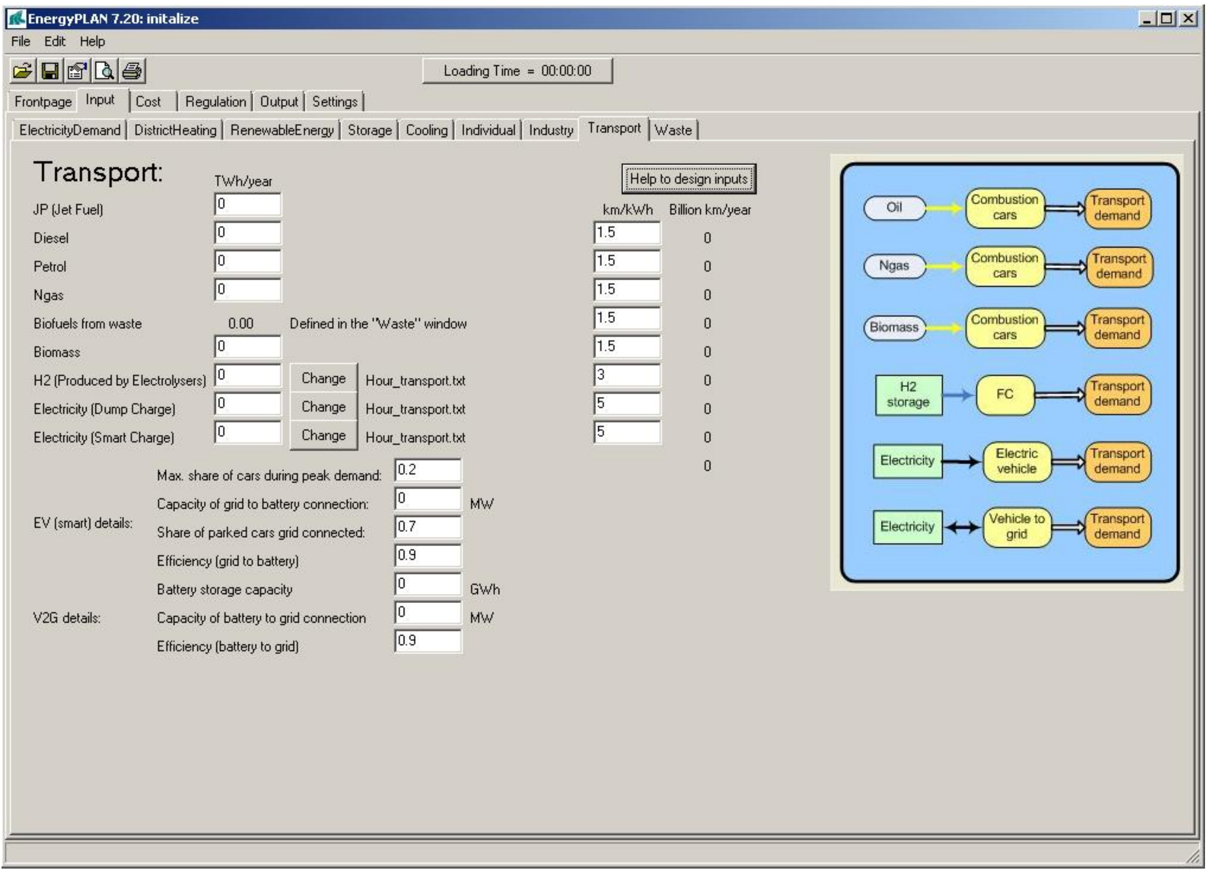
Industrial CHP: Energy Production

In order to quantify the capacity of industrial CHP, I had to contact the statistics department within the Irish energy agency, SEAI, who had the breakdown of CHP plants at their disposal. They could identify from their records how much CHP in Ireland was industrial and how much was dispatchable. From this they could also provide the amount of electricity and heat that was produced from both industrial and dispatchable CHP.

Industrial CHP: Distribution

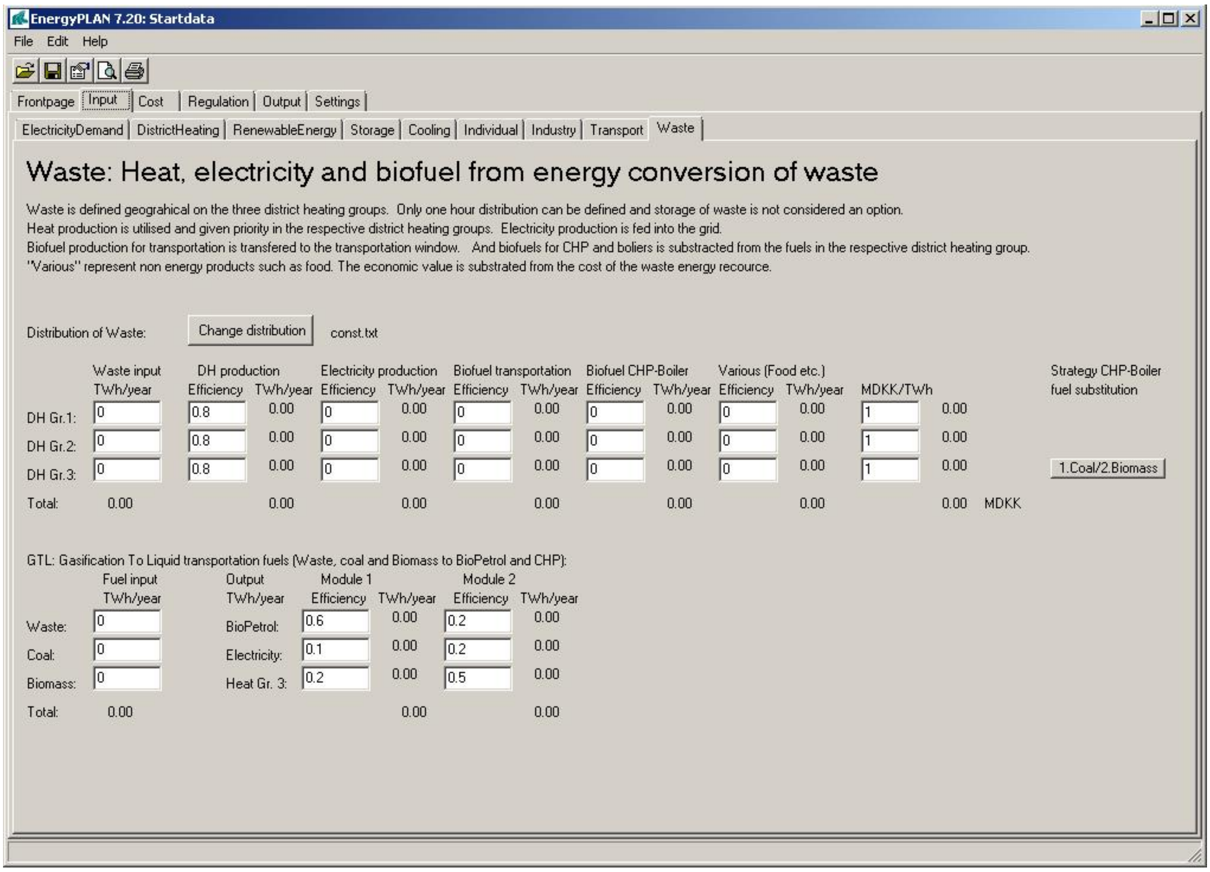
Since the industrial CHP in Ireland was not controlled by the TSO, I used the 'const.txt' distribution for Industrial CHP, which means the output was simply constant. It is considered the best proxy for modelling a production that cannot be controlled.

3.1.1.8 Transport



The amount of fuel used for transport is available by fuel type, including electricity, from the Energy Balance [16].

3.1.1.9 Waste



There is currently no waste used for energy production in Ireland so no data was required for the Irish reference model. However, Münster carried out a detailed energy system analysis of waste-to-energy options in [46], which could be useful if data is required.

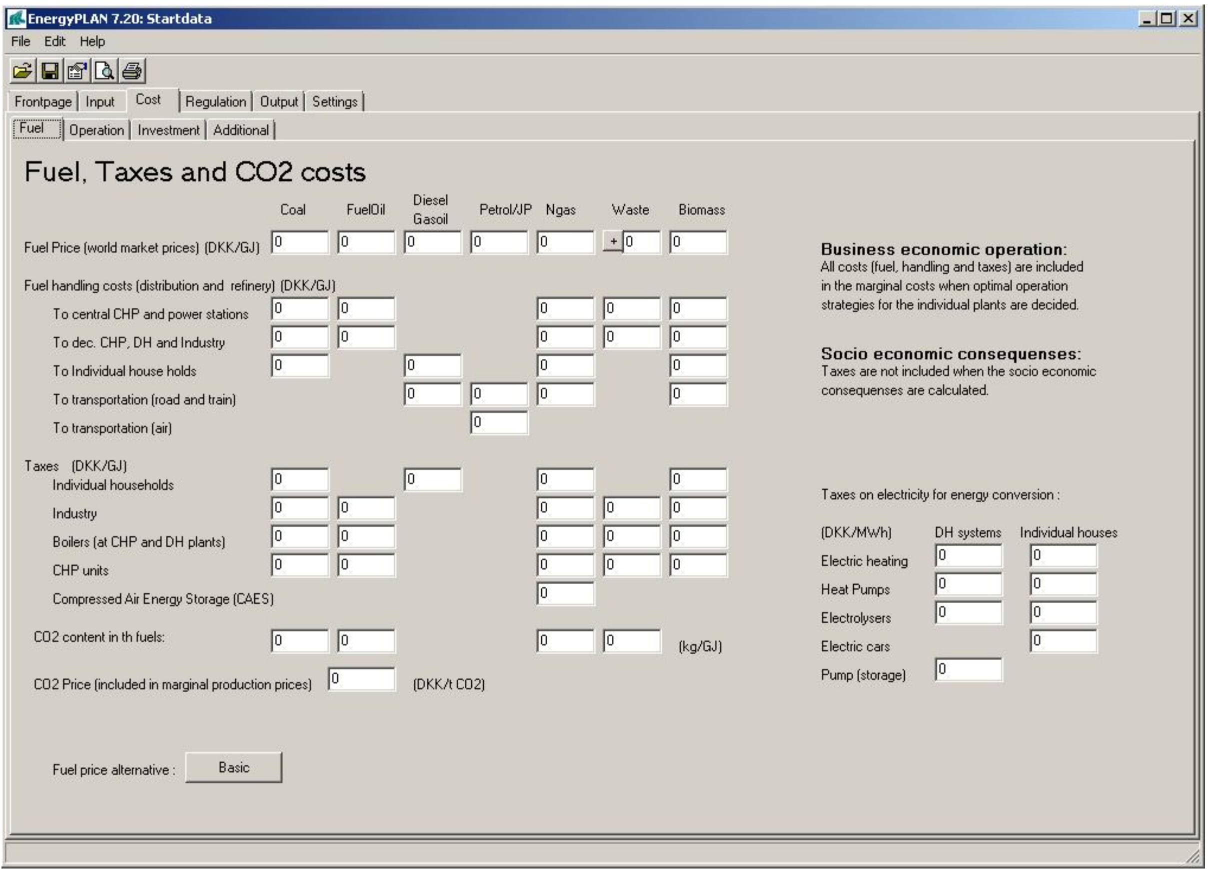
3.2 Economic Data Required

EnergyPLAN simulates the costs of an energy system in four primary categories:

1. Fuel costs: purchasing, handling, and taxes in relation to each fuel as well as their CO_2 costs.
2. Investment costs: capital required, the lifetime of each unit, and the interest rate on repayments.
3. Operation costs: the variable and fixed operation and maintenance costs for each production unit.
4. Additional costs: any extra costs not accounted for in the program by default e.g. the cost of insulating houses for increased energy efficiency.

These costs are used by EnergyPLAN to perform socio-economic and business-economic studies, as well as a market optimisation for the energy system.

3.2.1 Fuel Tab



3.2.1.1 Fuel and CO_2 Costs

The purchasing costs for each fuel were obtained for the year 2007, 2010/2015, and 2020, which were recommended by the International Energy Agency [47] and the Danish Energy Authority [48] and are displayed in Table 3-4. Also, if required the current market price for different fuels can be obtained from the links below:

- Crude Oil: http://www.oil-price.net/
- Coal: http://www.eia.doe.gov/cneaf/coal/page/coalnews/coalmar.html
- Natural Gas: http://www.bloomberg.com/markets/commodities/energyprices.html

Table 3-4
Fuel prices used for 2007, 2010/2015 and 2020 [47, 48].

(€/GJ)	Crude Oil ($/bbl)	Crude Oil	Fuel Oil	Gas Oil/ Diesel	Petrol/JP	Coal	Natural Gas	Biomass
2007	69.33	9.43	6.66	11.79	12.48	1.94	5.07	6.30
2010/2015	100	13.60	9.60	17.00	18.00	3.19	8.16	7.01
2020	110	14.96	10.56	18.70	19.80	3.11	9.16	7.45

The crude oil price was used to identify the cost of Fuel Oil, Diesel, and Petrol/Jet Fuel. As these fuels are refined from crude oil their prices are proportional to the crude oil price and hence, the price ratio between each of these and crude oil typically remains constant. Therefore, the following ratios recommended by the Danish Energy Authority was used to calculate these prices [48]: ratio of crude oil to fuel oil was 1 to 0.70, crude oil to diesel was 1 to 1.25, and crude oil to petrol/jet fuel was 1 to 1.33. Also, the fuel handling costs were obtained from the Danish Energy Agency [48] and are displayed in Table 3-5.

Table 3-5
Fuel handling costs [48].

€/GJ	Fuel Oil	Gas oil/Diesel	Petrol/JP	Coal	Natural Gas	Biomass
Power Stations (central)	0.228	0.228	-.-	0.067	0.428	1.160
Distributed CHP, district heating & industry	1.914	1.807	-.-	-.-	1.165	1.120
Individual households	-.-	2.905	-.-	-.-	2.945	6.118
Road transport	-.-	3.159	4.257	-.-	-.-	11.500 [49]
Airplanes	-.-	-.-	0.696	-.-	-.-	-.-

3.2.1.2 Taxes

I rang the Irish revenue office to find out if there were any taxes on specific fuels or technologies and found that there was none. Note that Value Added Tax (VAT) is not included here.

3.2.1.3 CO_2 Content

In the EnergyPLAN model, three CO_2 emission factors are required: one for coal, oil, and natural gas. However, in this study coal and oil do not just account for a single fuel but instead, they account for a group of fuels. The coal category represents peat and coal as these were modelled as a single fuel: this is a method which has been carried out in previous models of the Irish energy system [50] due to the similar power plant efficiencies and CO_2 emissions of the two fuels. The oil category represents a number of different types of oil including kerosene, diesel, and coke. Therefore, the CO_2 emission factors for coal and oil were calculated based on fuel consumptions from the Irish Energy Balance [16], and CO_2 emission factors recommended by SEAI [20] for the various fuels they represent. In conclusion, the CO_2 emission factor used for coal/peat was 100.63 kg/GJ (see Table 3-6), for oil was 73.19 kg/GJ (see Table 3-7) and for natural gas was 57.1 kg/GJ [20].

Table 3-6
CO_2 emission factors for coal and peat.

Fuel	Consumption (TWh) [16]	Consumption (% of Total)	CO_2 Emission Factor (kg/GJ) [20]
Coal	17.425	65.09	94.60
Milled Peat	6.186	23.11	116.70
Sod Peat	2.167	8.09	104.00
Briquetted Peat	0.992	3.71	98.90
Total	**26.770**	**100.00**	**100.63**

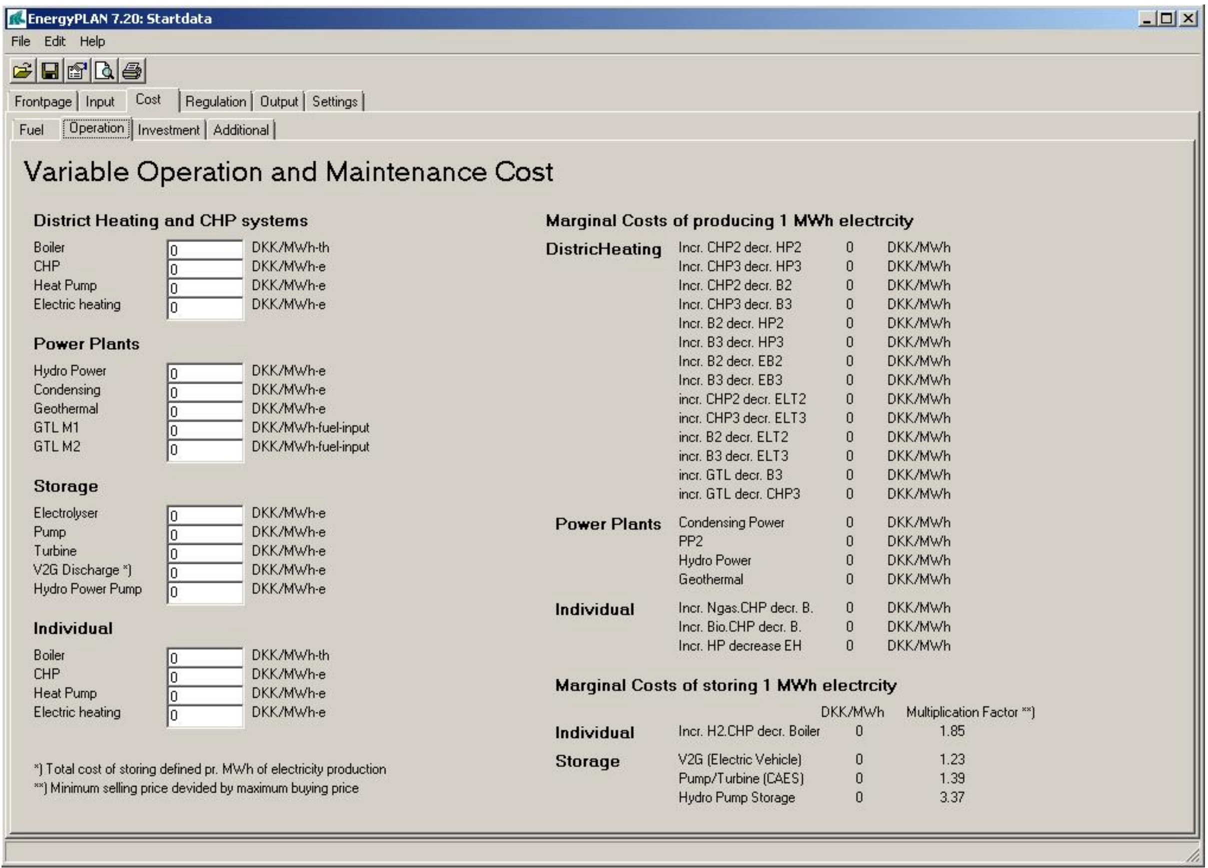
Table 3-7
CO_2 emission factor for oil.

Fuel	Consumption (TWh) [16]	Consumption (% of Total)	CO_2 Emission Factor (kg/GJ) [20]
Gasoil	45.230	43.35	73.3
Gasoline	17.425	21.40	70.0
Jet Kerosene	12.134	11.63	71.4
Kerosene	10.620	10.18	71.4
Fuel Oil (Residual Oil)	8.528	8.17	76.0
Coke	3.637	3.49	100.8
LPG	1.856	1.78	63.7
Naphtha	0.012	0.01	73.3
Total	**104.342**	**100.00**	**73.2**

3.2.1.4 CO_2 Price

There is no carbon tax in Ireland at the moment. However, Ireland participates in the European carbon trading scheme and therefore there is a cost associated with carbon, even though it is not an internal government tax. For information on carbon costs, visit http://www.pointcarbon.com.

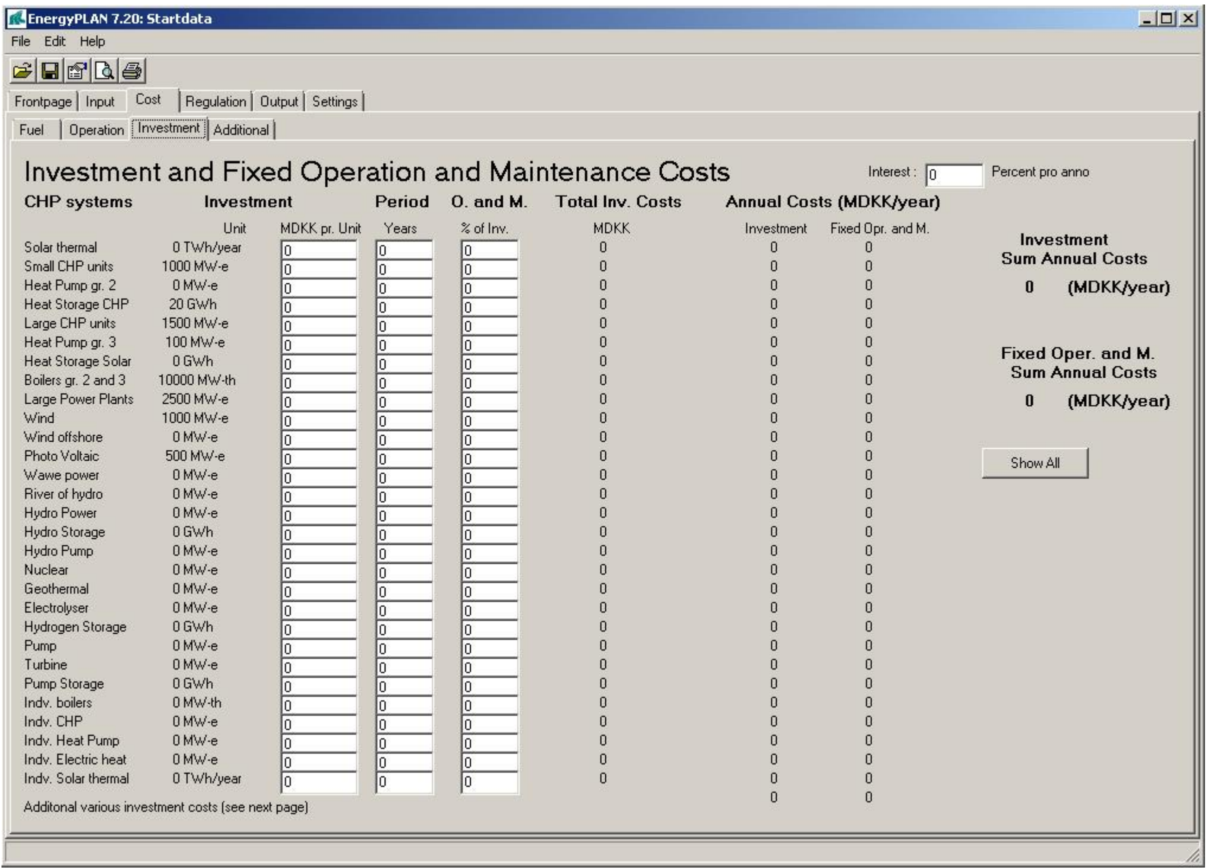
3.2.2 Operation Tab



Under this tab you must enter the variable operation and maintenance costs. These are the costs that occur if the technology in question is used. For example, an annual service has to be done every year regardless of how often the generating plant operates. Therefore, this is a fixed operation and maintenance charge. However, if the generating plant generates 1 GWh it must get a second service costing €1500. Therefore, the generating plant has a variable operation and maintenance cost of €1500/GWh or €1.50/MWh, as this second service will only be necessary if the plant actually operates.

For the condensing plant, I found the variable operation and maintenance costs for each type of power plants from [51], and calculated an overall variable O&M cost of 1.84 €/MWh as displayed in Table 3-8. For the PHES facilities, I obtained the variable operation and maintenance costs from [52], and to date I have not found the variable operation and maintenance cost for the individual units.

3.2.3 Investment Tab



Under this tab you must enter the investment, lifetime, and fixed operation and maintenance costs. These costs are used for to calculate the annual costs of each component based on a fixed rate repayment loan: the governing equations for these calculations are discussed in detail in the EnergyPLAN user manual [1]. The investment and operation costs for condensing power plants were obtained from [51], and are displayed in Table 3-8.

Table 3-8
Investment, fixed O&M, and variable O&M costs for Irish condensing power plants [51].

Plant Type	Investment Costs (M€/MW)	Fixed O&M Costs (€/MW/year)	Variable O&M Costs (€/MWh)	2007 Irish Capacity / Fuel Type
Steam turbine, coal fired, advanced steam process, 2004	1.100	16000	1.800	852.5 MW / Coal 806 MW / Oil
Steam turbine, coal fired advanced steam process, 20% co-firing of biomass, 2004	1.200	22000	3.000	345.6 MW / Peat
Gas turbine single cycle, (40 - 125 MW), 2004	0.485	7350	2.500	719 MW / Gas
Gas turbine combined cycle (100 - 400 MW), 2004	0.525	14000	1.500	2806 MW / Gas
Gas turbine combined cycle (10 – 100 MW), 2004	0.700	10000	2.750	208 MW / Gas

The onshore wind and offshore wind costs were obtained from [53]: investment costs for onshore wind are 1.2 M€/MW and offshore wind is €1.6 M€/MW, while the fixed O&M costs are 6 €/MWh for onshore wind and 8.70 €/MWh for offshore wind[5]. The investment costs for hydro power in Ireland were obtained from the British Hydropower Association [54]: the investment cost for hydro stations below 100 MW is 1.765 M€/MW, the fixed O&M costs are approximately 2.7% of the investment and the variable O&M costs are approximately 1.3% of the investment. The costs for PHES in Ireland were found from Gonzalez *et al.* [52] as 0.476 M€/MW and 7.89 M€/GWh for the initial investment, 0.6% of the investment for the fixed O&M cost, and 3 €/MWh for the variable O&M cost.

For the individual heating units (such as boilers, electric heaters, solar) I found the investment and fixed O&M costs by contacting the suppliers as displayed in Table 3-9. Remember to include the installation costs for boilers and solar systems such as the installation of the central heating system, which can be obtained from [55]. The type of individual heating systems in Ireland (by fuel type) was got from a report carried out by the Irish Central Statistics Office (CSO) [56]. Finally, just to note that taxes should not be included in the costs inputted here. Therefore, if a supplier is contacted to obtain the costs, ensure the price quoted is without tax.

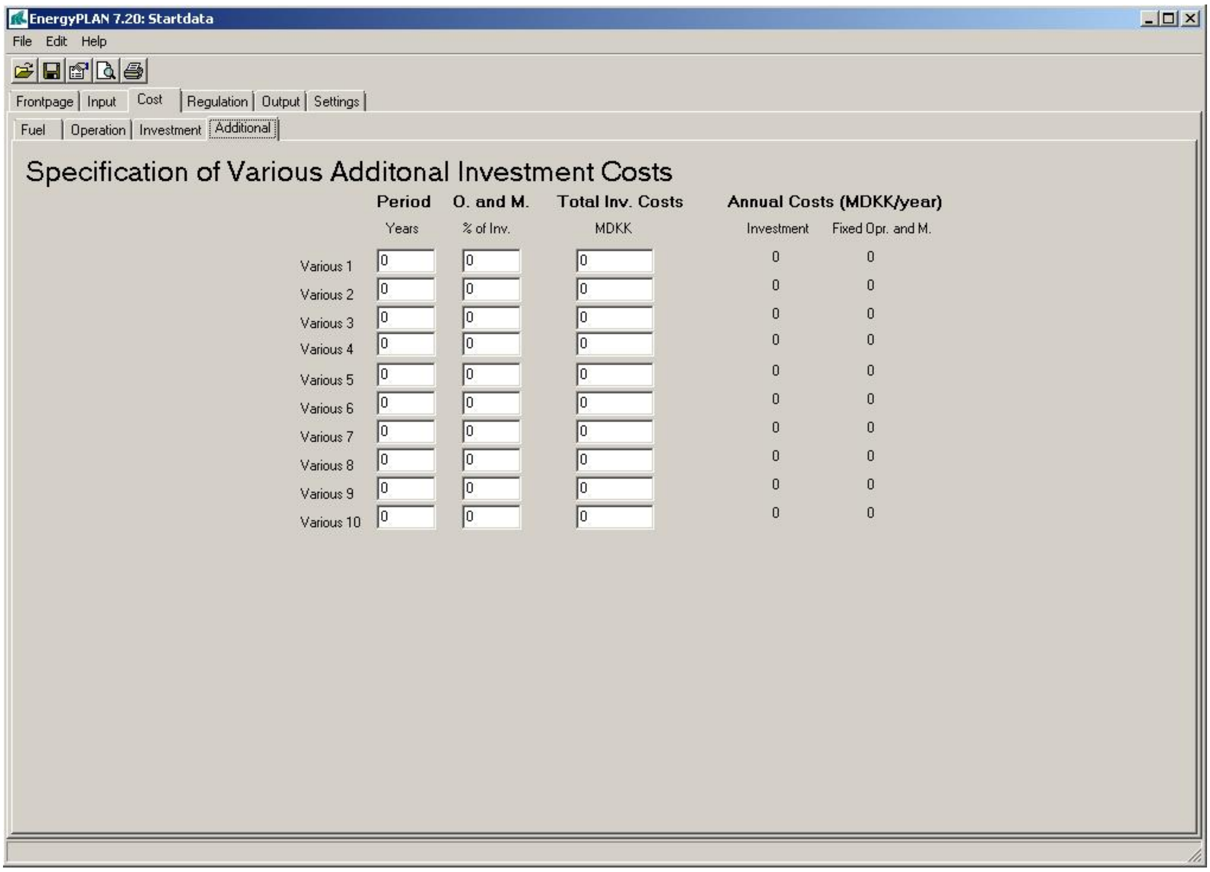
Table 3-9
Costs (excluding taxes) of individual heating systems for the reference model of the Irish energy system.

Fuel Type	Size	Cost Including Installation (€)	Lifetime (years)	O&M Costs (€/year)
Oil	26 kW	14750	15	110
Biomass	19 kW	19500	15	110
Natural Gas	26 kW	14750	15	110
Solid Fuel	21 kW	15300	15	110
Electric Boiler	12 kW	15500	15	0
Electric Heaters	20 kW	6000*	20	0
Solar Thermal	2400 kWh/year	5900	35	55

***Does not account for electric transmission upgrades that may be necessary for widespread installations.**

[5] This does not include the balancing costs associated with wind power.

3.2.4 Additional Tab



This can be used if there are any additional costs which have not been accounted for. For example, the cost of insulating houses to reduce energy demands may be accounted for here.

4 Areas of Difficulty

Although a large degree of EnergyPLAN is intuitive, there were some areas which I found difficult to understand at first. Therefore, a few aspects of the model are discussed in more detail here.

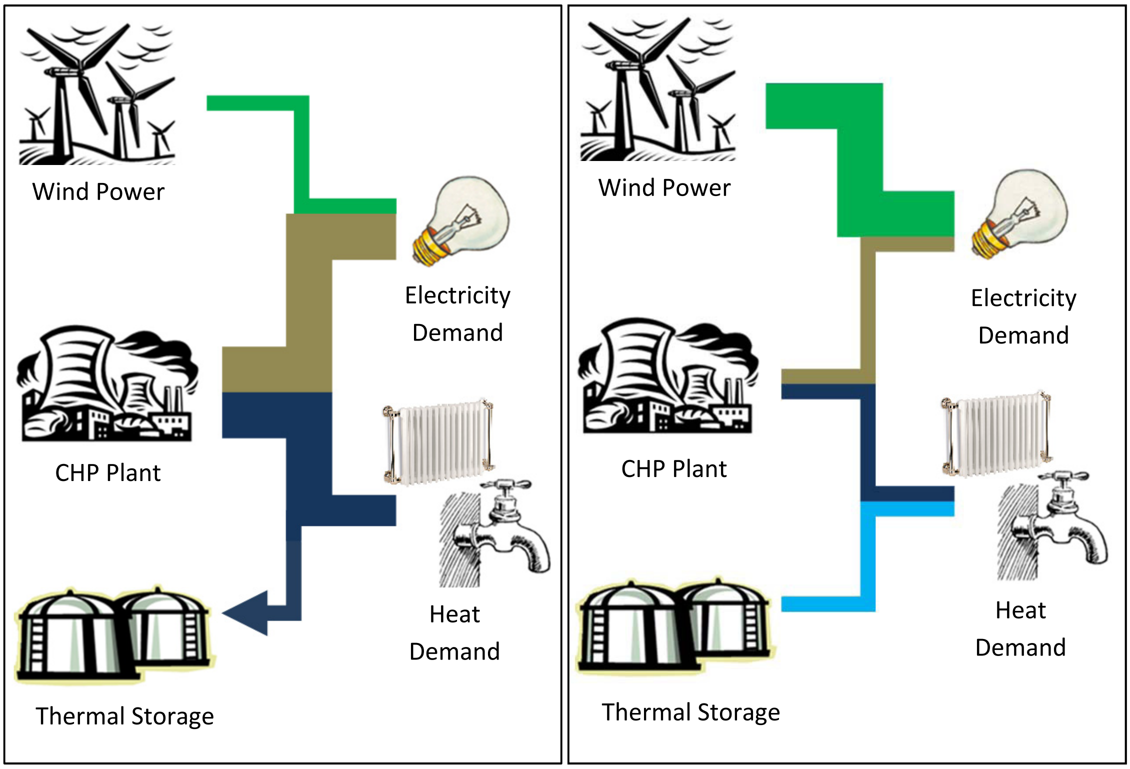
4.1 Thermal Energy System

As there are very little CHP plants or no significant district heating networks in Ireland, heat is usually generated at the point of demand, so I did not fully understand how a thermal energy system worked. As EnergyPLAN can model this type of energy system, a brief outline is provided. To illustrate the flexibility induced by thermal energy storage on such a system, a snapshot of the power production during different scenarios is presented below. The system in question contains a CHP plant, wind turbines, a thermal storage, a hot water demand, and an electrical demand as illustrated in Figure 18.

During times of low wind power, a lot of electricity must be generated by the CHP plants to accommodate for the shortfall in power production. As a result, a lot of heat is also being produced from the CHP plant as seen in Figure 18a. The high production of heat means that production is now greater than demand, and consequently, heat is sent to the thermal storage.

Conversely, at times of high wind power, the CHP plants produce very little electricity and heat. Therefore, there is now a shortage of heat so the thermal storage is used to ensure that demand is met, as seen in Figure 18b.

Note: This system can be simulated by choosing the Technical Optimisation 2: Balancing Heat and Electricity Demands under the Regulation tab in EnergyPLAN.



(a) (b)

Figure 18: Energy system with district heating and thermal energy storage during (a) a low wind scenario and (b) a high wind scenario.

This system has been put into practice in Denmark which has the highest wind penetration in the world. Also, Lund and Mathiesen have created a roadmap for Denmark towards achieving a 100% renewable energy system using a thermal energy system [4-8].

4.2 District Heating Groups

After learning about the operation of the thermal storage energy system, the next question that comes to mind relates to the CHP inputs under the 'Input -> DistrictHeating' tab. Under this tab there are three district heating (DH) categories:

1. DH without CHP: These are systems that use boilers, waste heat or some other form of heat supply but do not use CHP.
2. DH with small CHP plants: This category represents CHP plants, which cannot operate without a heat load.
3. DH with large CHP plants: This category specifies the amount of centralised CHP capacity. The primary difference between these and group 2, is the fact that these plants do not need to create heat during the production of electricity. They can remove the heat from their system using water (usually from a river or the sea).

4.3 Technical Optimisation vs. Market Optimisation

There are two kinds of studies that can be carried out in EnergyPLAN:

1. Technical Optimisation (tries to minimise fossil fuel consumption and can be carried out without any cost inputs).
2. Market Optimisation (tries to minimise the operation costs of the system).

The technical optimisation is based on the technical abilities of the components within the energy system. The difference between demand and supply is met as long as the power producing units are capable of completing the task. Only in situations where the power producing units are not able to meet demand is power imported from the external market, and where excess energy is produced (i.e. during high wind speeds) energy is exported to the external market. There are four types of technical optimisation:

1. Balancing Heat Demands: This option performs a technical optimisation where heat producing plants must operate according to the heat demand. The units chosen to supply the heat demand are chosen in the following order:
   i. Solar Thermal.
   ii. Industrial CHP.
   iii. Heat Production from Waste.
   iv. CHP Heat.
   v. Heat Pumps.
   vi. Peak Load Boilers.

   This also affects electricity production: Under this regulation, the amount of heat that CHP units produce, and hence the amount of electricity they produce is dependent on the heat demand at that time.
2. Balancing Both Heat and Electricity Demands: This option performs a technical optimisation where the export of electricity is minimised, primarily by replacing CHP production with boilers or heat pumps[6] when there is excess electricity. By doing this the electricity consumption is increased (i.e. more electric boilers or heat pumps) and the electricity produced is decreased (i.e. less CHP production). Also for this operating strategy, if there is condensing power plant production on the grid and there is CHP capacity available, then the CHP replaces it and the excess heat produced is sent to a thermal storage. A graphical illustration of this option is displayed in Figure 18. This ensures that the energy system operates with the largest efficiency possible.

[6] Heat pumps are powered by electricity to transfer heat from one heat source (i.e. ground or water) into another heat source (i.e. a district-heating network).

3. Option 2 but "Reducing CHP also when partly needed for grid stabilisation": As stated this is largely the same as option 2. In option 2, CHP is reduced when there is a large output from renewable energy sources. However, in option 3, CHP is also reduced if it is required for grid stabilisation[7].
4. Option 1 using the Triple Tariff: As stated this is largely the same as option 1. However, in this option, CHP plants do not operate according to the heat demand, but instead they operate according to the 'Triple Tariff'. The Triple Tariff was introduced in Denmark to encourage CHP units to produce electricity during peak hours. Therefore, CHP plants got paid 3 times more for producing electricity during peak hours (times) than any other time of the day. As a result, thermal storage became very common with CHP plants, so they could store the excess heat created while output was high during peak electricity hours. This regulation option is used to simulate the Triple Tariff.

The market optimisation is designed to match supply and demand at the least cost, rather than on the minimum fuel consumption. For this optimisation two primary steps are completed:

1. The short-term marginal cost[8] of producing electricity and/or heat is calculated for each power producing unit.
2. The least-cost combination of production units is chosen to supply the demand.

For a detailed explanation of the calculations completed in both the technical optimisation and the market optimisation, read chapter 6 and 7 respectively in the EnergyPLAN user manual [1].

4.3.1 Business-economic vs. Socio-economic calculations

Economic results from EnergyPLAN can be divided into two types of studies:

1. Socio-economic costs: Taxes are not included.
2. Business-economic costs: Taxes are included.

The socio-economic studies are designed to minimise the costs to society i.e. the cost for the region/country to provide the energy necessary. In a socio-economic study the aim is to identify the costs associated with the Technical Optimisation. This way you can optimise the performance of the energy system without the restrictions imposed by economic infrastructures. Therefore, the following steps can be followed:

1. Complete a Technical Optimisation identifying the optimum technical operation of the energy system, for example the system with minimum Critical Excess Electricity Production (CEEP) or minimum CO_2.
2. Complete a socio-economic study to identify the costs associated with the technical optimisation.

The business-economic studies show what can be done while being profitable for a business or person. Once the socio-economic study is completed, the market-economic study should be done to identify how the existing market infrastructure obstructs the optimal technical solution. Therefore, after completing steps 1 and 2 above:

3. Carry out a business-economic market optimisation to identify how the existing system prevents the introduction of the optimal technical solution.
4. Make changes to the existing tax system to outline how the existing market could be adjusted to promote the optimal technical solution.

Sometimes, socio-economic costs can include the following aspects also:

1. Job Creation.
2. Balance of Payment[9].
3. Public Finances.

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[7] The electric grid needs to be maintained at a certain frequency and voltage. Power plants usually provide ancillary services that ensure this frequency and voltage are maintained. If the frequency or voltage is not maintained, the electric grid will stop working.

[8] Marginal Cost: Is the cost at which there is enough supply to meet demand.

[9] http://en.wikipedia.org/wiki/Balance_of_payments.

4. Environmental Costs.

However, these calculations are not made by the EnergyPLAN model. Instead, these benefits must be calculated externally by the user based on the investments made in the different energy system sectors. These calculations are discussed further in [57].

4.4 Optimisation criteria for an Energy System

It is very important to know how EnergyPLAN identifies that one energy system is better than an alternative energy system. There five primary variables that are recorded when doing this are:

1. PES (Primary Energy Supply): This is the total energy required within the energy system.
2. CO_2: This is the amount of CO_2 produced within the energy system.
3. Annual costs: The annual costs required to supply the required energy demand.
4. EEEP (Exportable Excess Electricity Production): This is the amount of electricity that had to be exported from the energy system, AND it was possible to export because the required transmission out of the energy system was available.
5. CEEP (Critical Excess Electricity Production): This is the amount of electricity that had to be exported from the energy system, BUT COULD NOT be exported because the required transmission was not available.

How important each of these parameters is depends on the objective of your study. Exercise four in the EnergyPLAN training (which is available from the EnergyPLAN website [1]) provides a good example of how these parameters are used to compare alternative energy systems. Finally, other parameters may also be used to compare energy systems, but these are the most common.

4.5 External Electricity Market Price

Under the regulation tab, an external electricity market price can be defined. The distribution is NOT indexed like other distributions in EnergyPLAN: instead the actual values in the distribution are used. The distribution can be manipulated by an 'Addition Factor' and a 'Multiplication Factor'. The addition factor is used to represent the cost of CO_2, because when a CO_2 cost is increased or introduced, it usually increases the cost of electricity by a constant amount for each hour. The multiplication factor is usually used to model an increase in fuel prices, as these usually increase the cost of electricity proportionally during each hour.

4.6 Operation Strategy for Electricity Storage

In EnergyPLAN, electricity storage is described in the form of pumped hydroelectric energy storage (PHES) as this is the largest and most common form of electricity storage in use today [58]. However, this can be used to define any type of electricity storage which has a charging capacity (i.e. pump/compressor), discharge capacity (i.e. turbine), and a storage capacity. When defining the electricity storage capacities available, it is also possible to define an electricity storage operation strategy. Once again, as EnergyPLAN uses PHES as a reference, the question asked in EnergyPLAN when defining an operation strategy is "Allow for simultaneous operation of turbine and pump: YES/NO", which is displayed in Figure 19.

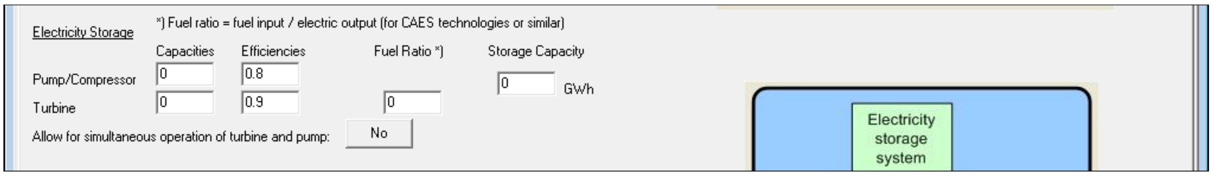


Figure 19: Electricity storage parameters and operation strategy in EnergyPLAN.

Historically, PHES (and other large-scale electricity storage) facilities have typically been constructed with a single penstock system as they were designed to maximise electricity generation from baseload power plants i.e. by charging during the night when electricity prices were low (due to a high percentage of baseload power) and discharging during the day when electricity prices were high (due to a high demand). Therefore, they could not, or never needed to, charge and discharge at the same time. To simulate this scenario in EnergyPLAN, select NO for "Allow for simultaneous operation of turbine and pump". However, if energy storage devices are designed especially to integrate fluctuating renewable energy, there may be additional benefits when using PHES that can charge and discharge at the same time. This can be achieved in a single PHES facility by installing two penstocks, as displayed in Figure 20, or also by installing multiple single penstock system PHES facilities on the same energy system i.e. one can charge while the other is discharging at the same time. By using a double penstock system, the PHES introduces more flexibility onto the energy system and hence it can aid the integration of more renewable energy. As a result, this operating strategy is also possible in EnergyPLAN by selecting YES when asked "Allow for simultaneous operation of turbine and pump".

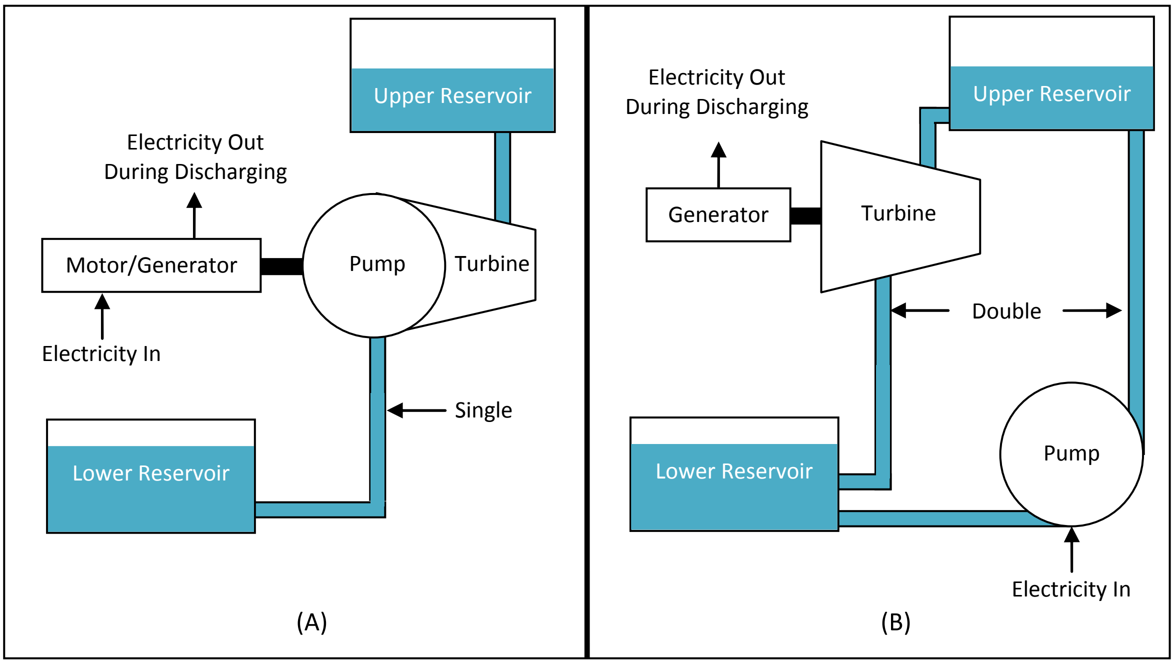


Figure 20: One PHES facility with (A) a single penstock system and (B) a double penstock system.

So how do these operating strategies affect the hourly operation of the system in EnergyPLAN? To illustrate this, an example is presented in Table 4-1 using the parameters defined in Table 4-2. As seen in Table 4-1, the primary advantage of a double penstock PHES facility relates to grid stabilisation: to see how the grid stabilisation percentage is calculated, see section 8.3 of the EnergyPLAN user manual. As the pump and turbine can operate together, a double penstock system can store excess wind production using the pump, while also producing grid stabilising power using the turbine. In contrast, the single penstock system has to prioritise one of these as the pump and turbine cannot operate together. From Table 4-1 it is clear that the single penstock system prioritises the pump and therefore, the excess electricity is sent to the PHES while the power plants (PP) must now provide the grid stabilising power. As a result, a system with single penstock PHES facility typically requires more fuel (i.e. more PP production) than a system with a double penstock PHES. Also, as a double penstock can charge and discharge at the same time, the storage capacity does not fill up as quickly as a single penstock system. Therefore, double penstock system can achieve higher fluctuating renewable energy penetrations at lower storage capacities than a single penstock system.

Table 4-1
Results for hours 1-10 when using a single and a double penstock PHES operation strategy in EnergyPLAN.

hour	elec. demand	wind power	pp	pump	turbine	storage	stab. -load	import	CEEP	EEEP
Double Penstock System: YES										
1*	397	194	0	0	203	136	170	0	0	0
2	374	266	1	6	113	0	100	0	0	0
3*	362	400	38	209	134	0	100	0	0	0
4	346	522	0	400	224	40	100	0	0	0
5	**331**	**750**	**0**	**740**	**321**	**230**	**100**	**0**	**0**	**0**
6	323	616	0	557	264	346	100	0	0	0
7	326	618	0	557	265	460	100	0	0	0
8	335	860	0	893	369	714	100	0	0	0
9	346	772	0	757	331	906	100	0	0	0
10	354	672	0	606	288	1031	100	0	0	0
Single Penstock System: NO										
1	397	194	0	0	203	4747	170	0	0	0
2	374	266	114	6	0	4752	100	0	0	0
3	362	400	171	209	0	4919	100	0	0	0
4	346	522	224	101	0	5000	100	0	298	0
5	**331**	**750**	**0**	**0**	**321**	**4598**	**100**	**0**	**740**	**0**
6	323	616	264	502	0	5000	100	0	55	0
7	326	618	0	0	265	4669	100	0	557	0
8	335	860	369	414	0	5000	100	0	479	0
9	346	772	0	0	331	4586	100	0	757	0
10	354	672	288	517	0	5000	100	0	89	0

***Values highlighted in red and green relate to section 4.7 of this report.**

Table 4-2
Parameters used in EnergyPLAN for the sample calculations on the two PHES operation strategies.

Parameter	Capacity*
Electricity demand	4 TWh
Condensing power plants	500 MW
Wind energy	2000 MW
Pump capacity	1000 MW
Turbine capacity	1000 MW
Pump efficiency	0.8
Turbine efficiency	0.8
Storage capacity	5 GWh
Regulation: Minimum grid stabilisation share	0.3 (i.e. 30%)

***All values were entered using the default distributions provided when opening EnergyPLAN.**

4.6.1 Storage capacity for the double penstock system strategy

It should be noted that when using a double penstock system, the storage capacity may never be recorded as full during the hourly values. This is due to the calculation procedure in EnergyPLAN. As stated previously, a double penstock system can charge using excess electricity, while also discharging to provide grid stabilisation. Therefore, at the beginning of each hour EnergyPLAN must decide how much energy will be stored due to excess electricity and how much will be discharged to provide grid stabilisation. To do this the following sequence is used by EnergyPLAN:

1. The amount of excess wind power can be stored is calculated i.e. is there enough pump capacity and storage capacity available to send the excess electricity.
2. It calculates the electricity that needs to be discharged to meet the grid stabilisation requirements.
3. Based on these figures, the electricity that must be imported or exported is evaluated.

Once again, by looking at an example this should become clear. Let's take the values from hour 887 in Table 4-3. At the beginning of this hour there was a demand of 442 MW and a wind production of 1200 MW. Therefore, by following the steps outlined above, EnergyPLAN did the following:

1. The storage capacity from the hour before was 4351 MWh, while the total capacity was 5000 MWh. Therefore, the total capacity available for the next hour was 649 MWh, which equates to a pump demand of 812 MW (i.e. **649**/0.8). Hence there is only room for 812 MW of excess electricity production in the storage during this hour.
2. As the total production during this hour is now 1200 MW of wind, there is no grid stabilising power operating. The regulation used states that 30% of all production must be grid stabilising. However, if the turbine starts producing power, it too will be adding to the production and hence the amount of grid stabilisation required will increase. For example, if the turbine provides 30% of the wind production, which is 360 MW (i.e. 0.3*1200), then the total production is now 1560 MW, but 360/1560 is only 23%, which is less than 30%. Therefore, the total power that must come from the turbine must account for its own production also and is calculated from (see section 8.3 of the EnergyPLAN user manual for full details on grid stabilisation calculations [1]):

   Turbine = 0.3*(Wind+Turbine) = 0.3*(1200+Turbine) => 0.7Turbine = 360 => Turbine = 514 MW

   As the turbine needs to produce 514 MW, it means that **643** MWh (514/0.8) must be removed from the storage facility, so the balance in the storage facility during this hour is **4351** + **649** – **643** = **4357** MWh.
3. Now that EnergyPLAN has evaluated that the maximum electricity it can store is 812 MW and the total electricity it needs for stabilisation is 514 MW, it can equate how much electricity is left for export, which is 1200 + 514 - 812 - 442 = 460 MW. Note that this has a tolerance of ±1 MW as the decimal place may be greater or less than 0.5.

An important issue to notice here is the value recorded for the storage facility at the end of the hour. Even though the value recorded was 4357 MWh, the storage capacity was full during the calculations i.e. after the pump demand was added: **4351** + **649** = 5000 MWh. Therefore, when analysing the results for a double penstock, the 'Maximum Storage' for the PHES facility may not register as the storage capacity, even though it has been full during the analysis.

For clarity purposes, let's look at another example: hour 5 from Table 4-1:

1. There is 1000 MW and 5000 MWh of pump and storage capacity available respectively.
2. There is 750 MW of wind and 0 MW of grid stabilising power. Therefore, the turbine capacity required is: Turbine = 0.3*(Wind+Turbine) => Turbine = 321 MW.
3. Now that the total production is 1071 MW (750+321), but the demand is only 331 MW, 740 MW is sent to the storage as there is sufficient pump and storage capacity available. Therefore, the balance for the storage is 592 MWh (740*0.8) in and 401 MWh out (321/0.8), which means the value at the end of the hour is 40 + 592 - 401 = 231 MWh.
4. Finally, all the excess power was sent to the storage and all of the grid stabilising power was provided by the turbine, so no export or import occurred.

Finally, the single penstock is evaluated in the same way, except if excess power and grid stabilisation must be provided at the same time, the excess power is prioritised (i.e. pump operates) and the power plants (PP) provide the grid stabilisation (i.e. as the turbine cannot operate when the pump is operating).

Table 4-3
Calculating the hour pump and turbine demand for a double penstock PHES.

Hour	Elec. Demand	Wind Power	PP	Pump	Turbine	Storage	stab. load	Import	CEEP	EEEP
885	500	1230	0	1000	527	4220	100	0	257	0
886	472	1212	0	975	519	4351	100	0	284	0
887	**442**	**1200**	**0**	**812**	**514**	**4357**	**100**	**0**	**461**	**0**
888	403	1008	0	804	432	4460	100	0	233	0
889	383	982	0	675	421	4474	100	0	345	0
890	363	1116	0	658	478	4402	100	0	574	0

4.7 Description of 'stab.-load' from EnergyPLAN results window

As displayed in Figure 21, there are a number of grid stabilisation regulations that can be specified under the Regulation tab. This includes that "Minimum grid stabilisation production share" (MGSPS), which specifies the percentage of production that must be from grid stabilising units (i.e. power plants, hydro, etc). It is important to remember that this is a percentage of total production and not total demand, which is outlined in detail in section 8.3 of the EnergyPLAN user manual [1].

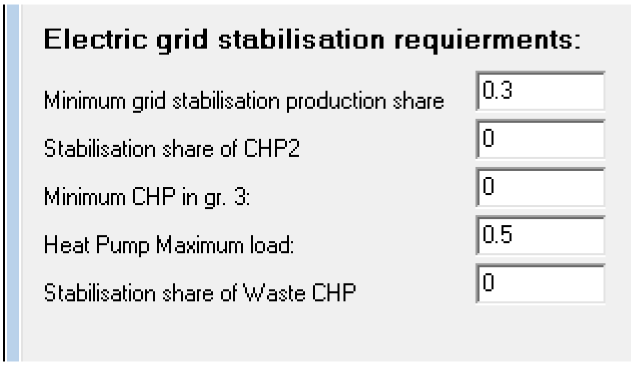
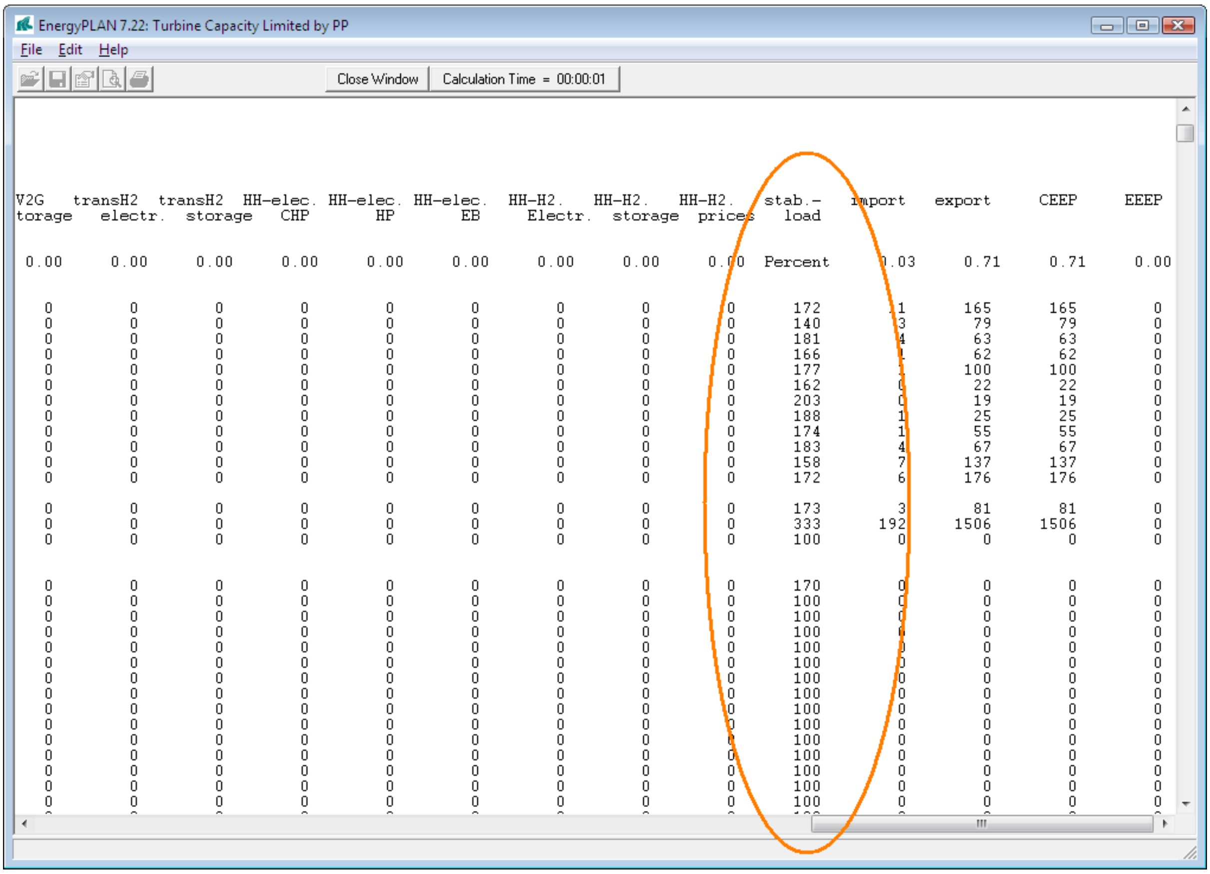


Figure 21: Grid stabilisation criteria in the EnergyPLAN model.

To measure if the system provided the MGSPS during each hour of the simulation, EnergyPLAN calculates the "stab.-load", as shown in Figure 22. This illustrates the percentage of the MGSPS that was satisfied during each hour. This section illustrates how the stab.-load is calculated.



V2G torage	transH2 electr.	transH2 storage	HH-elec. CHP	HH-elec. HP	HH-elec. EB	HH-H2. Electr.	HH-H2. storage	HH-H2. prices	stab.-load	import	export	CEEP	EEEP
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Percent	0.03	0.71	0.71	0.00
0	0	0	0	0	0	0	0	0	172	1	165	165	0
0	0	0	0	0	0	0	0	0	140	3	79	79	0
0	0	0	0	0	0	0	0	0	181	4	63	63	0
0	0	0	0	0	0	0	0	0	166	1	62	62	0
0	0	0	0	0	0	0	0	0	177	1	100	100	0
0	0	0	0	0	0	0	0	0	162	0	22	22	0
0	0	0	0	0	0	0	0	0	203	0	19	19	0
0	0	0	0	0	0	0	0	0	188	1	25	25	0
0	0	0	0	0	0	0	0	0	174	1	55	55	0
0	0	0	0	0	0	0	0	0	183	4	67	67	0
0	0	0	0	0	0	0	0	0	158	7	137	137	0
0	0	0	0	0	0	0	0	0	172	6	176	176	0
0	0	0	0	0	0	0	0	0	173	3	81	81	0
0	0	0	0	0	0	0	0	0	333	192	1506	1506	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	170	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0

Figure 22: Stab. Load results displayed in EnergyPLAN.

In section 8.3 of the EnergyPLAN user manual, it states that the percentage of electricity production from grid stabilising units, GridStab, is found from:

$$GridStab = \frac{e_{Stab}}{d_{Stab}} * 100 \quad (4)$$

Where e_{Stab} is the total electricity production from grid stabilising units and d_{Stab} is the minimum grid stabilisation production share that was specified in EnergyPLAN (as shown in Figure 21). Using this value the stab.-load is then calculated from:

$$stab.-load = \frac{GridStab}{MGSPS} \quad (5)$$

To make this clear, let's look at hour 1 for a double penstock system in Table 4-1. In hour 1 of Table 4-1, all of the production units are highlighted in red and all of the demand units are highlighted in green. Therefore, for hour 1 the total production is 397 MW, with 203 MW produced by the turbine and 194 MW produced by wind power. However, only the PHES turbine provides grid stabilising power and as a result, the GridStab value for this hour is (203/397)*100 = 51%. However, the MGSPS required is 30%, see Table 4-2 and Figure 21. Therefore, the stab.-load is 51%/30% = 170%, as displayed in Table 4-1.

Let's calculate the stab.-load for hour 3 of the double penstock system in Table 4-1 also. It is clear from Table 4-1 that during this hour the total production is 572 MW, with 400 MW from wind power, 38 MW from power plants, and 134 MW from the PHES turbine. As specified in the EnergyPLAN user manual, both power plants and the PHES turbine can provide grid stabilising power. Therefore, the total grid stabilising power production for hour 3 is 172 MW (38+134). This means that GridStab = (172/572)*100 = 30% and stab.load=30%/30% = 100%.

4.8 Abbreviations for the Results window

In the results window, there are a number of columns which represent various technologies within the EnergyPLAN simulation.

Table 4-4: Abbreviations displayed in the results window of the EnergyPLAN model.

Abbreviation	Input
elec.demand	"Sum(Demand excl. elec. Heating)" under the Input->ElectricityDemand tab.
elec.dem cooling	"Electricity Consumption" under the Input->Cooling tab.
Fixed Exp/Imp	"Fixed Import/Export" under the Input->ElectricityDemand tab
district heating	Sum of "Demand" under Groups I, II, and 3 of Input->DistrictHeating tab.
wind power	"Estimated Post Correction Production" for the renewable energy selected on the first row of "Renewable Energy Source" under the Input->RenewableEnergy tab.
PV	"Estimated Post Correction Production" for the renewable energy selected on the second row of "Renewable Energy Source" under the Input->RenewableEnergy tab.
Wave power	"Estimated Post Correction Production" for the renewable energy selected on the third row of "Renewable Energy Source" under the Input->RenewableEnergy tab.
River hydro	"Estimated Post Correction Production" for the renewable energy selected on the fourth row of "Renewable Energy Source" under the Input->RenewableEnergy tab.
Hydro power	"Estimated annual production" in the "Hydro Power" section under the Input->RenewableEnergy tab.
Hydro pump	Operation of the hydro pump. The capacity is defined in "Pump Capacity" in the "Hydro Power" section under the Input->RenewableEnergy tab.
Hydro storage	Energy in the hydro storage. The capacity is defined in "Storage" in the "Hydro Power" section under the Input-RenewableEnergy tab.
Hydro Wat-Sup	Incoming water to the hydro storage. It is defined in "Annual Water supply" in the "Hydro Power" section under the Input->RenewableEnergy tab.
Hydro Wat-Loss	Sometimes the water flowing into the hydro plant exceeds the demand required and hence, water has to go through the spillway and it is lost.
solar thermal	Sum of all the "Result TWh/year" at the end of all the "Solar thermal" inputs under Groups I, II, and 3 of Input->DistrictHeating tab.
cshp1 heat	"DH prod" for the "DH Gr.1" row under the Input->Industry tab.
waste1 heat	"DH production" in the first "DH Gr. 1" row under the Input->Waste tab.
DHP heat	Demand from district heating units under the input "Demand" of the "Group 1" section in the Input->DistrictHeating tab.
cshp2 heat	"DH prod" for the "DH Gr.2" row under the Input->Industry tab.
waste2 heat	"DH production" in the first "DH Gr. 2" row under the Input->Waste tab.
Geoth2 heat	This is the "DH production" produced by the "Geothermal operated by absorption hear pump on steam from waste CHP plants" for the "DH Gr.2" under the Input->Waste tab.
Geoth2 steam	This is the "Steam for Heat Pump" produced by the "Geothermal operated by absorption hear pump on steam from waste CHP plants" for the "DH Gr.2" under the Input->Waste tab.
Geoth2 storage	This is the "Steam Storage" produced by the "Geothermal operated by absorption hear pump on steam from waste CHP plants" for the "DH Gr.2" under the Input->Waste tab.
chp2 heat	The amount of heat produced from the CHP units in "Group 2" of the Input->DistrictHeating tab. The capacity and thermal efficiency of CHP units available to produce this heat are defined in the "CHP" & "Therm." inputs respectively, which are also under the "Group 2" section.

Abbreviation	Input
hp2 heat	The amount of heat produced from the Heat Pump units in "Group 2" of the Input->DistrictHeating tab. The capacity and coefficient of performance for the heat pump units available to produce this heat are defined in the "Heat Pump" & "COP" inputs respectively, which are also under the "Group 2" section.
boiler heat	The amount of heat produced from the boiler units in "Group 2" of the Input->DistrictHeating tab. The capacity and efficiency for the boiler units available to produce this heat are defined in the "Boiler" & "Therm." inputs respectively, which are also under the "Group 2" section.
EH2 heat	Heat produced from the electric boiler in group 2 of district heating. This occurs if CEEP regulation number 4 is used under the Regulation tab.
ELT2 heat	Heat produced from the Electrolyser in "Group 2" under the Input->ElecStorage tab.
storage CHP gr2	Energy available in "Heat storage gr.2" for CHP under the Input->DistrictHeating tab.
heat2-balance	The balance between the heat produced (i.e. from Industrial CHP, Waste, Geothermal, CHP, HP, Boilers, Electric Boilers, and Electrolysers), and the heat demand (i.e. "Demand input) under "Group 2" in the Input->DistrictHeating tab.
cshp3 heat	"DH prod" for the "DH Gr.3" row under the Input->Industry tab.
waste3 heat	"DH production" in the first "DH Gr. 3" row under the Input->Waste tab.
Geoth3 heat	This is the "DH production" produced by the "Geothermal operated by absorption hear pump on steam from waste CHP plants" for the "DH Gr.3" under the Input->Waste tab.
Geoth3 steam	This is the "Steam for Heat Pump" produced by the "Geothermal operated by absorption hear pump on steam from waste CHP plants" for the "DH Gr.3" under the Input->Waste tab.
Geoth3 storage	This is the "Steam Storage" produced by the "Geothermal operated by absorption hear pump on steam from waste CHP plants" for the "DH Gr.3" under the Input->Waste tab.
chp3 heat	The amount of heat produced from the CHP units in "Group 3" of the Input->DistrictHeating tab. The capacity of CHP units available to produce this heat is defined in the "CHP" input, which is also under the "Group 3" section.
hp3 heat	The amount of heat produced from the Heat Pump units in "Group 3" of the Input->DistrictHeating tab. The capacity and coefficient of performance for the heat pump units available to produce this heat are defined in the "Heat Pump" & "COP" inputs respectively, which are also under the "Group 3" section.
boiler heat r	The amount of heat produced from the boiler units in "Group 3" of the Input->DistrictHeating tab. The capacity and efficiency for the boiler units available to produce this heat are defined in the "Boiler" & "Therm." inputs respectively, which are also under the "Group 3" section.
EH3 heat	Heat produced from the electric boiler in "Group 3" of district heating. This occurs if CEEP regulation number 5 is used under the Regulation tab.
ELT3 heat	Heat produced from the Electrolyser in "Group 3" under the Input->ElecStorage tab.
storage CHP gr3	Energy available in "Heat storage gr.2" for CHP under the Input->DistrictHeating tab.
heat3-balance	The balance between the heat produced (i.e. from Industrial CHP, Waste, Geothermal, CHP, HP, Boilers, Electric Boilers, and Electrolysers), and the heat demand (i.e. "Demand input) under "Group 3" in the Input->DistrictHeating tab.
flexible eldemand	Sum of "Flexible demand (1 day)", "Flexible demand (1 week)", and "Flexible demand (4 weeks)" inputs under the Input->ElectricityDemand tab PLUS the electricity demand for "Electricity (Dump Charge)" under the Input->Transport tab.
hp elec.	The electricity required to power the heat pumps in "Group 2" and "Group 3" under the Input->DistrictHeating tab.

Abbreviation	Input
cshp elec.	Sum of "Electricity production" in the first "DH Gr.1", "DH Gr.2", and "DH Gr.3" rows in the Waste section only under the Input->Waste tab PLUS sum of "Electricity prod" for "DH Gr.1", "DH Gr.2", and "DH Gr.3" under the Input->Industry tab.
chp elec.	The electricity produced by the CHP units in "Group 2" and "Group 3" under the Input->DistrictHeating tab.
pp elec.	The electricity produced by the "Condensing" power plant units in "Group 3" under the Input->DistrictHeating tab.
pp2 elec.	The electricity produced by the "PP2" power plant units in "Group 3" under the Input->DistrictHeating tab.
geother. Elec.	The electricity produced by "Geothermal Power" and "Nuclear Power" under the Input->RenewableEnergy tab.
pump elec.	The electricity demand required to power the "Pump/Compressor" in the "Electricity Storage" section under the Input->ElecStorage tab.
turbine elec.	The electricity produced by the "Turbine" in the "Electricity Storage" section under the Input->ElecStorage tab.
pump-storage	The energy contained in the "Storage Capacity", which is in the "Electricity Storage" section under the Input->ElecStorage tab. The total energy put into the storage is equal to the "pump elec." multiplied by the "Pump/Compressor" efficiency and the total energy removed is equal to the "turbine elec." divided by the "Turbine" efficiency.
ELT2 elec.	The electricity consumed by the Electrolyser in "Group 2" under the Input->ElecStorage tab.
H2stor elt. 2	Energy stored in the form of fuel in the "Hydrogen Storage" of "Group 2" under the Input->ElecStorage tab.
ELT3 elec.	The electricity consumed by the Electrolyser in "Group 3" under the Input->ElecStorage tab.
H2stor elt. 3	Energy stored in the form of fuel in the "Hydrogen Storage" of "Group 3" under the Input->ElecStorage tab.
V2G Demand	This is the electricity required by the smart/V2G electric vehicles for transport purposes only (i.e. not the demand used when acting as a grid storage facility) and it is obtained by multiplying the "Electricity (Smart Charge)" input by the "Efficiency (grid to battery)" input under the Input->Transport tab. Note that the "Electricity (Dump Charge)" input is treated separately in the "flexible eldemand" results.
V2G Charge	This is the electricity demand taken from the grid for the smart/V2G electric vehicles and is from the "Electricity (Smart Charge)" input under the Input->Transport tab. Note that this could be higher if the V2G is used as a storage facility for the grid (i.e. energy is passed in and out of the cars). Note also that the "Electricity (Dump Charge)" input is treated separately in the "flexible eldemand" results already discussed.
V2G Discha.	This is the amount of electricity supplied from the smart/V2G cars to the grid. Its maximum value is obtained by multiplying the "Capacity of battery to grid connection" input by the "Share of parked cars grid connected". When comparing this value to other hourly values, the "Efficiency (battery to grid)" will also need to be considered.
V2G Storage	This is the amount of energy in the "Battery storage capacity" under the Input->Transport tab. Energy can be removed at 100% efficiency from this storage for transport (i.e. for the V2G Demand). However, the total energy put into the storage is equal to the "V2G Charge" multiplied by the "Efficiency (grid to battery)" and the total energy removed is equal to the "V2G Discha." divided by the "Efficiency (battery to grid).
transH2 electr.	The electricity consumed by the electrolyser which creates hydrogen for the transport sector. The value depends on the capacity and efficiency defined for "Transport" under the Input->ElecStorage tab, as well as the "H2 (Produced by Electrolysers) under the Input->Transport tab.

Abbreviation	Input
transH2 storage	This is the "Hydrogen Storage" capacity for "Transport" contained in the Input->ElecStorage tab.
HH-elec.CHP	The "Estimated Electricity Production" from the "H2 micro CHP", "Ngas micro CHP", and the "Biomass micro CHP" under the Input->Individual tab.
HH-elec. HP	The "Estimated Electricity Production" from the "Heat Pump" under the Input->Individual tab. This will increase as the "Capacity Limit" is reduced, as an electric boiler will supply the shortfall in heat supply at peak times.
HH-elec. EB	The "Estimated Electricity Production" from the "Electric heating" under the Input->Individual tab.
HH-H2. Electr.	The electricity consumed by the "Micro CHP" electrolyser under the Input->ElecStorage tab.
HH-H2 storage	The "Hydrogen Storage" capacity for "Micro CHP" under the Input->ElecStorage tab.
HH-H2 prices	The "H2 micro CHP" will only operate if it is cheaper than using a conventional boiler. Therefore, EnergyPLAN calculates the price of purchasing hydrogen and compares it to the price of operating a conventional boiler.
HH-heat Demand	Sum of "Heat Demand" for the "H2 micro CHP", "Ngas micro CHP", "Biomass micro CHP", "Heat Pump", and "Electric Heating" under the Input->Individual tab.
HH-heat CHP+HP	Sum of "Heat Demand" for the "H2 micro CHP", "Ngas micro CHP", "Biomass micro CHP", and "Heat Pump" under the Input->Individual tab.
HH-heat Boiler	This is the total amount of heat supplied by the boiler component only in the "H2 micro CHP", "Ngas micro CHP", and "Biomass micro CHP". This is dependent on the "Heat Demand" and the "Capacity Limit" of these technologies, which are defined under the Input->Individual tab.
HH-heat Solar	The sum of the "Solar Thermal Output" which was built in conjunction with the "H2 micro CHP", "Ngas micro CHP", "Biomass micro CHP", "Heat Pump", and "Electric Heating" under the Input->Individual tab.
HH-heat Storage	The operation of the "Heat Storage" which was built in conjunction with the "H2 micro CHP", "Ngas micro CHP", "Biomass micro CHP", and "Heat Pump" under the Input->Individual tab.
HH-heat Balance	This is the balace between supply and demand for the "H2 micro CHP", "Ngas micro CHP", "Biomass micro CHP", "Heat Pump", "Electric Heating", "Heat Storage", and "Solar Thermal" under the Input->Individual tab. Note, at least one full row needs to be complete for the heat balance to be activated.
stab.-load	This needs to be 100% to ensure that the "Minimum grid stabilisation production share" under the Regulation tab is met. It is explained in detail in the User's Guide to EnergyPLAN.
import	This is the amount of electricity that needed to be imported due to a shortage in supply or to ensure grid constraints were met. Note that this can exceed the "Maximum imp./exp. Cap:" defined under the Regulation tab.
export	This is the amount of electricity that needed to be exported due to an oversupply or to ensure grid constraints were met. Note that this can exceed the "Maximum imp./exp. Cap:" defined under the Regulation tab.
CEEP	This is the amount of electricity that was exported which did exceed the "Maximum imp./exp. Cap:" defined under the Regulation tab.
EEEP	This is the amount of electricity that was exported without exceeding the "Maximum imp./exp. Cap:" defined under the Regulation tab.
Nordpool prices	This is the "Price Distribution" in the "External Electricity Market Definition" section under the Regulation tab AFTER it has been manipulated by the "Addition factor" and the "Multiplication Factor".
Nordpool-prod	This is the "Price Distribution" in the "External Electricity Market Definition" section under the Regulation tab AFTER it has been manipulated by the "Addition factor" and the "Multiplication Factor". Also, for a market optimisation, the price elasticity is also considered. It is used to determine the units which can afford to buy electricity (i.e. heat pumps, electrolysers, energy storage, etc).

Abbreviation	Input
System prices	The system price is the resulting price after the NordPool price has been influenced by the import/export of electricity as defined by the price electricity input in the Regulation tab. The system price is lower (than the NordPool price) when there is export and higher when there is import.
DKmarket prices	This is the market price for the energy system being simulated, which is calculated based on the units operating, their capacities, and their corresponding costs from the Cost->Fuel and the Cost->Operation tabs.
Btl-neck prices	This is the price difference between the external market price "System Price" and the market being simulated "DKmarket prices".
import payments	This is the cost of importing electricity and it is obtained by multiplying the "import" by the "System Price". The value displayed needs to be multiplied by 1000 to obtain the true figure and it is a monetary value.
export payments	This is the revenue from exporting electricity and it is obtained by multiplying the "export" by the "System Price". The value displayed needs to be multiplied by 1000 to obtain the true figure and it is a monetary value.
blt-neck payment	These are the costs that occur due to bottlenecks that occur when import/export reaches its maximum capacity. It is calculated by multiplying the "Btl-neck prices" by the import/export capacity. Note that this is then divided by 2, as the revenue from bottlenecks is normally split between the 2 operators on each side of the interconnector.
addexport payment	The is the cost/revenue that occurs due to the "Fixed Import/Export" which was defined under the Input->ElectricityDemand tab. It is the "Fixed Exp/Imp" in the results window multiplied by the "DKmarket prices".
DHP and Boilers	This is the amount of gas consumed for "DH" systems without CHP, which is "Group 1", plus the gas consumed by the boilers in "Group 2" and "Group 3", under the Input->DistrictHeating tab.
CHP2 CHP3	This is the amount of gas consumed for CHP plants in "Group 2" and "Group 3" under the Input->DistrictHeating tab.
PP CAES	This is the amount of gas consumed for the "Condensing" and "PP2" units in "Group 3", under the Input->DistrictHeating tab, as well as for CAES energy storage facilities under the Input->ElecStorage tab.
Individual	This is the amount of gas consumed for the "Ngas boiler" and the "Ngas micro CHP", under the Input->Individual tab.
Transp.	This is the amount of "Ngas" consumed under the Input->Transport tab.
Indust. Various	This is the amount of "Ngas" consumed by "Industry" and "Various", under the Input->Industry tab.
Demand Sum	The is the total gas demand: "DHP and Boilers" + "CHP2 CHP3" + "PP CAES" + "Individual" + "Transp." + "Indust. Various".
Biogas	This is the "Input to Gas Grid" from the "Biogas Plant" under the Input->Biomass Conversion tab.
Syngas	This is the "Input to Gas Grid" from the "Gasification Plant" under the Input->Biomass Conversion tab.
Storage	This is the amount of gas consumed from (positive) or sent to (negative) the gas storage facility during each hour of the simulation.
Storage Content	This is the amount of gas in the gas storage facility.
Sum	This is the difference between demand and supply for gas.
Import	If the "Sum" results indicate that there is a shortage in gas, then it is imported.
Export	If the "Sum" results indicate that there is excess gas, then it is exported.

5 Verifying Reference Model Data

Once all the data has been inputted into EnergyPLAN, the final step is to verify that the model created is operating the same as the energy system that you are trying to simulate.

The first step is to ensure that all the capacities and distributions are correct, including interconnection capacity that is placed under the Regulation tab. Afterwards, the energy outputs from the model must be compared with those of the actual energy system. There are five guidelines listed below that may be useful for completing this task (see Figure 23 also):

1. Ensure the electricity demand is correct (including demand, heating, cooling, and interconnection).
2. Confirm the consumption is also correct at point 2.
3. Check that the production units, other than the power plants, are producing the required amount of energy.
4. Are the power plants generating the correct amount of energy for each fuel type? If steps 3 and 4 are correct, but the power plants are not generating the correct amount of energy, then the power plant efficiency under the Input -> DistrictHeating tab needs to be adjusted.
5. Is the total amount of fuel being used within the energy system correct?

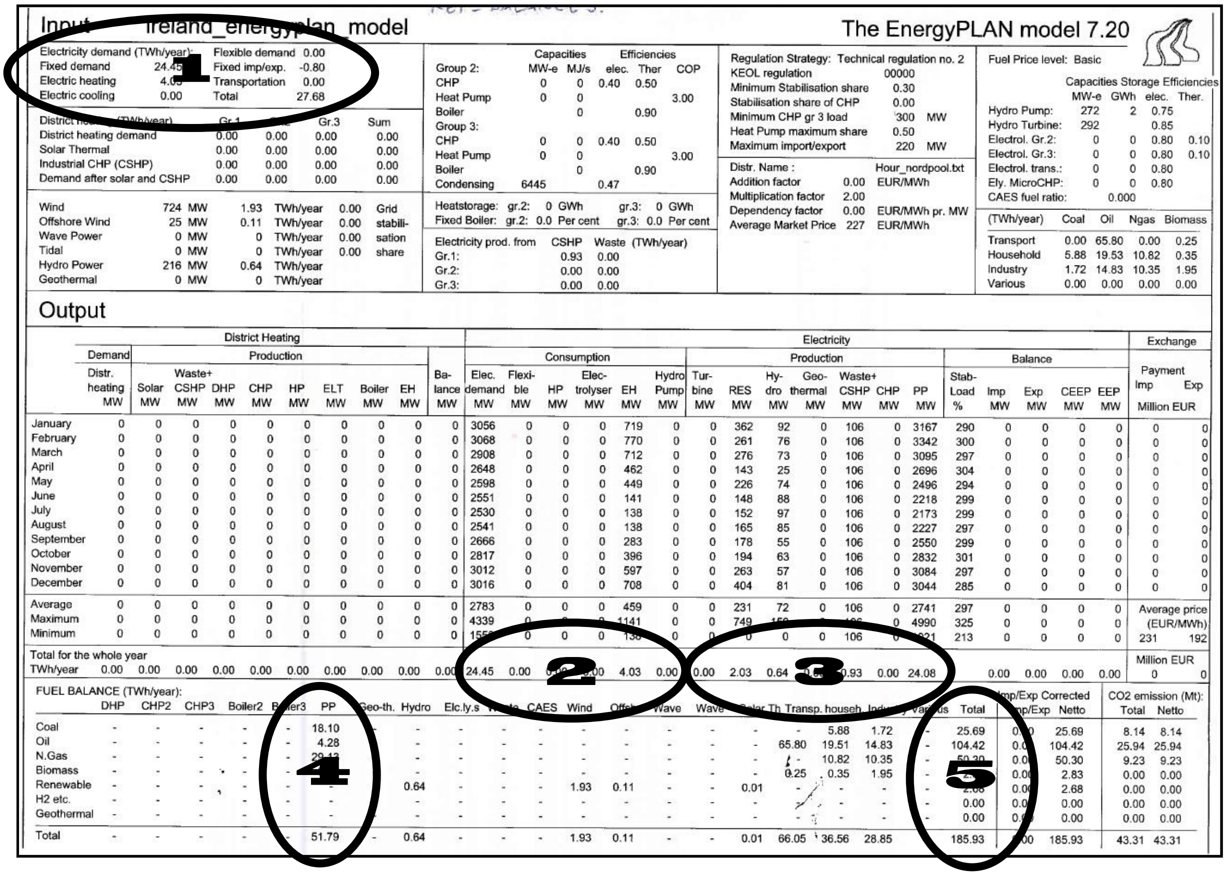


Figure 23: Verifying the EnergyPLAN model is functioning accurately.

6 Common Error Screens

These are some of the common error screens that I saw during the time that I used EnergyPLAN, with a brief explanation of their cause.

6.1 Wrong Number of Data Points

If you do not have 8784 data points within a distribution in your model, you will get an error that says ***"is not a valid floating point value"*** as shown in Figure 24. You need to have 8784 data points so that there is a data point for each hour of the year (366 hours * 24 days).

Figure 24: Error that occurs with the wrong number of data points in a distribution.

6.2 Distribution File Location

If the distribution file that you have used is not located in the Distributions folder that you downloaded with the EnergyPLAN model, you will receive an error that says **File not found: location\distribution_name.txt** as shown in Figure 25.

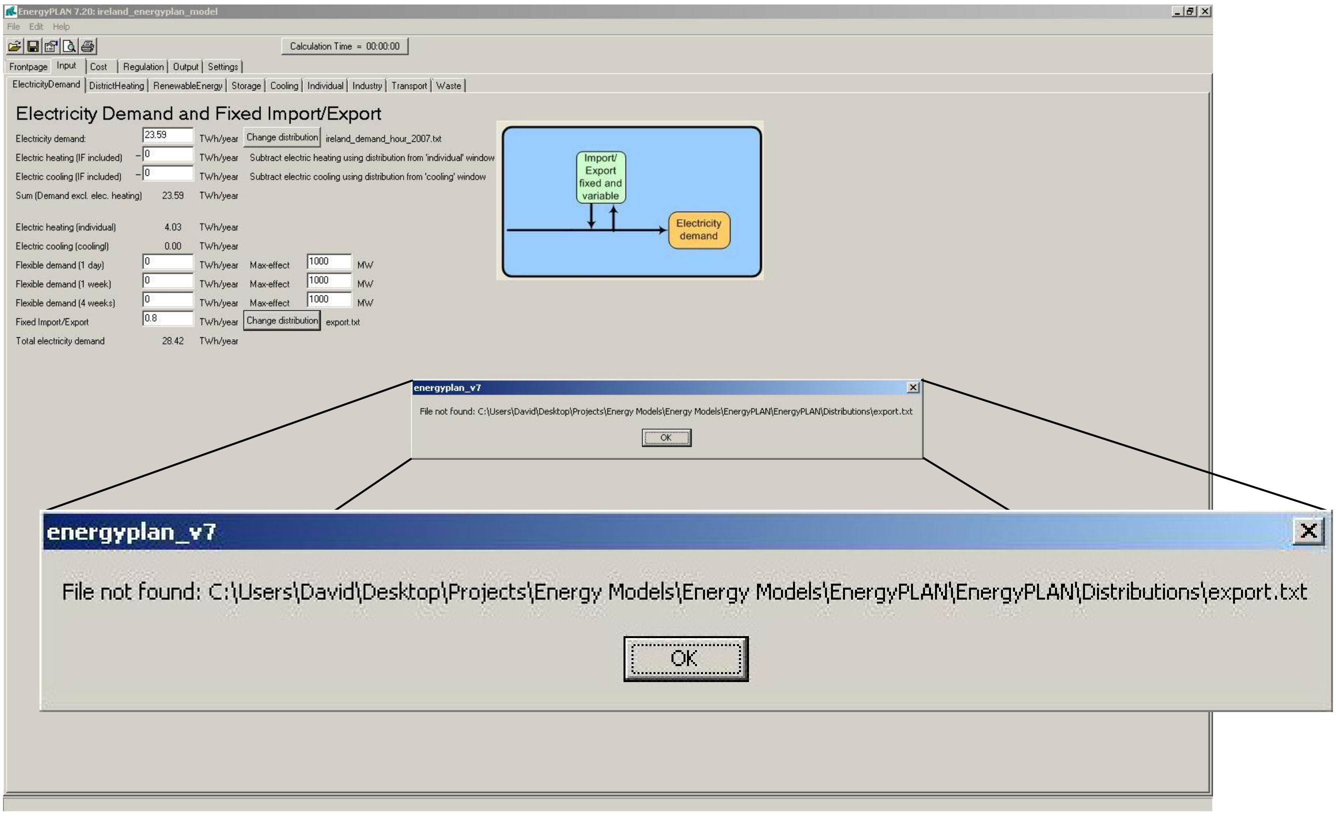


Figure 25: Error that occurs when the distribution is placed in the wrong folder.

6.3 Warnings

A WARNING sign will be activated on the results screen (see Figure 26) and on the results printout (see Figure 27) if any of the three following incident happens:

1. Excess electricity production.
2. Grid stabilisation is below requested level.
3. The specified electricity demand (e.g. for BEV) cannot be met by the capacity of power plants in combination with import on the transmission line capacity.

For example, Figure 26 below illustrates the warning displayed on the results screen of the EnergyPLAN tool when excess electricity production occurs, while Figure 27 illustrates the same warning on the results printout of EnergyPLAN.

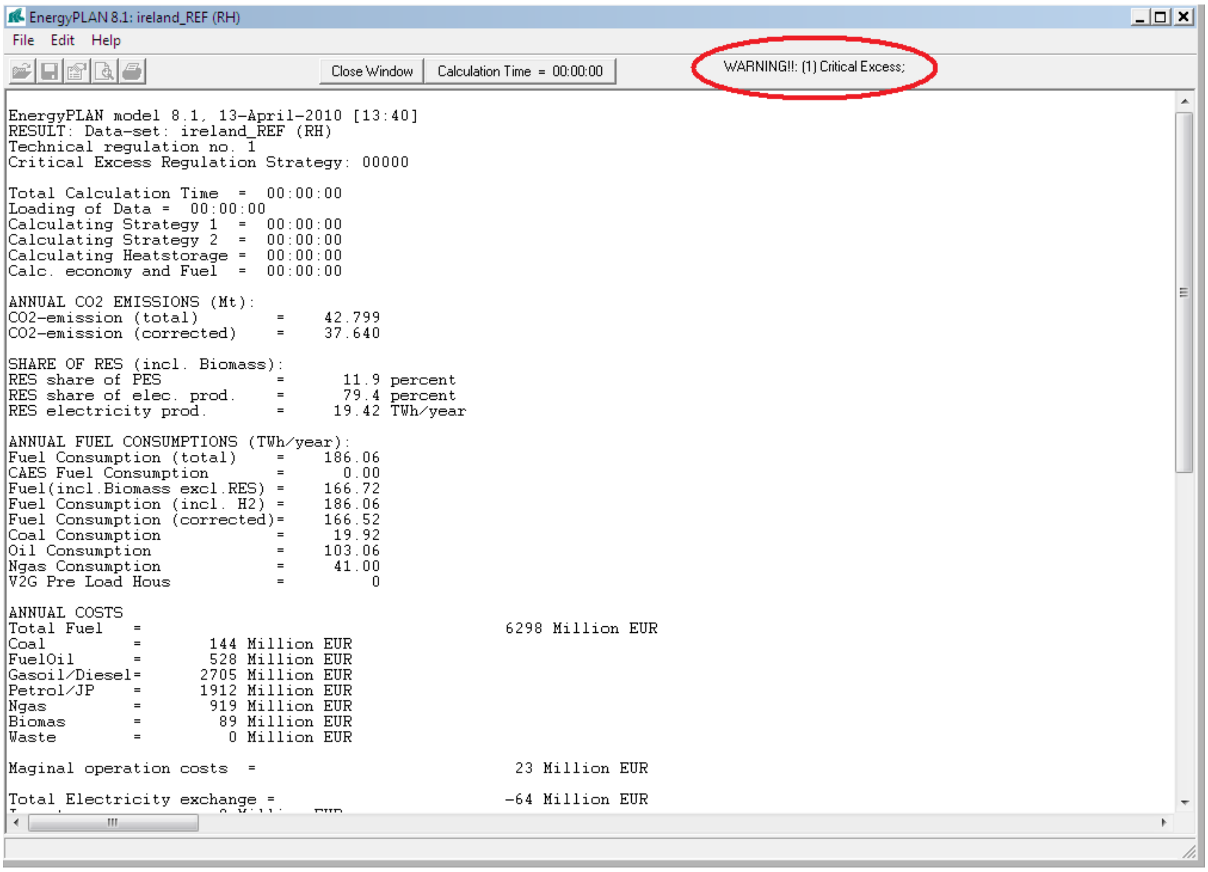


Figure 26: Sample of the WARNING for excess electricity production on the results screen of EnergyPLAN.

Input ireland_REF (RH) — The EnergyPLAN model 8.1

Electricity demand (TWh/year): Fixed demand 24.45; Electric heating 4.03; Electric cooling 0.00
Flexible demand 0.00; Fixed imp/exp. -1.31; Transportation 0.00; Total 27.17

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0.00	0.00	0.00	0.00
Solar Thermal	0.00	0.00	0.00	0.00
Industrial CHP (CSHP)	0.00	0.00	0.00	0.00
Demand after solar and CSHP	0.00	0.00	0.00	0.00

Wind	6986 MW	18.60	TWh/year	0.00	Grid
Offshore Wind	25 MW	0.08	TWh/year	0.00	stabili-
River Hydro	216 MW	0.65	TWh/year	0.00	sation
Photo Voltaic	0 MW	0	TWh/year	0.00	share
Hydro Power	0 MW	0	TWh/year		
Geothermal	0 MW	0	TWh/year		

	Capacities MW-e	Capacities MJ/s	Efficiencies elec.	Efficiencies Ther	COP
Group 2:					
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Group 3:					
CHP	500	549	0.46	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Condensing	6445		0.46		

Heatstorage: gr.2: 0 GWh gr.3: 0 GWh
Fixed Boiler: gr.2: 0.0 Per cent gr.3: 0.0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0.00	0.00
Gr.2:	0.00	0.00
Gr.3:	0.93	0.00

Regulation Strategy: Technical regulation no. 1
KEOL regulation 00000
Minimum Stabilisation share 0.30
Stabilisation share of CHP 0.00
Minimum CHP gr 3 load 500 MW
Heat Pump maximum share 0.50
Maximum import/export 220 MW

Distr. Name : ireland_SEMO_2008_hourly.txt
Addition factor 12.00 EUR/MWh
Multiplication factor 0.32
Dependency factor 0.00 EUR/MWh pr. MW
Average Market Price 37 EUR/MWh

Fuel Price level:

	Capacities MW-e	Storage GWh	Efficiencies elec.	Ther.
Hydro Pump:	272	2	0.80	
Hydro Turbine:	292		0.80	
Electrol. Gr.2:	0	0	0.80	0.10
Electrol. Gr.3:	0	0	0.80	0.10
Electrol. trans.:	0	0	0.80	
Ely. MicroCHP:	0	0	0.80	

CAES fuel ratio: 0.000

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0.00	65.80	0.00	0.25
Household	5.88	19.53	10.82	0.35
Industry	1.72	14.83	10.35	1.95
Various	0.00	0.00	0.00	0.00

Output WARNING!!: (1) Critical Excess;

District Heating

	Demand: Distr. heating MW	Production: Solar MW	Waste+ CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba- lance MW
January	0	0	0	0	549	0	0	0	0	-549
February	0	0	0	0	549	0	0	0	0	-549
March	0	0	0	0	549	0	0	0	0	-549
April	0	0	0	0	549	0	0	0	0	-549
May	0	0	0	0	549	0	0	0	0	-549
June	0	0	0	0	549	0	0	0	0	-549
July	0	0	0	0	549	0	0	0	0	-549
August	0	0	0	0	549	0	0	0	0	-549
September	0	0	0	0	549	0	0	0	0	-549
October	0	0	0	0	549	0	0	0	0	-549
November	0	0	0	0	549	0	0	0	0	-549
December	0	0	0	0	549	0	0	0	0	-549
Average	0	0	0	0	549	0	0	0	0	-549
Maximum	0	0	0	0	549	0	0	0	0	-549
Minimum	0	0	0	0	549	0	0	0	0	-549
Total for the whole year TWh/year	0.00	0.00	0.00	0.00	4.83	0.00	0.00	0.00	0.00	-4.83

Electricity / Exchange

	Consumption: Elec. demand MW	Flexi- ble MW	HP MW	Elec- trolyser MW	EH MW	Hydro Pump MW	Production: Tur- bine MW	RES MW	Hy- dro MW	Geo- thermal MW	Waste+ CSHP MW	CHP MW	PP MW	Balance: Stab- Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Payment Imp Million EUR	Payment Exp Million EUR
January	2840	0	0	0	719	117	77	3508	0	0	106	500	1372	125	0	1985	1829	156	0	23
February	2803	0	0	0	770	79	51	2521	0	0	106	500	1539	164	0	1171	1071	100	0	13
March	2674	0	0	0	712	84	51	2669	0	0	106	500	1405	153	0	1401	1293	108	0	15
April	2622	0	0	0	462	55	35	1327	0	0	106	500	1275	196	0	378	311	68	0	7
May	2576	0	0	0	449	74	47	2100	0	0	106	500	1228	169	0	1162	1070	92	0	11
June	2829	0	0	0	141	52	35	1381	0	0	106	500	1202	194	0	459	396	63	0	7
July	2809	0	0	0	138	50	32	1460	0	0	106	500	1121	187	0	497	432	65	0	9
August	2822	0	0	0	138	61	37	1581	0	0	106	500	1093	175	0	482	409	73	0	7
September	2822	0	0	0	283	58	39	1664	0	0	106	500	1419	192	0	687	613	74	0	12
October	2885	0	0	0	396	56	36	1806	0	0	106	500	1371	175	0	530	457	72	0	8
November	2911	0	0	0	597	87	54	2460	0	0	106	500	1450	160	0	1006	899	108	0	13
December	2811	0	0	0	708	129	82	3886	0	0	106	500	1453	120	0	2351	2179	172	0	23
Average	2783	0	0	0	459	75	48	2200	0	0	106	500	1326	167	0	1012	916	96	Average price	(EUR/MWh)
Maximum	4430	0	0	0	1141	272	292	7065	0	0	106	500	3997	321	0	7419	7199	220		
Minimum	1356	0	0	0	138	0	0	0	0	0	106	500	0	100	0	0	0	0	40	17
Total for the whole year TWh/year	24.45	0.00	0.00	0.00	4.03	0.66	0.42	19.33	0.00	0.00	0.93	4.39	11.65		0.00	8.89	8.05	0.84	Million EUR 0	147

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo-th.	Hydro	Elc.ly.s	Waste	CAES	Wind	Offsh.	Hydro	PV	Solar.Th	Transp.	househ.	Industry	Various	Total	Imp/Exp Corrected Imp/Exp	Imp/Exp Corrected Netto	CO2 emission (Mt): Total	CO2 emission (Mt): Netto
Coal	-	-	3.37	-	-	8.95	-	-	-	-	-	-	-	-	-	-	-	5.88	1.72	-	19.92	-6.83	13.09	7.21	4.74
Oil	-	-	0.80	-	-	2.12	-	-	-	-	-	-	-	-	-	-	65.80	19.51	14.83	-	103.06	-1.62	101.44	27.16	26.73
N.Gas	-	-	5.43	-	-	14.40	-	-	-	-	-	-	-	-	-	-	-	10.82	10.35	-	41.00	-10.99	30.01	8.43	6.17
Biomass	-	-	0.05	-	-	0.14	-	-	-	-	-	-	-	-	-	-	0.25	0.35	1.95	-	2.74	-0.11	2.64	0.00	0.00
Renewable	-	-	-	-	-	-	-	-	-	-	-	18.60	0.08	0.65	-	0.01	-	-	-	-	19.34	0.00	19.34	0.00	0.00
H2 etc.	-	-	0.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Geothermal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Total	-	-	9.65	-	-	25.60	-	-	-	-	-	18.60	0.08	0.65	-	0.01	66.05	36.56	28.85	-	186.06	-19.54	166.52	42.80	37.64

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Figure 27: Sample of the WARNING for excess electricity production on the results printout of EnergyPLAN.

7 Conclusions

The EnergyPLAN model is extremely useful because it is simple to use. However, this simplicity creates a responsibility on the user to ensure that the data inputted is as accurate and relevant as possible. The time required to build the reference model is cumbersome as there is a lot of false paths along the way. However, the wave of possibilities that present themselves upon completion of the reference model, ensure that the time spent searching for data becomes a worthy experience.

Once the reference model is completed, it is possible to build and analyse energy systems with endless quantities of renewable energy, conventional plant, energy storage, and transport technologies, in a relatively short period of time.

Finally, the level of detail discussed in this report is not necessary for every study completed using EnergyPLAN, especially in relation to the distributions used. Therefore, before spending a large period of time gathering data, ensure that the data is required for the accuracy of the results.

8 Appendix

8.1 Ireland's Energy Balance 2007

Ireland's Provisional Energy Balance 2007 (TWh)

2007 Units = TWh	Coal	Bituminous Coal	Anthracite + Manufactured Ovoids	Coke	Lignite	Peat	Milled Peat	Sod Peat	Briquettes	Oil	Crude	Refinery Gas	Gasoline	Kerosene	Jet Kerosene	Fueloil	LPG	Gasoil / Diesel /DERV	Petroleum Coke	Naphta	Bitumen	White Spirit	Lubricants	Natural Gas	Renewables	Hydro	Wind	Biomass	Landfill Gas	Biogas	Liquid Biofuel	Solar	Geothermal	Electricity	Heat	TOTAL
Indigenous Production	0.000	0.000	0.000	0.000	0.000	6.876	4.711	2.165	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4.304	5.211	0.667	1.959	1.991	0.278	0.111	0.179	0.015	0.012	0.000	0.000	16.390
Imports	16.517	16.077	0.380	0.000	0.060	0.000	0.000	0.000	0.000	122.814	40.573	0.000	14.817	5.820	12.916	6.863	1.527	32.151	3.872	0.000	2.765	1.393	0.117	45.631	0.295	0.000	0.000	0.146	0.000	0.000	0.149	0.000	0.000	1.413	0.000	186.669
Exports	0.036	0.000	0.036	0.000	0.000	0.092	0.000	0.000	0.092	15.105	0.000	0.000	0.321	0.202	0.000	13.181	0.176	0.171	0.000	0.152	0.000	0.831	0.070	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.082	0.000	15.315
Mar. Bunkers	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.324	0.000	0.000	0.000	0.000	0.000	0.769	0.000	0.555	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.324
Stock Change	1.059	0.999	0.044	0.000	0.016	1.374	1.393	-0.002	-0.017	2.209	-0.311	0.000	0.044	-0.218	0.560	1.519	0.031	0.490	0.059	0.035	0.000	0.000	0.000	-0.012	-0.078	0.000	0.000	-0.001	0.000	0.000	-0.077	0.000	0.000	0.000	0.000	4.552
Primary Energy Supply (incl non-energy)	17.540	17.076	0.388	0.000	0.076	8.158	6.103	2.163	-0.108	108.593	40.263	0.000	14.540	5.399	13.476	-5.568	1.381	31.916	3.930	-0.117	2.765	0.562	0.047	49.923	5.427	0.667	1.959	2.135	0.278	0.111	0.250	0.015	0.012	1.331	0.000	190.972
Primary Energy Requirement (excl. non-energy)	17.540	17.076	0.388	0.000	0.076	8.158	6.103	2.163	-0.108	105.220	40.263	0.000	14.540	5.399	13.476	-5.568	1.381	31.916	3.930	-0.117	0.000	0.000	0.000	49.923	5.427	0.667	1.959	2.135	0.278	0.111	0.250	0.015	0.012	1.331	0.000	187.598
Transformation Input	13.071	13.071	0.000	0.000	0.000	6.186	6.186	0.000	0.000	44.634	40.263	0.093	0.000	0.000	0.000	4.233	0.003	0.042	0.000	0.000	0.000	0.000	0.000	31.830	0.384	0.000	0.000	0.038	0.278	0.068	0.000	0.000	0.000	0.729	0.000	96.833
Public Thermal Power Plants	13.071	13.071	0.000	0.000	0.000	5.010	5.010	0.000	0.000	4.275	0.000	0.000	0.000	0.000	0.000	4.233	0.000	0.042	0.000	0.000	0.000	0.000	0.000	29.092	0.279	0.000	0.000	0.001	0.278	0.000	0.000	0.000	0.000	0.000	0.000	51.727
Combined Heat and Power Plants	0.000	0.000	0.000	0.000	0.000	0.082	0.082	0.000	0.000	0.096	0.000	0.093	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.000	0.000	0.000	2.738	0.105	0.000	0.000	0.037	0.000	0.068	0.000	0.000	0.000	0.000	0.000	3.021
Pumped Storage Consumption	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.546	0.000	0.546
Briquetting Plants	0.000	0.000	0.000	0.000	0.000	1.093	1.093	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.093
Oil Refineries & other energy sector	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	40.263	40.263	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.182	0.000	40.445
Transformation Output	0.000	0.000	0.000	0.000	0.000	1.100	0.000	0.000	1.100	39.049	0.000	1.085	6.108	2.459	0.000	14.322	0.468	14.490	0.000	0.117	0.000	0.000	0.000	0.000	0.132	0.000	0.000	0.013	0.102	0.017	0.000	0.000	0.000	25.505	0.000	65.786
Public Thermal Power Plants	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.102	0.000	0.000	0.000	0.102	0.000	0.000	0.000	0.000	23.330	0.000	23.432
Combined Heat and Power Plants - Electricity	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.030	0.000	0.000	0.013	0.000	0.017	0.000	0.000	0.000	1.826	0.000	1.856
Combined Heat and Power Plants - Heat	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pumped Storage Generation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.349	0.000	0.349
Briquetting Plants	0.000	0.000	0.000	0.000	0.000	1.100	0.000	0.000	1.100	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.100
Oil Refineries	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	39.049	0.000	1.085	6.108	2.459	0.000	14.322	0.468	14.490	0.000	0.117	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	39.049
Exchanges and transfers	0.194	-0.124	0.317	0.000	0.000	0.000	0.000	0.000	0.000	-0.085	0.000	0.000	-0.081	2.213	-2.213	0.306	0.000	-0.116	-0.194	0.000	0.000	0.000	0.000	0.000	-2.758	-0.667	-1.959	-0.013	-0.102	-0.017	0.000	0.000	0.000	2.758	0.000	0.109
Electricity	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-2.758	-0.667	-1.959	-0.013	-0.102	-0.017	0.000	0.000	0.000	2.758	0.000	0.000
Heat	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Other	0.194	-0.124	0.317	0.000	0.000	0.000	0.000	0.000	0.000	-0.085	0.000	0.000	-0.081	2.213	-2.213	0.306	0.000	-0.116	-0.194	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.109
Own Use and Distribution Losses	0.000	0.000	0.000	0.000	0.000	0.176	0.176	0.000	0.000	1.431	0.000	0.992	0.000	0.000	0.000	0.365	0.045	0.030	0.000	0.000	0.000	0.000	0.000	0.665	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.666	0.000	4.938
Available Final Energy Consumption	4.663	3.881	0.706	0.000	0.076	2.897	-0.258	2.163	0.992	101.493	0.000	0.000	20.566	10.072	11.264	4.461	1.802	46.217	3.736	0.000	2.765	0.562	0.047	17.427	2.417	0.000	0.000	2.097	0.000	0.044	0.250	0.015	0.012	26.198	0.000	155.096
Non-Energy Consumption	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.374	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.765	0.562	0.047	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.374
Final non-Energy Consumption (Feedstocks)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.374	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.765	0.562	0.047	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.374
Total Final Energy Consumption	4.354	3.568	0.709	0.000	0.076	3.159	0.000	2.167	0.992	100.064	0.000	0.000	22.325	10.620	12.134	4.295	1.853	45.188	3.637	0.012	0.000	0.000	0.000	18.424	2.476	0.000	0.000	2.156	0.000	0.044	0.249	0.015	0.012	25.867	0.000	154.343
Industry*	1.630	1.630	0.000	0.000	0.000	0.003	0.000	0.000	0.003	11.799	0.000	0.000	0.000	1.438	0.000	4.180	0.813	2.076	3.280	0.012	0.000	0.000	0.000	7.616	1.769	0.000	0.000	1.752	0.000	0.017	0.000	0.000	0.000	8.478	0.000	31.295
Non-Energy Mining	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.493	0.000	0.000	0.000	0.015	0.000	0.060	0.001	0.416	0.000	0.000	0.000	0.000	0.000	0.420	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.668	0.000	1.582
Food, beverages and tobacco	0.160	0.160	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.457	0.000	0.000	0.000	0.188	0.000	0.731	0.051	0.488	0.000	0.000	0.000	0.000	0.000	2.028	0.684	0.000	0.000	0.667	0.000	0.017	0.000	0.000	0.000	1.987	0.000	6.316
Textiles and textile products	0.075	0.075	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.119	0.000	0.000	0.000	0.009	0.000	0.036	0.018	0.056	0.000	0.000	0.000	0.000	0.000	0.017	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.096	0.000	0.308
Wood and wood products	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.146	0.000	0.000	0.000	0.018	0.000	0.070	0.000	0.058	0.000	0.000	0.000	0.000	0.000	0.046	1.085	0.000	0.000	1.085	0.000	0.000	0.000	0.000	0.000	0.348	0.000	1.626
Pulp, paper, publishing and printing	0.004	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.088	0.000	0.000	0.000	0.009	0.000	0.033	0.009	0.037	0.000	0.000	0.000	0.000	0.000	0.262	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.369	0.000	0.723
Chemicals & man-made fibres	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.563	0.000	0.000	0.000	0.076	0.000	0.294	0.015	0.179	0.000	0.000	0.000	0.000	0.000	1.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.189	0.000	3.182
Rubber and plastic products	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.070	0.000	0.000	0.000	0.002	0.000	0.008	0.006	0.054	0.000	0.000	0.000	0.000	0.000	0.113	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.373	0.000	0.556
Other non-metallic mineral products	1.391	1.391	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.913	0.000	0.000	0.000	0.032	0.000	0.126	0.037	0.439	3.280	0.000	0.000	0.000	0.000	0.635	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.635	0.000	6.574
Basic metals and fabricated metal products	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.763	0.000	0.000	0.000	1.037	0.000	2.619	0.030	0.078	0.000	0.000	0.000	0.000	0.000	2.058	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.869	0.000	6.690
Machinery and equipment n.e.c.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.096	0.000	0.000	0.000	0.008	0.000	0.029	0.024	0.035	0.000	0.000	0.000	0.000	0.000	0.154	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.200	0.000	0.450
Electrical and optical equipment	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.849	0.000	0.000	0.000	0.020	0.000	0.078	0.612	0.139	0.000	0.000	0.000	0.000	0.000	0.326	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.330	0.000	2.505
Transport equipment manufacture	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.031	0.000	0.000	0.000	0.002	0.000	0.006	0.001	0.022	0.000	0.000	0.000	0.000	0.000	0.098	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.107	0.000	0.236
Other manufacturing	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.003	0.211	0.000	0.000	0.000	0.023	0.000	0.090	0.011	0.074	0.000	0.012	0.000	0.000	0.000	0.029	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.307	0.000	0.549
Transport	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	65.812	0.000	0.000	22.325	0.000	12.134	0.000	0.012	31.341	0.000	0.000	0.000	0.000	0.000	0.000	0.249	0.000	0.000	0.000	0.000	0.000	0.249	0.000	0.000	0.052	0.000	66.113
Road Freight	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	13.798	0.000	0.000	0.000	0.000	0.000	0.000	0.000	13.798	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	13.798
Road Private Car	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.141	0.000	0.000	18.840	0.000	0.000	0.000	0.012	6.290	0.000	0.000	0.000	0.000	0.000	0.000	0.249	0.000	0.000	0.000	0.000	0.000	0.249	0.000	0.000	0.000	0.000	25.391
Public Passenger Services	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.088	0.000	0.000	0.526	0.000	0.000	0.000	0.000	1.562	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.088
Rail	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.500	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.500	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.052	0.000	0.552
Domestic Aviation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.625	0.000	0.000	0.019	0.000	0.607	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.625
International Aviation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	11.527	0.000	0.000	0.000	0.000	11.527	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	11.527
Fuel Tourism	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	7.364	0.000	0.000	2.121	0.000	0.000	0.000	0.000	5.243	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	7.364
Unspecified	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4.769	0.000	0.000	0.820	0.000	0.000	0.000	0.000	3.948	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4.769
Residential	2.420	1.653	0.699	0.000	0.068	3.155	0.000	2.167	0.988	13.113	0.000	0.000	0.000	9.182	0.000	0.000	0.897	2.676	0.358	0.000	0.000	0.000	0.000	6.896	0.282	0.000	0.000	0.262	0.000	0.000	0.000	0.015	0.005	8.064	0.000	33.930
Commercial/Public Services	0.303	0.285	0.010	0.000	0.008	0.000	0.000	0.000	0.000	6.405	0.000	0.000	0.000	0.000	0.000	0.115	0.132	6.159	0.000	0.000	0.000	0.000	0.000	3.913	0.095	0.000	0.000	0.061	0.000	0.027	0.000	0.000	0.006	8.711	0.000	19.427
Commercial Services	0.303	0.285	0.010	0.000	0.008	0.000	0.000	0.000	0.000	4.178	0.000	0.000	0.000	0.000	0.000	0.011	0.098	4.069	0.000	0.000	0.000	0.000	0.000	1.715	0.095	0.000	0.000	0.061	0.000	0.027	0.000	0.000	0.006	6.245	0.000	12.536
Public Services	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.227	0.000	0.000	0.000	0.000	0.000	0.103	0.034	2.090	0.000	0.000	0.000	0.000	0.000	2.198	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.466	0.000	6.892
Agricultural	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.936	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.936	0.000	0.000	0.000	0.000	0.000	0.000	0.080	0.000	0.000	0.080	0.000	0.000	0.000	0.000	0.000	0.561	0.000	3.577
Statistical Difference	0.310	0.313	-0.003	0.000	0.000	-0.262	-0.258	-0.004	0.000	-1.945	0.000	0.000	-1.759	-0.548	-0.870	0.166	-0.051	1.030	0.099	-0.012	0.000	0.000	0.000	-0.997	-0.058	0.000	0.000	-0.059	0.000	0.000	0.001	0.000	0.000	0.331	0.000	-2.621

* Industry sub-sectoral breakdown is based on the CIP 2004.

Last Updated :24 Sep 2008

Key

2007 Provisional

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Appendix F

Connolly D, Lund H, Mathiesen BV, Leahy M. Modelling the existing Irish energy-system to identify future energy costs and the maximum wind penetration feasible. Energy 2010;35(5):2164-2173.

Energy 35 (2010) 2164–2173

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Modelling the existing Irish energy-system to identify future energy costs and the maximum wind penetration feasible

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ARTICLE INFO

Article history:
Received 10 September 2009
Received in revised form
21 January 2010
Accepted 23 January 2010
Available online 2 March 2010

Keywords:
Modelling
Simulating
Reference model
Irish energy-system
Cost
Maximum wind penetration

ABSTRACT

In this study a model of the Irish energy-system was developed using EnergyPLAN based on the year 2007, which was then used for three investigations. The first compares the model results with actual values from 2007 to validate its accuracy. The second illustrates the exposure of the existing Irish energy-system to future energy costs by considering future fuel prices, CO_2 prices, and different interest rates. The final investigation identifies the maximum wind penetration feasible on the 2007 Irish energy-system from a technical and economic perspective, as wind is the most promising fluctuating renewable resource available in Ireland. It is concluded that the reference model simulates the Irish energy-system accurately, the annual fuel costs for Ireland's energy could increase by approximately 58% from 2007 to 2020 if a business-as-usual scenario is followed, and the optimum wind penetration for the existing Irish energy-system is approximately 30% from both a technical and economic perspective based on 2020 energy prices. Future studies will use the model developed in this study to show that higher wind penetrations can be achieved if the existing energy-system is modified correctly. Finally, these results are not only applicable to Ireland, but also represent the issues facing many other countries.

1. Introduction

By 2020, Ireland[1] has an obligation under EU initiatives to supply 20% of its total primary energy consumption from renewable sources [1]. Also, the Kyoto protocol only allows Ireland to increase its CO_2 emissions by 13% compared to 1990 levels [2] and in 2006, Ireland was 26.7% above 1990 levels [3]. As a result, the Irish government set a number targets for energy in 2007 [4]. These include: 30% of fuel from biomass at the three state-owned peat power-plants by 2015, no oil in electricity generation by 2020, 15% of electricity from renewable sources by 2010 and 33% by 2020, 500 MW of ocean energy by 2020, combined heat and power (CHP) needs to be expanded to 400 MW by 2010 and 800 MW by 2020, 5% of heat demand must come from renewable sources by 2010 and 12% by 2020, 5.75% of energy from biofuels by 2010 and 10% by 2020, and finally, a 20% reduction in overall energy demands by 2020. By setting these targets, the next step is identifying how these targets can be met, and if they are met, what is their significance for the Irish energy-system. In line with this, the aim of this work is to develop a model of the Irish energy-system to propose how these targets are met, and analyse the implications of these targets. The first step required in this process is to create a reference model by simulating a historical year, and ensuring that the model is functioning accurately. Therefore, this paper discusses the need for a model of the Irish energy-system and subsequently describes why EnergyPLAN was chosen to create this model. Finally, three initial investigations were carried out using the model developed: a comparison was made between the 2007 reference model developed and the actual performance of the Irish energy-system in 2007, the sensitivity of the existing Irish energy-system to various economic parameters was investigated, and finally, the maximum wind penetration feasible on the existing Irish energy-system was identified.

2. The Irish energy-system

The island of Ireland is located in the North-West of Europe and is divided into two countries: Northern Ireland and Ireland. In November 2007 the single electricity market operator (SEMO) was formed [5], which created a single electricity market on the island of Ireland. However, prior to this, the energy-systems in each of these countries were only connected via an electric interconnector.

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[1] Ireland refers to the Republic of Ireland only throughout this paper, unless otherwise stated.

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doi:10.1016/j.energy.2010.01.037

Table 1
Efficiencies calculated for power-plants of different fuel-type [7–10].

Plant type	Capacity (MW)	Electricity generated (TWh)	Fuel used (TWh)	Efficiency (%)
Natural gas PP	3525	13.38[a]	28.72	46.58
Coal PP	852	5.35	12.95	41.31
Peat PP	345	2.11	5.05	41.78
Oil PP	1014	1.94	4.18	46.41
Wind	724	1.88	–	–
Natural gas CHP	273	1.83	6.08	30.10[a]
Net import	220[b]	1.31	–	–
Hydro	216	0.66	–	–
Pumped hydro	292	0.35	0.55	63.63
Biomass	Co-combusted	0.14	0.41	34.15

[a] The thermal efficiency of the natural gas CHP plants is 53.36%.
[b] This is the maximum interconnection capacity used between Ireland and Northern Ireland in 2007.

As the model in this paper was developed as a reference model by simulating the year 2007, this paper only covers the energy-system in Ireland, although future models will include the electricity sector of Northern Ireland also.

Ireland has a population of approximately 4.4 million people and an area of approximately 70,000 km^2. In 2007, the electricity demand was 28.5 TWh with a peak load of 5085 MW and a minimum load of 1800 MW. The heat demand in Ireland for 2007 (excluding industrial processes) was 31.5 TWh, with 0.05% of this supplied by solar thermal, 13% supplied by electric heating, and 87% supplied by individual boilers. The transport sector in Ireland was almost completely powered by oil in 2007, including 31.34 TWh of diesel, 22.33 TWh of petrol, and 12.13 TWh of jet fuel. The only other fuel used was biofuel which provided 0.4% (0.249 TWh) of the transport demand. It is evident from the structure outlined here that the Irish energy-system is very segregated: other than electric heating there is no significant interaction between the electricity, heat and transport sectors. This is the situation within numerous other countries also [6], and results in both an inefficient and a rigid energy-system.

A prime example of inefficiencies within the Irish energy-system occurred within the electricity sector in 2007. Electricity generation in 2007 included a net import of 1.31 TWh from Northern Ireland as displayed in Table 1 [7–10]. Therefore, 27.19 TWh of electricity was generated within Ireland, with 84% of this coming from condensing power-plants using fossil fuels. As condensing power-plants can only produce electricity, the efficiencies of these plants are relatively low: as displayed in Table 1 the average efficiency is 44%. In comparison, the CHP facilities in Ireland have an efficiency of 82.8%, but they are only used to produce 6.5% of the electricity demand. Due to the widespread use of condensing power-plants and lack of CHP plants, 50.5% of the energy used in the Irish electricity sector in 2007 was wasted due to

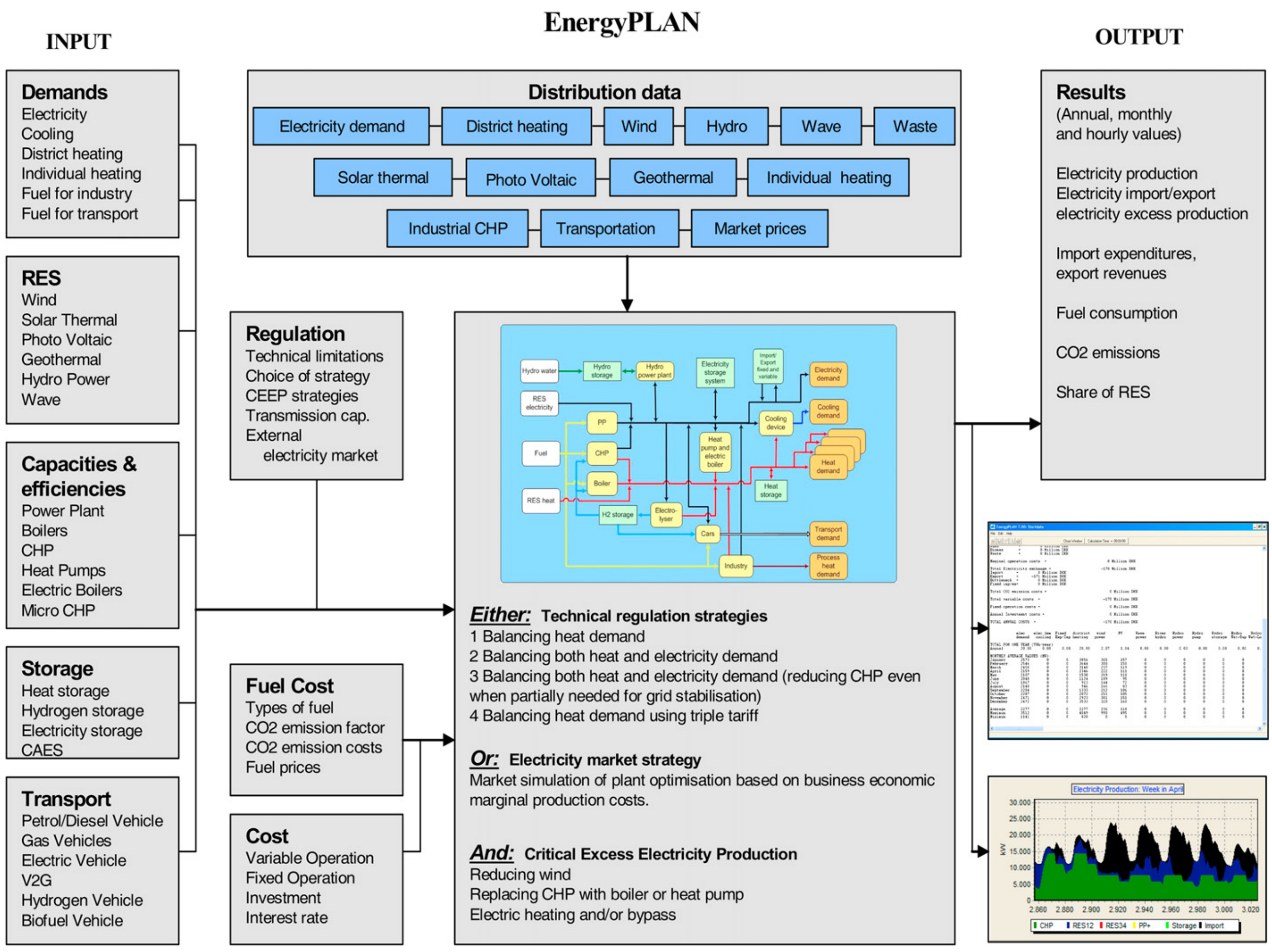

Fig. 1. The structure of the EnergyPLAN tool [18].

Table 2
Comparison of average monthly electricity demands obtained from the EnergyPLAN model and actual values for 2007.

Month	Average monthly electricity demand (MW)		Difference (MW)	Difference (%)
	Actual 2007	EnergyPLAN 2007		
January	3564	3559	−5	−0.14
February	3576	3573	−3	−0.09
March	3414	3386	−28	−0.82
April	3079	3084	5	0.18
May	3029	3025	−4	−0.14
June	2991	2970	−21	−0.71
July	2937	2947	10	0.34
August	2964	2960	−4	−0.15
September	3094	3105	11	0.36
October	3279	3281	2	0.07
November	3515	3508	−7	−0.20
December	3531	3519	−12	−0.35

losses [7]. From an economic point-of-view, this amounts to approximately €420 million of wasted fuel each year, which will only become more severe if a transition is not made to local renewable energy resources.

In relation to the rigidity of the Irish energy-system, the flexibility of the existing system needs to be improved to enable large-scale renewable energy penetrations by integrating the electricity, heat, and transport sectors more effectively. This is discussed in detail in [11] by analysing the benefits of technologies such as CHP, heat pumps, electric vehicles, hydrogen, etc., in combination with large-scale renewable energy. The rigidity of the existing Irish energy-system is evident in Table 1, as renewable energy only supplied 9.5% of the electricity generated in 2007 even though onshore wind alone could potentially supply 130% of the electricity demand in Ireland [12]. Therefore, it is imperative that alternatives are proposed to utilise these resources more effectively. Consequently, by developing a model of the Irish energy-system future alternatives can be examined to propose a more efficient, environmentally friendly, and economical energy-system.

Finally, a number of other studies have been already investigated the feasibility of integrating wind energy onto the Irish electric grid. In 2003, Gardner et al. [13] investigated the effects of additional wind energy in Ireland and identified that the most costly aspects of increasing the wind penetration are transmission reinforcement, wind curtailment, capital costs, and operating costs. In 2004, Electricity Supply Board (ESB) National Grid [14] also analysed the costs and implications for conventional power-plants associated with increasing the wind penetration in Ireland. The report concluded that increasing the wind penetration in Ireland from 0% to 11.7% would increase the total generation costs by €196 million, while peaking and mid-merit power-plants would require more frequent start-ups, need increased ramping, and have lower capacity factors. Finally, in 2007, Meibom et al. [15] modelled the

Table 3
Comparison of electricity produced for Ireland in 2007 and the EnergyPLAN simulation.

Production unit	2007 production [9] (TWh)	EnergyPLAN production 2007 (TWh)	Difference	
			TWh	%
Power-plants	23.56	23.54	0.02	0.08
Onshore wind	1.88[a]	1.86	0.06	3.20
Offshore wind		0.08		
Industrial CHP	0.93	0.93	0.00	0.00
Hydro power	0.66	0.65	−0.01	−1.52

[a] Onshore and offshore data could not be obtained separately.

Table 4
Comparison of total fuel consumed in Ireland in 2007 and the EnergyPLAN simulation.

Fuel	2007 fuel consumption (TWh)	EnergyPLAN fuel consumption	Difference	
			TWh	%
Oil	105.22	104.44	−0.78	−0.74
Natural gas	49.92	50.41	0.49	0.98
Coal/Peat	25.70	25.76	0.06	0.23
Biomass	2.77	2.83	0.06	2.17
Renewables	2.54	2.59	0.05	1.97

Irish electricity grid for the year 2020 using the WILMAR energy model [16]. The objective of this study was to identify the effects of large wind penetrations on the island of Ireland in relation to overall operation, costs, and emissions. Meibom et al. concluded that a wind penetration of 42% was feasible on the island of Ireland by 2020, which will reduce overall operation costs and the CO_2 emissions compared to 2007. In summary, a number of studies have already been carried out analysing the integration of wind energy in Ireland. However, both Gardner et al. [13] and ESB National Grid [14] used predicted data when analysing the year 2007, while Meibom et al. [15] focused on feasible wind penetrations in the year 2020. Therefore, the aim of this study is to outline the wind penetrations that can be achieved on the 2007 Irish energy-system, along with the economical and technical implications, using actual historical data. This will illustrate the wind penetrations that can be achieved immediately, without any major alterations to the Irish energy-system.

3. Methodology

To create a model of the Irish energy-system, a suitable energy tool needed to be identified. An investigation was carried out to identify which tool would be the most suitable with the following key objective: to identify how Ireland could integrate the most renewable energy into its energy-system. A detailed report comparing the functionality of 37 different tools has been completed [17], where it was concluded that EnergyPLAN was the most suitable tool to meet this objective. Therefore this comparison will not be discussed in detail here, but instead the primary reasons that EnergyPLAN was chosen are outlined, followed by a brief summary of the tool itself.

Firstly, EnergyPLAN considers the three primary sectors of any national energy-system: electricity, heat, and transport. As outlined in [11,18], the integration of these three sectors is crucial in order to

Table 5
CO_2 emissions for Ireland in 2007 and CO_2 emissions from the EnergyPLAN simulation.

Fuel	Consumption [9] (TWh)	CO_2 emission factor [7] (kg/GJ)	CO_2 emitted (Mt)
Gas oil	45.188[a]	73.30	11.92
Electricity	25.867	150.83	14.05
Gasoline	22.325	70.00	5.63
Natural gas	18.424[a]	57.10	3.79
Jet kerosene	12.134	71.40	3.12
Kerosene	10.620	71.40	2.73
Coal	4.354[a]	94.60	1.48
Fuel oil (residual oil)	4.295[a]	76.00	1.18
Coke	3.637	100.80	1.32
Sod Peat	2.167	104.00	0.81
LPG	1.853[a]	63.70	0.42
Peat Briquettes	0.992	98.90	0.35
Naphtha	0.012	73.30	0.003
Total			46.80

[a] Excludes fuel required for electricity generation.

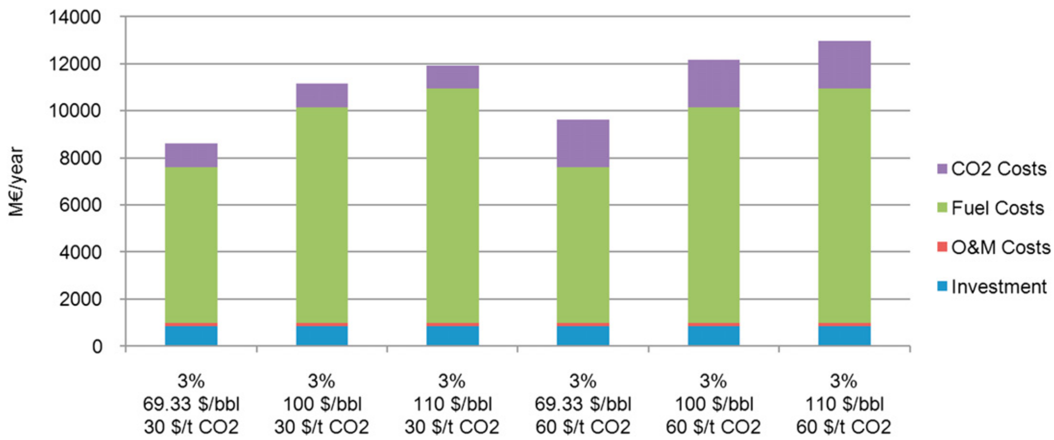

Fig. 2. Annual operating costs of the 2007 Irish energy-system for various fuel and CO_2 prices, using a real interest rate of 3%.

achieve large-scale penetrations of renewable energy. However, Ireland has very little integration between these sectors and therefore to utilise more renewable energy, it is essential that the energy-system is integrated more effectively. With this in mind, EnergyPLAN has a key advantage over a number of others tools considered. Secondly, EnergyPLAN has already been used to analyse several energy scenarios which are similar to the long-term objectives of this research. These include analysing the effects of large wind penetrations [19], the optimum combination of various renewable energy technologies in an energy-system [20,21], the benefits of energy storage [22–24], the benefits of integrating the electricity and heat sectors [25,26], as well as the transport sector [27], and finally the pathway towards a 100% renewable energy-system for Denmark [28,29]. These are typical of the studies required to identify how Ireland can work towards its 2020 energy targets and beyond. Finally, EnergyPLAN was also chosen for this study as it can be adapted to simulate a wide variety of national energy-systems. For example, EnergyPLAN has previously been used to analyse the energy-systems in Denmark, Estonia, Germany, Poland, Scotland, and Spain [30]. As these energy-systems use similar technologies to the Irish energy-system, it was evident that EnergyPLAN could be used for this study.

The main purpose of EnergyPLAN is to assist in the design of national or regional energy-planning strategies on the basis of technical and economic analysis, resulting from the implementation of different energy-systems and investments. EnergyPLAN is a deterministic input/output tool which uses an hourly simulation over a period of one year. The structure of EnergyPLAN is illustrated in Fig. 1 [18]. General inputs are the demands, renewable energy sources, energy station capacities, costs, and a number of optional regulation strategies. Outputs are energy balances and the resulting annual productions, fuel consumption, import/export of electricity, and the total costs of the system including income from the exchange of electricity. EnergyPLAN uses analytical programming rather than iterations so the calculations are completed in a very short period of time. Also, the simulation process in EnergyPLAN has been kept relatively simple by aggregating all units in the various sectors mentioned and hence, not considering the differences in single units and the transmission among them. Otherwise, EnergyPLAN provides an advanced representation of the entire energy-system, by using hourly distributions of heat demands, electricity demands, wind production, wave production etc., as well as detailed operational strategies. A more detailed description of EnergyPLAN can be found at [31].

The technical inputs, assumptions, and sources used to create the reference model of the Irish energy-system in this paper are only relevant to Ireland. Consequently, these are not discussed here, but instead a full description of the technical data used is publicly available at [32]. More applicable to a global audience is the financial data used which is provided in the Appendix, as well as the accuracy of the model created which is illustrated in the results. Finally, the 'cost sensitivity' and 'maximum wind penetration' results obtained in this study for Ireland are extremely

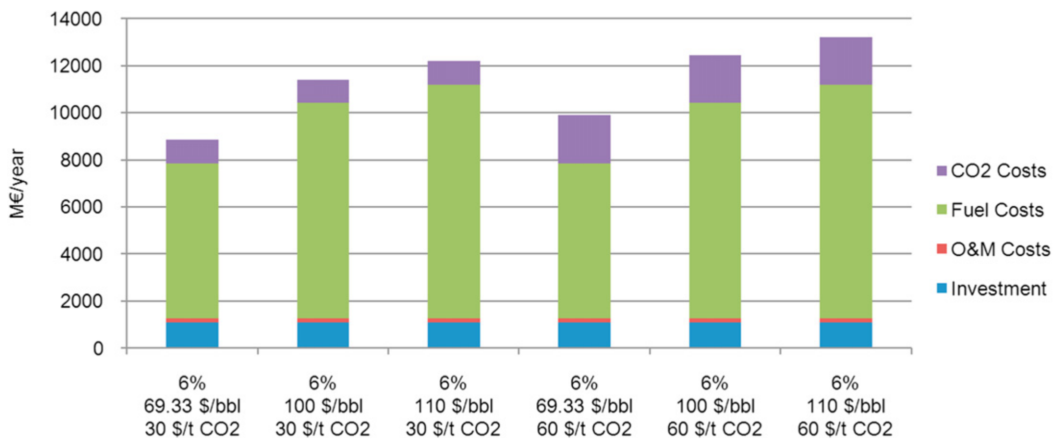

Fig. 3. Annual operating costs of the 2007 Irish energy-system for various fuel and CO_2 prices, using a real interest rate of 6%.

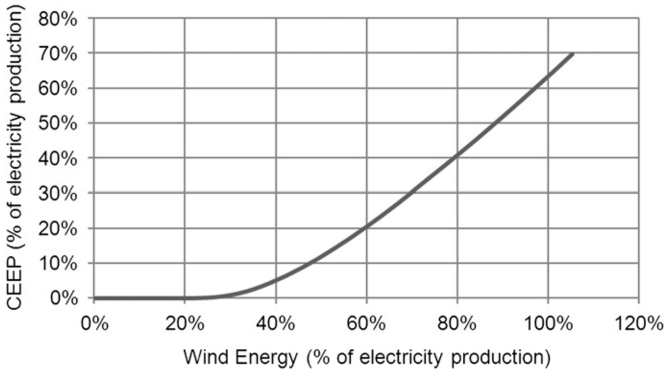

Fig. 4. Critical excess electricity production for increasing wind penetrations on the 2007 Irish energy-system.

applicable to numerous other countries. This is due to the similar structure of their segregated energy-systems i.e. the electricity, heat, and transport sectors are very independent one another, as displayed in [6]. Therefore, the results obtained in this study illustrate the issues ahead for numerous countries, in relation to energy costs and integrating large amounts of fluctuating renewable energy.

4. Results

Once the data was gathered and the model created using EnergyPLAN, three analyses were completed. Firstly, a comparison was made between the reference model created, and the actual performance of the Irish energy-system in 2007. This was completed to ensure that EnergyPLAN was capable of providing an accurate simulation of the Irish energy-system and follows a less detailed comparison which was completed in [33]. Secondly, the sensitivity of the existing Irish energy-system to various economic parameters was analysed: these include fuel prices, CO_2 prices, and interest rates. This analysis was completed to identify future energy costs within the Irish energy-system. Finally, as wind is the most abundant fluctuating renewable energy available in Ireland, a study was completed analysing the maximum wind penetration that could be achieved in Ireland, from a technical and economical point-of-view. The objective of this investigation was to illustrate the potential for immediate integration of a fluctuating renewable energy onto the Irish energy-system, without any major redevelopments. To reinforce this argument, the impact of large fluctuating renewable energy penetrations on conventional power-plants is also examined in detail.

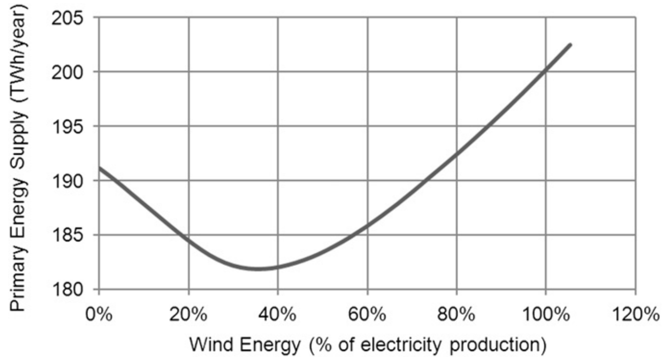

Fig. 5. Primary energy supply on the 2007 Irish energy-system for increasing wind penetrations.

4.1. Accuracy of the Irish reference model

Once the inputs were gathered, the reference model was simulated on a one-hour time resolution over the year 2007. The initial inputs have been continuously updated to improve the accuracy of the simulation, until a high level of accuracy was obtained. In this section, a comparison was made between the most recent version of the reference model and the actual figures from 2007.

The first parameter that was compared was the electricity demand. The total electricity generated for 2007 (28.5 TWh), including a 1.31 TWh net import was being simulated correctly in the model. Also, the distribution of the electricity generated over the year was being simulated correctly, as indicated by the average monthly electricity demands displayed in Table 2.

Once it was verified that the electricity demand was being simulated correctly, the electricity produced from various units was compared. As seen in Table 3, the total electricity generated from the various production units is very similar in both the actual 2007 figures [9] and the results from the reference model. The only significant difference occurred for wind power production, which is most likely attributed to the 8.5% variation in installed wind capacity at the beginning and end of 2007.[2] As power-plants contributed such a large proportion of the electricity supply, a further comparison was made for them.

Power-plant production could not be compared individually because EnergyPLAN aggregates the power-plants within an energy-system and consequently, the production from each power-plant is not available from the results. Therefore, electricity production was not compared for each power-plant, but instead the annual fuel consumed by each fuel-type of power-plant was compared: the fuel-types were natural gas, coal, oil, and biomass. From this comparison it was clear that the model provides an accurate representation of the actual events on the Irish energy-system in 2007, as the largest difference that occurred was 0.47%, which was for oil based power-plants.

After the electricity sector was analysed, the heat and transport sectors were compared with the reference model. However, all heat in Ireland is produced by individual boilers and all transport is powered by conventional vehicles. Therefore, due to the lack of integration between the sectors in the Irish energy-system, no hourly simulations are necessary in the heat or transport sectors. The only input required is the annual fuel requirements which are used as inputs in EnergyPLAN. Therefore, comparing the EnergyPLAN results with the actual data from 2007 would result in no difference, as it would be the same data. Therefore, for the heat and transport sectors, the accuracy of the model needs to be based on the assumptions made while constructing the input data, not on the figures produced by the model. As these are very specific to the Irish energy-system, these are not discussed here but can be freely obtained from [32].

Next the total fuel consumption within the Irish energy-system is compared with those calculated in EnergyPLAN. As seen in Table 4, the total fuel consumptions from actual 2007 figures and from the reference model are very similar for all fuels: the largest relative-difference occurred for biomass at 2.17%.

Finally, the actual CO_2 emissions for Ireland in 2007 were compared with those from the EnergyPLAN simulation. The total energy-related CO_2 emissions for Ireland in 2007 were calculated as 46.8 Mt using fuel consumptions from [9] and emission factors from [7], as seen in Table 5. In comparison, EnergyPLAN calculated

[2] There was an 8.5% increase in wind capacity in Ireland in 2007 from 723.8 MW to 785.2 MW.

Table 6
CEEP, PES, COMP, and costs for various wind penetrations on the 2007 Irish energy-system.

Wind energy, TWh (MW)	Wind penetration (%)	CEEP (TWh/year)	PES (TWh/year)	COMP ΔPES/ΔCEEP (–)	System costs[a] 2007 fuel prices (M€/year)	System costs[a] 2020 fuel prices (M€/year)
2 (724)[b]	6.53	0.00	188.92	–	8849	12,184
5 (1846)	17.56	0.00	185.27	–	8839	12,101
6 (2222)	21.07	0.00	184.14	–	8837	12,076
7 (2598)	24.58	0.04	183.19	24.25	8837	12,055
8 (2973)	28.09	0.15	182.47	6.55	8842	12,041
9 (3349)	**31.60**	**0.38**	**182.04**	**1.87**	**8853**	**12,037**
10 (3725)	35.11	0.74	181.89	0.42	8871	12,041
11 (4100)	38.62	1.23	181.97	−0.16	8894	12,054
12 (4476)	42.13	1.81	182.26	−0.50	8921	12,074

[a] Based on a CO_2 price of $30/t and a real interest rate of 6%.
[b] This is the wind energy on the reference energy-system for 2007.

the CO_2 emissions for Ireland in 2007 as 47.21 Mt. This is 0.88% (0.41 Mt) higher than those calculated from the statistics, and thus indicates that the reference model is providing an accurate representation of the Irish energy-system.

After completing the comparison between the reference model and the actual 2007 figures, it was concluded that the model was accurate: the largest difference recorded was 2.17%. Therefore, the model was used in this paper to analyse the economic sensitivity and maximum feasible wind penetrations for the existing Irish energy-system.

4.2. Economic sensitivity of Irish energy-system

In this section the reference model was used to identify the sensitivity of the Irish energy-system to fuel prices, CO_2 prices, and interest rates using the cost data discussed in the Appendix. For the simulation, no technical alterations were made to the Irish energy-system between now and 2020 so the effects of a business-as-usual scenario could be illustrated. To illustrate the economic consequences of a business-as-usual scenario, the first step was to calculate the annual operating costs of the Irish energy-system using the historical oil and CO_2 costs for 2007, which were $69.33/bbl and $30/t respectively [34]. Afterwards, the annual operating costs were also calculated for future oil and CO_2 prices: oil prices of $100/bbl and $110/bbl were used as these are predicted prices for 2010/2015 and 2020 respectively [34], while a second CO_2 cost of $60/t was used as it is double the existing CO_2 cost of $30/t, which is still lower than many of the estimated costs required to stabilise CO_2 emissions at an acceptable level [35]. In addition, the calculations were completed using two real interest rates: 3% (see Fig. 2) and 6% (see Fig. 3). The energy regulator in Ireland, Commission for Energy Regulation (CER), typically uses a real interest rate of approximately 3–4% when assessing the economic potential for constructing new power-plants [36,37]. Therefore, 3% was also used in this study for analysing the costs of the future costs in the Irish energy-system along with 6% to illustrate the sensitivity of the results. Finally, the annual operating costs calculated are not absolute energy-system costs as they do not include costs outside of the individual technologies, i.e. transmission lines, but they do enable the various alternatives to be directly compared as this is a business-as-usual scenario. Also, investment costs were not included for the transport sector.

By analysing the results displayed in Figs. 2 and 3, the sensitivity of the existing Irish energy-system to various economic parameters can be identified. It is evident from these results, that fuel prices form the most substantial part of the Irish energy-system's annual costs. In addition, the CO_2 price also has a significant effect on the overall system costs, with CO_2 penalties costing approximately the same, or more, than the investment costs for each scenario analysed. Also, the annual O&M costs make up a very small amount of the overall system costs. This is partly due to the exclusion of investment costs in the transport sector, but also due to the segregated system currently in use in Ireland. As the power-plants used in the Irish energy-system are designed for a single purpose they are relatively easy to operate i.e. condensing power-plants produce electricity only, boilers produce heat only, and conventional vehicles provide transport. This causes a relatively simple (i.e. low investment and O&M costs) but inefficient (i.e. high fuel costs) system.

This costs analysis also indicates that future oil and CO_2 prices will have huge implications on the future cost of energy in Ireland. By 2020, if the cost of oil is $110/bbl and the cost of CO_2 remains at $30/t, then the annual cost of fuel for the Irish energy-system will be 44% higher than they are today. If the CO_2 price does double in order to mitigate climate change, then the annual cost of fuel for the Irish energy-system in 2020 will be 58% more expensive than today. This economic risk illustrates how important it is for Ireland to reduce its dependence on all fossil fuels, and convert to a renewable energy-system.

Table 7
Hourly fluctuations in power-plant output for various wind penetrations.

Wind energy (TWh)	Wind penetration (%)	Max ramp up (MW)	Max ramp down (MW)	Number of hours with ramp ups			Number of hours with ramp downs		
				>1000 MW	>500 & <1000 MW	>250 & <500 MW	>1000 MW	>500 & <1000 MW	>250 & <500 MW
2[a]	6.77	785	692	0	241	756	0	7	759
5	17.56	868	1042	0	258	806	1	23	895
6	21.07	897	1157	0	271	812	1	32	923
7	24.58	934	1272	0	282	810	1	50	927
8	28.09	1051	1386	1	282	794	1	59	922
9	**31.60**	**1179**	**1501**	**1**	**280**	**782**	**1**	**83**	**891**
10	35.11	1307	1616	2	274	778	1	89	886
11	38.62	1387	1730	2	275	762	1	102	878
12	42.13	1336	1845	6	263	756	1	111	865

[a] This is the wind energy on the reference energy-system for 2007.

Table 8
Fuel prices used for 2007, 2010/2015 and 2020 [34,38].

(€/GJ)	Crude oil ($/bbl)	Crude oil	Fuel oil	Gas oil/diesel	Petrol/JP	Coal	Natural gas	Biomass
2007	69.33	9.43	6.66	11.79	12.48	1.94	5.07	6.30
2010/2015	100	13.60	9.60	17.00	18.00	3.19	8.16	7.01
2020	110	14.96	10.56	18.70	19.80	3.11	9.16	7.45

4.3. Maximum feasible wind penetration on Irish energy-system

The final analysis completed using this reference model was an investigation into the maximum wind penetration that could be achieved on the 2007 Irish energy-system. The critical excess electricity production (CEEP)[3] and the primary energy supply (PES)[4] for the entire Irish energy-system were recorded, as the annual wind energy production was varied from 0% to 105% (0–30 TWh) of the annual electricity production in Ireland: see Fig. 4 and Fig. 5, respectively.

The CEEP results in Fig. 4 and Table 6 illustrate that no excess electricity occurs on the Irish energy-system up to a wind energy penetration of approximately 21%. After this point, the CEEP increases relatively slowly until a wind penetration of approximately 50%, when the gradient increases substantially. Meanwhile, the lowest fuel consumption shown in Fig. 5 and Table 6 occurs at a wind penetration of approximately 36%, with similar increases in fuel demand above and below this point. An optimum wind penetration could not be identified using these initial results, but boundaries could be created. The minimum wind penetration that is advantageous to the Irish energy-system is at least 21% as up to this point there is no CEEP and fuel consumption is reducing. Also, the maximum wind penetration that should be used is approximately 36%, as at this point both the CEEP and PES are increasing. Therefore, the 'optimum technical' wind penetration for the existing Irish energy-system in 2007 is between 21% and 36%.

To identify the technically optimum point, a compromise is needed between the increase in CEEP and the resulting impact on the PES, as the wind penetration increases. As a result, a compromise coefficient, COMP, was created which is the ratio between the reduction in PES, ΔPES, and the increase in CEEP, ΔCEEP, as the wind penetration increases from one simulation to the next:

$$\text{COMP} = \frac{\Delta \text{PES}}{\Delta \text{CEEP}} \tag{1}$$

The COMP coefficient illustrates the benefits of adding wind capacity (i.e. a reduce energy consumption and hence a lower PES), against the disadvantages of adding wind capacity (i.e. increasing the fluctuating power on the energy-system and hence increasing CEEP). The maximum feasible wind penetration occurs when the COMP coefficient is less than 1. Therefore, the COMP coefficient states that wind energy should no longer be added to the system when, the increase in electricity that you are forced to export is greater than the reduction in energy that you need to power your system. From the results in Table 6 for example; when the wind energy on the reference system is increased from 9 TWh to 10 TWh, then the increase in forced electricity exports is increased by 0.36 TWh and the total energy demand is only decreased by 0.15 TWh. Therefore, the additional 1 TWh of wind has caused the system to generate twice as much energy that it can no longer consume than it has saved. Consequently, it is evident that the largest feasible wind penetration defined by COMP is 31.6%: after this point the reduction in energy consumption is less than the increase in CEEP (i.e. COMP < 1), and before this point the reduction in energy consumption is larger than the increase in CEEP (i.e. COMP > 1). For some systems this could be classified as a conservative approach: if fossil fuel prices are extremely high, then the wasted energy created by the addition of wind could be classified as acceptable. Therefore, the costs of the Irish energy-system were also analysed to compare with COMP.

Using a CO_2 price of $30/t and a real interest rate of 6%, which is the worst case scenario for investing in wind power in the future, the cost of the existing Irish energy-system was calculated for various wind penetrations using 2007 and 2020 fuel prices, which is displayed in Table 6. Firstly, these results indicate that the existing Irish energy-system is more expensive than alternative energy-systems with higher wind penetrations, under both 2007 and 2020 fuel prices. Secondly, although a wind penetration of 31.6% was identified previously as the optimum from a technical point-of-view, a wind penetration of 21% is the optimum from an economic point-of-view when considering 2007 fuel prices. However, when using 2020 fuel prices, the technical 'optimum' becomes the same as the economic 'optimum', at a wind penetration of 31.6%. This is due to the sensitivity of the existing Irish energy-system to fuel prices, as previously displayed in Figs. 2 and 3. The economic results from Table 6 indicate that as fuel prices increase to 2020 levels, the most economical energy-system will be achieved in Ireland by integrating the maximum wind penetration that is technically feasible. It is worth noting that the 'optimum' wind penetrations discussed here are only for the 2007 Irish energy-system. Future alterations to the Irish energy-system have not been included (but will be in future studies), and hence larger feasible wind penetrations are likely to be identified in future studies.

Finally, the next issue discussed is the effect of increasing wind penetrations on conventional power-plants. The hourly demand on power-plants was analysed for different wind penetrations, and the scale and frequency of power-plant ramping was analysed. The results are displayed in Table 7 and show that higher wind penetrations increase the demand for ramping power-plants both up and down. For a wind penetration of 31.60% (which was previously deemed the optimum wind penetration in the existing Irish energy-system), the power-plants in the Irish energy-system would need to be able to ramp up by a maximum of 1179 MW, and ramp down by a maximum of 1501 MW. In addition, the power-plants would need to be able to ramp up/down between 500 MW and 1000 MW 280/83 times respectively, and between 250 MW and 500 MW 782/891 times respectively. It is evident that ramping demands on power-plants between 250 and 500 MW, for a wind penetration of 31.60% and the reference model are very similar. However, there are significant increases in ramping requirements of $+/-500$ MW as wind penetrations increase. Therefore, ramping capabilities within this range should be a key issue for future power-plants that are built on the Irish energy-system, to encourage the integration of more renewable energy.

[3] CEEP is the amount of excess electricity produced that could not be used in the energy-system. The consequences of CEEP are forced export (if adequate interconnection capacity does not exist) or stopping the wind turbines to reduce production.

[4] PES is the total fuel consumption within the energy-system, which includes electricity, heat, and transport.

Table 9
Fuel handling costs [38].

€/GJ	Fuel oil	Gas oil/diesel	Petrol/JP	Coal	Natural gas	Biomass
Power stations (central)	0.228	0.228	–	0.067	0.428	1.160
Distributed CHP, district heating & industry	1.914	1.807	–	–	1.165	1.120
Individual households	–	2.905	–	–	2.945	6.118
Road transport	–	3.159	4.257	–	–	11.500 [39]
Airplanes	–	–	0.696	–	–	–

Table 10
Investment, fixed O&M, and variable O&M costs for Irish condensing power-plants [41].

Plant type	Investment costs (M€/MW)	Fixed O&M costs (€/MW/year)	Variable O&M costs (€/MWh)	2007 Irish capacity/ fuel-type
Steam turbine, coal fired, advanced steam process, 2004	1.100	16,000	1.800	852.5 MW/Coal; 806 MW/Oil
Steam turbine, coal fired advanced steam process, 20% co-firing of biomass, 2004	1.200	22,000	3.000	345.6 MW/Peat
Gas turbine single cycle (40–125 MW), 2004	0.485	7350	2.500	719 MW/Gas
Gas turbine combined cycle (100–400 MW), 2004	0.525	14,000	1.500	2806 MW/Gas
Gas turbine combined cycle (10–100 MW), 2004	0.700	10,000	2.750	208 MW/Gas

Table 11
Costs (excluding taxes) of individual heating systems for the reference model of the Irish energy-system.

Fuel-type	Size	Cost including installation (€)	Lifetime (years)	O&M costs (€/year)
Oil	26 kW	14,750	15	110
Biomass	19 kW	19,500	15	110
Natural gas	26 kW	14,750	15	110
Solid fuel	21 kW	15,300	15	110
Electric boiler	12 kW	15,500	15	0
Electric heaters	20 kW	6000[a]	20	0
Solar thermal	2400 kWh/year	5900	35	55

[a] Does not account for electric transmission upgrades that may be necessary for widespread installations.

5. Conclusions

The development of an energy model for the Irish energy-system has been discussed in this study. Firstly, the accuracy of the model has been verified by comparing the results of the model with actual statistics from the year 2007. From these results it is clear that the model is sufficiently accurate for use in future studies that will focus on the integration of renewable energy into the Irish energy-system. After validating the accuracy of the model, this study then illustrated the huge vulnerability of the Irish energy-system to future fuel prices and CO_2 prices. Results illustrate that fuel costs could increase by at least 44% in 2020 due to fuel price increases alone, and by an additional 14% if CO_2 prices are doubled to mitigate climate change. Afterwards, the maximum wind penetration feasible on the Irish energy-system from a technical and economic perspective was identified. It was concluded that based on 2020 fuel prices, both the technically and economically optimum wind penetration occurs at approximately 30% for the existing Irish energy-system. Finally, the effect of high wind penetrations on conventional generation was investigated. Here, it was concluded that the ramping capabilities of the power-plants needs to increase by approximately double to incorporate a wind penetration of approximately 30%. If this can be achieved with existing power-plants, then this wind penetration can be achieved now on the existing Irish energy-system. Finally, using this model will be used in future studies to identify even larger renewable energy penetrations for Ireland.

6. Future work

All the results displayed in this paper were obtained by analysing the existing Irish energy-system based on the year 2007. Although these results have provided some excellent indications for the future, the next step will be to develop alternatives based on future energy-systems and not the existing energy-system. Alternative energy-systems will then be designed with a particular focus on the integration of renewable energy. As the CEEP, PES, and hence the COMP coefficient are system dependent, i.e. dependent on the system analysed, changes on both the production side and the consumption side will affect the values. Therefore, it is anticipated that much higher renewable energy penetrations will be identified for the Irish energy-system, when future alternative scenarios are incorporated into the model. Future alternatives could involve analysing any of the following in Ireland: large-scale CHP and district heating, electric vehicles, energy storage, increased interconnection, introduction of demand side management, etc.

Acknowledgements

The findings in this article result from a research project at the University of Limerick, which has been supported financially by the Irish Research Council of Science, Engineering & Technology (IRCSET) and Science Foundation Ireland (SFI) under Grant Number 06/CP/E007. Preliminary results of the paper were presented and discussed at the Joint Action on Climate Change (JAOCC) conference in Aalborg, Denmark, on the 10th June 2009 [33].

Appendix. Cost data used

To complete the economic analysis in this study, a number of costs had to be gathered. The purchasing costs for each fuel were obtained for the years 2007, 2010/2015, and 2020 and are displayed in Table 8. These are predicted prices from the International Energy Agency [34] and the Danish Energy Authority [38].

The crude oil price was used to identify the cost of fuel oil, diesel, and petrol. As these fuels are refined from crude oil, their prices are proportional to the crude oil price and hence, the price ratio between each of these and crude oil typically remains constant. Therefore, the following ratios recommended by the Danish Energy Authority were used to calculate these prices [38]: ratio of crude oil to fuel oil was 1–0.7, crude oil to diesel was 1–1.25, and crude oil to petrol was 1–1.33. Also, the fuel handling costs were obtained from the Danish Energy Agency [38] and Sustainable Energy Ireland [39] as displayed in Table 9.

After consulting with the Irish revenue office, it was found that there are currently no taxes (other than value added tax) placed on fuels in Ireland. Also, at the time of this study there was no carbon tax in Ireland. However, Ireland does participate in the European carbon trading scheme so these costs had to be accounted for. To identify this cost, historical trading prices were obtained from [40] and an average value of €20.63/tCO_2 ($30/t$CO_2$) was found for the year 2007.

The condensing power-plant costs were obtained from a report completed by the Danish Energy Authority, Ekraft System, and Eltra[5] [41], and are displayed in Table 10. Using these details the aggregate cost of condensing plant on the Irish energy-system was calculated as 0.733 M€/MW, with a fixed O&M cost of 14,081 €/MW/year and a variable O&M cost of 1.84 €/MWh.

The onshore wind and offshore wind costs were also obtained from the Danish Energy Authority [42]: investment costs for onshore wind are 1.2 M€/MW and offshore wind is €1.6 M€/MW, while the fixed O&M costs are 6 €/MWh for onshore wind and 8.70 €/MWh for offshore wind.[6] The investment cost for the hydro power in Ireland was obtained from the British Hydropower Association [43]: the investment cost for hydro stations below 100 MW is 1.765 M€/MW, the fixed O&M costs are approximately 2.7% of the investment, while the variable O&M costs are approximately 1.3% of the investment. The costs for pumped hydroelectric energy storage in Ireland were found from [44] as €0.473.6 M€/MW and €7.89/GWh for the initial investment, 3000 €/MW for the fixed O&M cost, and 3 €/MWh for the variable O&M cost.

Finally, the investment and O&M costs were obtained for the individual heating systems used in the 2007 Irish energy-system as displayed in Table 11. This ensured that all costs within the heating and electricity sectors were accounted for in the reference model.

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Appendix G

Connolly D, Lund H, Mathiesen BV, Pican E, Leahy M. The technical and economical implications of integrating fluctuating renewable energy using energy storage. Submitted to the Journal of Renewable Energy.

Renewable Energy 43 (2012) 47–60

Contents lists available at SciVerse ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

The technical and economic implications of integrating fluctuating renewable energy using energy storage

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ARTICLE INFO

Article history:
Received 21 January 2011
Accepted 3 November 2011
Available online 4 January 2012

Keywords:
Pumped hydroelectric
Energy storage
Technical optimisation
Economic optimisation
Wind power
Renewable energy

ABSTRACT

This paper investigates how large-scale energy storage can assist the integration of fluctuating renewable energy by using the Irish energy system, pumped hydroelectric energy storage (PHES), and wind power as a case study. In total three key aspects were investigated in relation to PHES: its operation, size, and cost. From the results it was evident that PHES can increase the wind penetration feasible on the Irish energy system and also reduce its operating costs. However, under predicted 2020 fuel prices and a conventional 6% interest rate, these savings may not be sufficient since the savings are sensitive to changes in the PHES capacities used, fuel prices, interest rates, and the total annual wind energy produced. Finally, the optimum capacities of PHES identified for Ireland in 2020 were compared to two other alternatives which required the same investment: domestic heat pumps and district heating with CHP. These alternatives offer similar savings to PHES, but are not as sensitive to changes in fuel prices, interest rates, and wind power production. This outlines the importance of considering all sectors of an energy system when assessing future alternatives, as significant savings are feasible using existing technologies, especially by integrating the electricity and heat sectors.

1. Introduction

It is essential that flexibility is introduced to an energy system if the penetration of fluctuating renewable energy is to be increased. One technology which is ideally suited for increasing energy flexibility is energy storage. A wide range of energy storage technologies currently exist, each with its own advantages, constraints, applications, and potential [1]. Currently, pumped hydroelectric energy storage (PHES) is the largest and most mature form of energy storage available in the world, but it is widely believed that suitable locations to construct new PHES facilities are limited [2–4]. Conversely though, recent studies have indicated that suitable PHES locations are more common than originally anticipated [5–7], especially in Ireland[1] [8–10]. Consequently, the feasibility of building large-scale energy storage is no longer the only major concern, but instead the implications of large-scale energy storage also need to be determined, especially in relation to the integration of fluctuating renewable energy. Therefore, the primary objective of this work is analyse the technical and economic implications of using large-scale energy storage to integrate fluctuating renewable energy, by using the Irish energy system, wind power, and PHES as a case study.

Many previous studies have focused on these issues also, but these are primarily devoted to two types of small-scale applications: stand-alone wind-PHES systems [11–16] and PHES on island[2] energy systems [17–26]. Within these studies there are a wide range of key issues analysed in relation to the wind-PHES system such as its operation, sizing, cost, and effect on other technologies. Although this variety of concerns outlines the complexity associated with PHES and the integration of wind energy, it is unclear if the conclusions made in these studies can be translated onto national[3] electricity systems, especially since there is much less research relating to PHES on national electric grids. Some examples include Benitez *et al.* [27] who analysed the impacts of additional

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[1] Unless otherwise specified, Ireland refers to the Republic of Ireland only throughout this paper.

[2] Island electricity systems refer to small-scale stand-alone energy systems where the installed generating capacity is usually between 1 and 100 MW.

[3] National electricity systems refer to large-scale interconnected energy systems where the installed generating capacities are usually above 1 GW.

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doi:10.1016/j.renene.2011.11.003

Nomenclature

Symbols

C_{Pump}	Capacity of PHES pump, MW
$C_{Storage}$	Capacity of the PHES storage, GWh
$C_{Turbine}$	Capacity of PHES turbine, MW
CEEP	Critical excess electricity production, TWh/year
COMP	Compromise coefficient
FFD	Fossil fuel demand, TWh/year
MFWP	Maximum feasible wind penetration, TWh/year
PES	Primary energy supply, TWh/year
e_{CEEP}	Hourly critical electricity production, MWh
e_{PP}	Hourly power plant electricity production, MWh
e_{Pump}	Hourly PHES pump electricity consumption, MWh
$e_{Turbine}$	Hourly PHES turbine electricity production, MWh
S_{PHES}	Hourly energy stored in the PHES facility, GWh
η_{Pump}	Efficiency of the PHES when pumping
$\eta_{Generation}$	Efficiency of the PHES when generating

Abbreviations

CHP	Combined heat and power
EV	Electric vehicle
IEA	International Energy Agency
PHES	Pumped hydroelectric energy storage
PP	Power plant
REF	Reference energy system
REF2020	Reference energy system for the year 2020
SEMO	Single electricity market operator

wind capacity on the Alberta electricity network in Canada, concluding that when PHES is added in conjunction with wind power it can provide most of the peak-load requirements of the system and thus, peak-load gas generators are no longer required. Dursun and Alboyaci [28] carried out a detailed review of previous wind-PHES studies and outlined how this solution could be employed in Turkey, by utilising the mountainous areas around the Black Sea and electrical infrastructure to other hydro facilities. Black and Strbac [29,30] examined the benefits of PHES on the British energy system for a wind penetration of 20%, which equates to an installed wind capacity of 26 GW. After paying particular attention to reserve requirements and systems costs, the authors concluded that the value of PHES is very dependent on the flexibility of the conventional generation also on the system. The results also indicated that energy storage could reduce system costs, wind curtailment, and the amount of energy required for conventional generation. Lund and Salgi [31,32] simulated compressed air energy storage (CAES) on the Danish energy system. The authors found that due to the high amount of electricity production from combined heat and power (CHP) plants, there is not enough ‘electricity-only’ generating hours in the CHP dominated Danish system to warrant the construction of the CAES facility. Krajačić *et al.* [33] analysed how Portugal could achieve a 100% renewable electricity system where wind and PHES play a key role. On a system which had a maximum peak demand of 8777 MW, the authors indicated that approximately 6000 MW and 4500 GWh of storage is required, hence outlining the scale of storage necessary for integrating large-scale wind penetrations. In relation to Ireland, Tuohy and O'Malley [34] used the Wilmar Planning Tool to simulate the All-Ireland electricity grid with and without a 500 MW 5 GWh PHES facility for wind capacities between 3 GW and 15 GW, which is 17–80% of the total electricity demand. The results indicated that the PHES plants did not have any impact on the operation of the system until the wind penetration exceeded 40%. Also, even though it reduced the operating costs of the system, the additional capital costs were too high to justify its construction. However, the authors did emphasise that future work should analyse the implications of different capacities and operating strategies for the PHES facility. In 2010 Nyamdash *et al.* [35] did this by analysing the implications of energy storage on the 2006 All-Ireland electricity grid with wind capacities of 1300 MW, 1950 MW, and 2550 MW. In this study, wind power and energy storage were dispatched together under three different operation strategies: one where the wind-hydro system provided a 24 h baseload output and replaced baseload plant, a second where it charged for 12 h at night and discharged for 12 h during the day by replacing mid-merit plant, and thirdly, where it generated for 6 peak hours of the day and replaced peaking plant. Each operating strategy was analysed for a PHES power capacity ranging from 0 MW to 1800 MW. The results indicated that the baseload and peaking strategies increased the variability of wind, but the mid-merit strategy decreased it. Also, a subsequent economic assessment was carried out which indicated that the revenue made by the energy storage under all three strategies was not sufficient to make it an attractive investment. Therefore, the authors concluded that without any economic subsidy, energy storage would not be an attractive investment.

In summary, the majority of island studies conclude that PHES increases the wind penetrations feasible and reduces operating costs. However, studies completed on national electric grids are more ambiguous and hence, it is difficult to assess how details included in island studies are related to national energy systems. Therefore, this study will contribute to this debate by quantifying the additional wind penetrations feasible on the Irish electric grid due to the introduction of PHES and subsequently, investigate the economic savings associated with this additional wind energy. Afterwards, a sensitivity analysis is carried out to validate the trends identified during this research. Furthermore, as the model used in this study considers the entire energy system (i.e. electricity, heat, and transport), it is also used to compare PHES to alternative technologies which can also reduce the total operating costs of the Irish system. Finally, although this study focuses on wind energy and PHES, the results are indicative of those that would be obtained when analysing any form of fluctuating renewable energy such as wave, tidal, and photovoltaic, as well as any form of large-scale energy storage such as compressed air, flow batteries, and electric vehicles.

2. Methodology

To analyse the implications of PHES, a detailed model of the Irish energy system was constructed. After considering a wide range of various energy tools to do this [36,37], the EnergyPLAN tool was chosen [38]. The main purpose of EnergyPLAN is to assist in the design of national or regional energy-planning strategies on the basis of technical and economic analysis, resulting from the implementation of different energy systems and investments. EnergyPLAN is a deterministic input/output tool which uses an hourly simulation over a period of one year. The structure of EnergyPLAN is illustrated in Fig. 1. General inputs are the demands, renewable energy sources, energy station capacities, costs, and a number of optional regulation strategies. Outputs are energy balances and the resulting annual productions, fuel consumption,

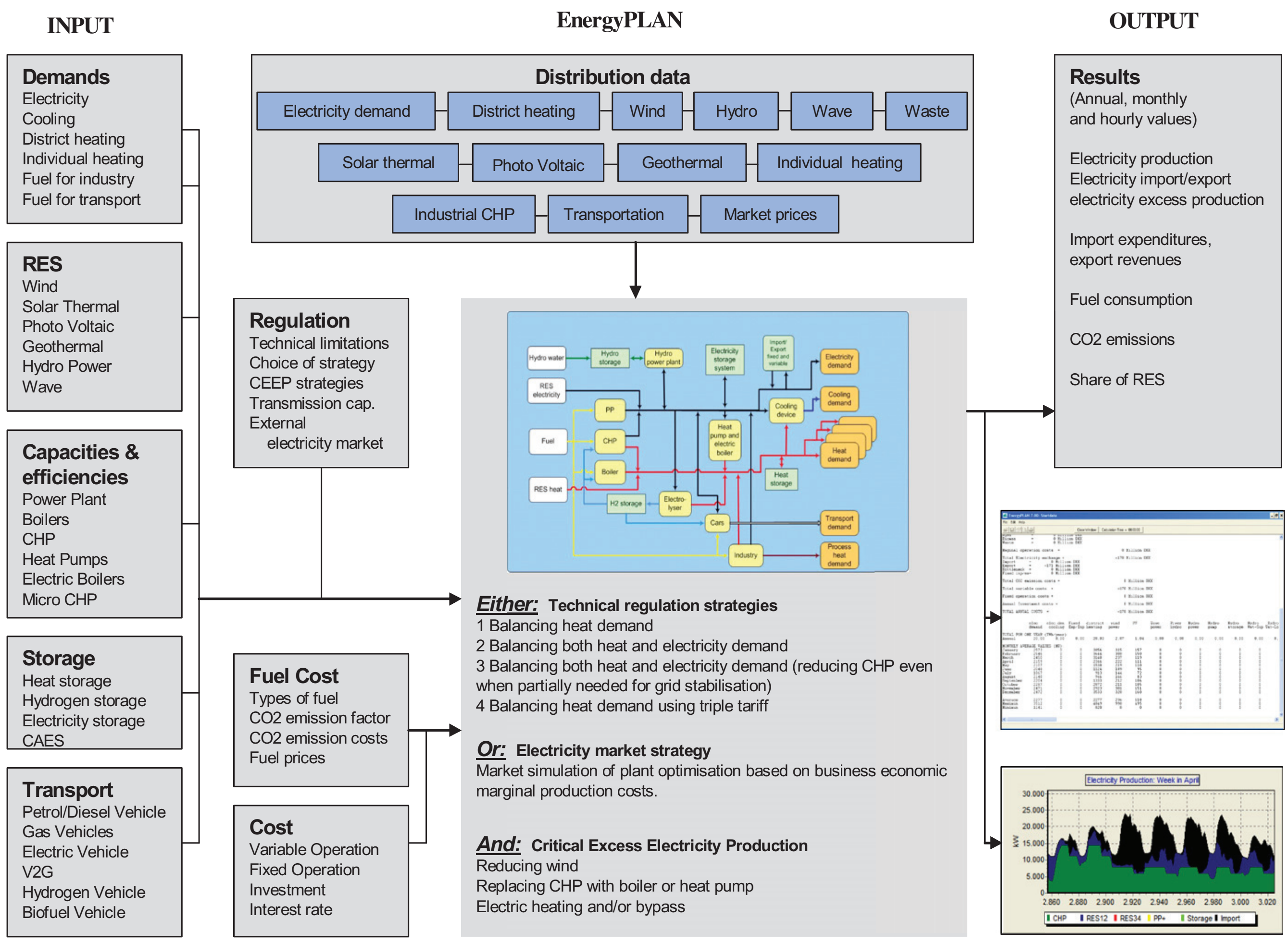

Fig. 1. The structure of the EnergyPLAN model [38].

import/export of electricity, and the total costs of the system including income from the exchange of electricity. EnergyPLAN uses analytical programming rather than iterations so the calculations are completed in a very short period of time (<10 s). Also, the simulation process in EnergyPLAN has been kept relatively simple by aggregating all units in the various sectors mentioned and hence, not considering the differences in single units and the transmission among them. Otherwise, EnergyPLAN provides an advanced representation of the entire energy system, by using hourly distributions of heat demands, electricity demands, wind production, wave production etc., as well as detailed operational strategies. A more detailed description of EnergyPLAN along with a selection of case studies can be found at [38], while it is compared to numerous other energy tools in [36].

To ensure that EnergyPLAN was able to simulate the Irish energy system accurately, a model was initially constructed based on the year 2007 [39–41]. Subsequently, the results from this model were compared to actual historical data, where the largest difference recorded was 2.2% [41]. Therefore, it was concluded that EnergyPLAN could model the Irish energy system accurately. Afterwards, a model was constructed based on the same principals for the 2020 Irish energy system (REF2020) so the implications of PHES could be analysed. The business-as-usual reference model was constructed using the annual energy consumption and demand data projected by the Sustainable Energy Authority of Ireland (SEAI) [42]. More specifically, the 2020 model was based on the "White Paper Plus" scenario proposed by SEAI for 2020, which is summarised in Table 1. The total electricity demand assumed was 34 TWh with an average demand of approximately 3400 MW, a peak of 5500 MW, and a minimum demand of 1900 MW, while the installed generation capacity for various types of plants is outlined in Table 2. A detailed description of the assumptions made during the construction of this reference model is available in [39–41].

When simulating PHES in EnergyPLAN during this study, the primary focus was to integrate the maximum feasible wind penetration (MFWP) and hence, a technical optimisation was used. For a technical optimisation, PHES is charged during hours when critical excess electricity production (CEEP)[4] occurs in the energy system (i.e. if $e_{CEEP} > 0$) [38]. In this case the electricity demand for the PHES pump (e_{Pump}) is found as the minimum value in Equation (1), which considers the CEEP, e_{CEEP}, the available space in the PHES facility ($C_{Storage} - S_{PHES}$), and the maximum capacity of the PHES pump, C_{Pump}. Subsequently, the energy stored in the PHES facility after operating the pump is calculated using Equation (2), where S_{PHES} is the current volume of energy stored in the PHES facility and η_{Pump} is the efficiency of the PHES when pumping.

[4] CEEP is the amount of excess electricity produced that could not be used in the energy system. The consequences of CEEP are forced export (if adequate interconnection capacity exists) or stopping the wind turbines to reduce production.

Table 1
Projected energy balance for the Irish energy system in 2020 (White Paper Plus Scenario) [42].

2020 White Paper Plus Energy Balance Units = ktoe	Coal	Peat	Oil	Transport Oil			Natural gas	Renewables	Breakdown of Renewable Energy						Electricity	Total
				Jet kerosene	Gasoline/Petrol	Gasoil/Diesel/DERV			Hydro	Wind	Wave	Biomass	Solar	Geothermal		
Primary energy requirement (A+B)	*606*	*483*	*8721*	*800*	*1873*		*3916*	*2481*	*91*	*718*	*118*	*1450*	*20*	*84*	*−127*[a]	*16080*
Power plant consumption (A)	373	338	345				2397	500				500				3453[b]
Power plant production	137	120	118				1356	1109	91	718	118	183				1732[b]
Transmission & distribution losses															242	242
Total final energy consumption (B)	*233*	*146*	*8376*	*800*	*1873*		*1519*	*1055*				*950*	*20*	*84*	*2447*	*13776*
Industry	98		877				778	345				345			630	2728
Transport			5933	800	1873	3259	0	464				464			95	6492
Residential	112	146	1210				516	103				141	20	84	648	2734
Commercial/Public services	23		60				225	143							998	1448
Agricultural			296												76	373

[a] Negative sign indicates an electricity net import.
[b] This value represents fossil fuel power plants only.

$$e_{\text{Pump}} = \min\left[e_{\text{CEEP}}, \frac{C_{\text{Storage}} - S_{\text{PHES}}}{\eta_{\text{Pump}}}, C_{\text{Pump}}\right] \quad (1)$$

$$S_{\text{PHES}_{\text{new}}} = S_{\text{PHES}} + \left(e_{\text{Pump}} {}^{*} \eta_{\text{Pump}}\right) \quad (2)$$

Conversely, the PHES is discharged when it is possible to replace power plant production with power from the PHES facility (i.e. if $e_{\text{PP}} > 0$) [38]. Therefore, the electricity produced by the turbine, e_{Turbine}, is found as the minimum value in Equation (3), which considers the power plant capacity which can be replaced, e_{pp}, the current energy available in the PHES facility, S_{PHES}, and the maximum capacity of the PHES turbine, C_{Turbine}. Subsequently, the volume of energy remaining in the PHES after operating the turbine is identified using Equation (4), where $\eta_{\text{Generation}}$ is the efficiency of the PHES when it is generating electricity.

$$e_{\text{Turbine}} = \min\left[e_{\text{PP}}, \left(S_{\text{PHES}} {}^{*} \eta_{\text{Generation}}\right), C_{\text{Turbine}}\right] \quad (3)$$

$$S_{\text{PHES}_{\text{new}}} = S_{\text{PHES}} - \frac{e_{\text{Turbine}}}{\eta_{\text{Generation}}} \quad (4)$$

In summary, where possible the simulation will use wind power directly to satisfy the electricity demand, but when grid constraints prevent this, the PHES stores the excess wind power so it can be used at a later time. Two primary assumptions were made to ensure that the electricity grid is operated in a stable fashion. Firstly, it was assumed that the minimum output from electrical power plants was never below 700 MW during each hour simulated and secondly, as recommended by the Irish TSO [43], 30% of the electricity production during each hour had to be supplied from grid stabilising units such as thermal power plants and hydro stations. Finally, A detailed explanation of the equations and operating principals associated with the EnergyPLAN tool is available from [38].

3. Results and discussion

As outlined above, some of the key issues identified in relation to wind and PHES during the wide range of island studies included the PHES operation, size, and cost. Therefore, in this paper these key issues were analysed when modelling wind and PHES on the 2020 Irish energy system.

3.1. Operation

Historically, PHES facilities have typically been constructed with a single penstock system as they were designed to maximise electricity generation from baseload power plants i.e. by charging during the night when electricity prices were low (due to a high percentage of baseload power) and discharging during the day

Table 2
Installed capacities in the 2020 reference model of the Irish energy system [42].

Technology	Installed capacity (MW)
Coal power plants	845
Peat power plants	346
Open cycle gas turbines	1091
Combined cycle gas turbines	3013
Waste incineration	89
Wind turbines	3100
Wave powers	500
Hydroelectricity	260
Interconnection	580

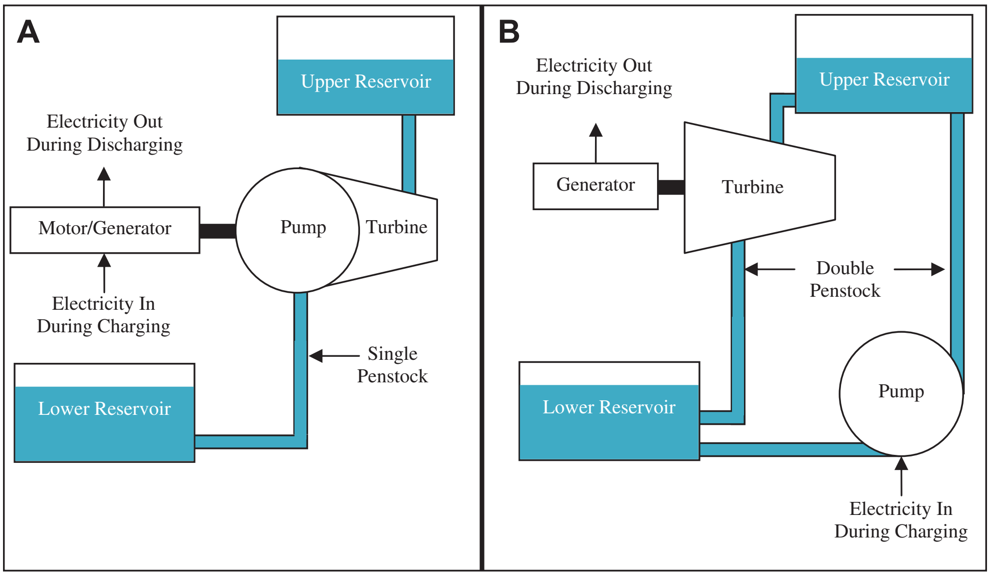

Fig. 2. One PHES facility with (A) a single penstock system and (B) a double penstock system.

when electricity prices were high (due to a high demand). However, if energy storage devices are designed especially to integrate fluctuating renewable energy, there may be additional benefits when using PHES that can charge and discharge at the same time. This can be achieved in a single PHES facility by installing two penstocks, as displayed in Fig. 2, or also by installing multiple single penstock system PHES facilities on the same energy system i.e. one can charge while the other is discharging at the same time. By using a double penstock system, the PHES introduces even more flexibility onto the energy system which should aid the integration of wind power. Therefore, both of these operating strategies were used to simulate a 2500 MW and 25 GWh PHES facility on the 2020 Irish energy system, with increasing penetrations of wind power.

The CEEP recorded for both operating strategies when wind power is added to the Irish energy system is outlined in Fig. 3, while Fig. 4 displays the corresponding primary energy supply (PES) and CO_2 emissions. These results illustrate that PHES can reduce the amount of excess electricity created with the introduction of wind power, while also reducing the corresponding PES and CO_2 emissions. Also, is evident from Figs. 3 and 4 that when the PHES facility operates as a double penstock system, there is less CEEP, PES, and CO_2 emissions compared to the single penstock operating strategy. To identify the cause of this, the hourly operation of the system was analysed.

From these hourly values it became apparent that the grid stabilisation constraints were significantly limiting the effectiveness of the single penstock PHES. The primary objective of adding PHES is to minimise excess electricity production (i.e. reduce CEEP) and use it to replace thermal power production (i.e. reduce PES). However, as 30% of the production must come from grid stabilising units during each hour, wind power cannot always be used directly so it must be sent to the PHES facility. During these hours of excess wind, the single PHES cannot be used to provide grid stabilisation as it is being charged by the wind power and hence, the power plants must operate to provide grid stabilisation. Therefore, a single penstock PHES has to reduce CEEP and use the power plants to meet demand (Fig. 5, Option A), or dump the CEEP and replace the power plant production (Fig. 5, Option B). However, as displayed in Fig. 5, both of these options will result in lower wind penetrations and correspondingly higher fuel consumption. In contrast, a double penstock system enables the PHES to store excess wind energy while at the same time providing ancillary services to the grid, which is also displayed in Fig. 5. Therefore, during these hours a double penstock PHES facility can store CEEP by charging, while at the same time it can be discharged to replace power plant production (until such point that power plant production has reached its minimum limit, which was 700 MW in this study). This is the root cause for the lower CEEP, PES, and CO_2 emissions

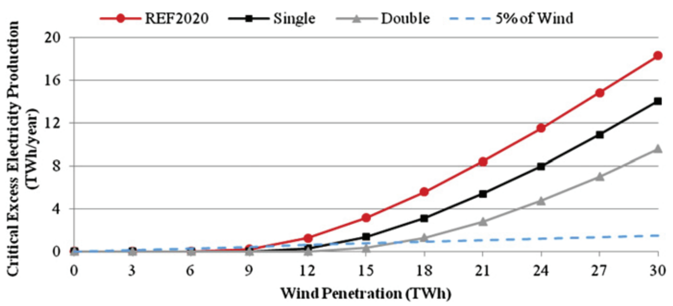

Fig. 3. CEEP for the 2020 Irish energy system, a 2500 MW/25 GWh single PHES, and a 2500 MW/25 GWh double PHES for wind penetrations of 0–100% (0–30 TWh) of electricity demand. The '5% of Wind' represents the acceptable amount of excess electricity production in section 3.3.

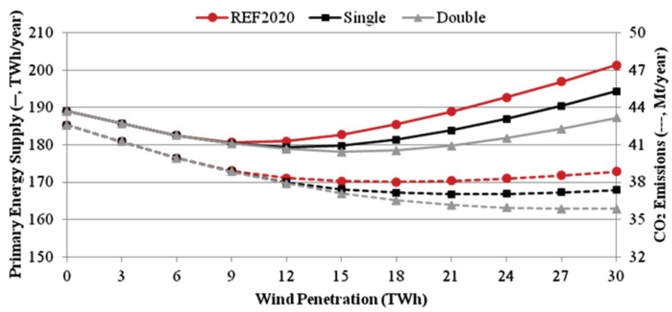

Fig. 4. Primary energy supply and CO_2 emissions when a 2500 MW/25 GWh single and double penstock system is added to the 2020 Irish energy system, for wind penetrations of 0–100% (0–30 TWh) of electricity demand.

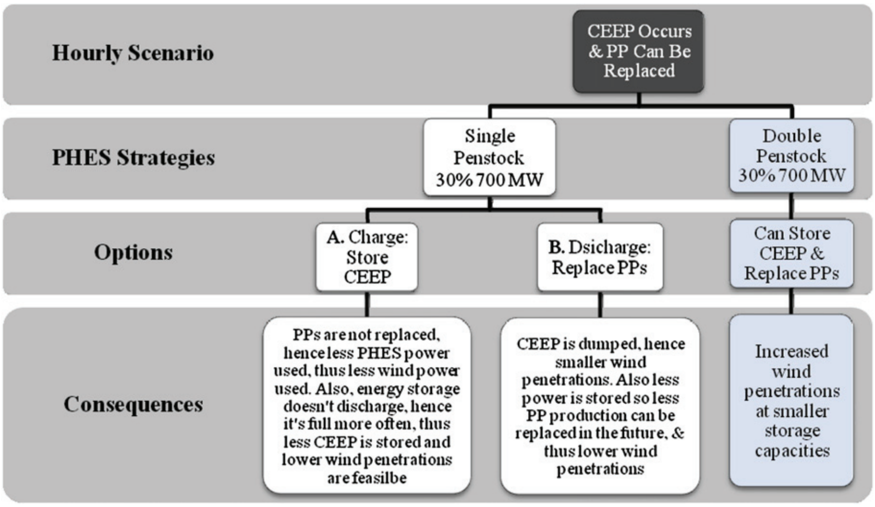

Fig. 5. Consequences of using a single or double penstock system for PHES facilities.

recorded in Figs. 3 and 4. A pictorial illustration of this issue is also provided by Connolly [44].

Finally, it is important to note that there is an underlying assumption in the modelling that only centralised power stations and hydro facilities can provide grid stabilisation. However, in future energy systems, grid stabilisation could be provided from decentralised units also [45], which could reduce the benefits of large-scale PHES. Due to the 40 year lifetime of PHES, this could be an important factor when constructing a new facility. Furthermore, when a single PHES was simulated with no grid constraints on the 2020 Irish energy system, it achieved greater reductions in CEEP, PES, and CO_2 emissions than the double penstock PHES simulated here, thus outlining the significant role of grid constraints.

To summarise, this section has illustrated that under traditional grid constraint assumptions, adding conventional PHES to the Irish energy system will reduce CEEP, PES, and CO_2 emissions. A double penstock operating strategy is more effective than a single penstock system, as it can accommodate these grid constraints by charging and discharging at the same time. Therefore, the following section investigates if the extra flexibility from a double penstock system is worth the additional investment required.

3.2. Costs

The annual operating costs of the Irish energy system are made up of investment repayments, fuel costs, fixed O&M costs, variable O&M costs, as well as the exchange of electricity over the interconnector. A detailed description of the equations used to calculate these costs is outlined in [38,40,41]. A range of assumptions had to be made in relation to investment costs, operation and maintenance costs, and lifetimes to analyse the costs of adding wind power and PHES to the 2020 Irish energy system. Those assumed for wind turbines and PHES are all displayed in Table 3, while the costs assumed for all the other components[5] on the Irish energy system are outlined in [39–41]. Although there are a wide range of costs reported for a single PHES [46,47], no historical data was identified for the double PHES. Therefore, it was assumed that the double PHES would cost twice as much as a single PHES, considering the additional penstock, grid infrastructure, and components that would be required. This also accounts for a scenario where two single penstock PHES facilities need to be constructed to create a double penstock operating strategy. For the initial cost assessment, fuel prices corresponding to an oil price of $100/bbl for 2020 were assumed (see Table 4), along with an interest rate of 6% which has been used when assessing other energy infrastructure in Ireland [48]. Also, based on 2020 projections by the International Energy Agency (IEA), a CO_2 cost of $50/t was incorporated into the calculations [49].

Using these assumptions, the cost of a 2500 MW/25 GWh PHES on the 2020 Irish energy system while operating as both a single and a double penstock system was simulated for wind penetrations of 0–100% (0–30 TWh) of the electricity demand. As displayed in Fig. 6, the results indicate that the PHES facility does not increase the wind penetration enough to warrant the initial investment required, with the reference scenario proving to be the most economical. In addition, the results suggest that the double penstock is not worth the additional investment required as it is more expensive than the single penstock operating strategy up to a wind penetration of 18 TWh (60%). However, this analyses was completed using one PHES capacity only and hence, the next section investigates if alternative capacities could be used to make PHES more economical.

Table 3
Costs assumed for PHES and wind turbines [46,47,50,51].

Plant type[a]	Pump-turbine investment (€M/MW)	Storage investment (€M/GWh)	Fixed O&M (% of investment)	Variable O&M (€/MWh)	Lifetime (years)
Single PHES	0.50	7.5	1.5	1.5	40
Double PHES[b]	1.00	7.5	1.5	1.5	40
Wind turbines	1.14	0.0	1.8	0.0	20

[a] Transmission costs were not considered as the Irish TSO, EirGrid, has not specified which technologies are responsible for individual costs of transmission.
[b] However, it was assumed that a double penstock would require more transmission than a single penstock, which is incorporated in the investment cost.

3.3. Size

A PHES facility has three capacities: pump, turbine, and storage. The objective in this section is to identify if any combination of these three will improve the economics of PHES. When analysing PHES, many national-scale studies have not assessed the optimum relationship between these capacities for the integration of wind

[5] All other investment costs remain the same in the analyses completed in this study and hence, they are not essential to this study.

Table 4
Fuel prices used for analyses (€/GJ) [49,52].

Crude oil ($/bbl[a])	Crude oil	Fuel oil	Gas Oil/diesel	Petrol/JP	Coal	Natural gas	Biomass
100	13.60	9.60	17.00	18.00	3.19	8.16	7.00
150	20.40	14.40	25.50	27.00	4.23	12.49	7.00

[a] Assumed exchange rate of €1 = $1.282.

power [27,29,30], particularly in relation to Ireland [34,35]. Therefore, the objective here is to identify what combination of these capacities would be most suitable for both a single and double PHES.

Firstly, a definition was created to determine the maximum feasible wind penetration (MFWP) for each scenario analysed, which was: the MFWP occurs when the CEEP exceeds 5% of the total annual wind energy produced[6]. This is illustrated graphically in Fig. 3, where it can be seen that the MFWP is 30%, 43%, and 55% for the REF2020, Single PHES, and Double PHES scenarios respectively. Using this definition, the MFWP was identified for a range of PHES storage capacities, while operating with infinite pump and turbine capacities. As a recent study in Ireland [9] has suggested that PHES storage capacities in excess of 100 GWh are now technically and economically feasible, the results were evaluated up to a storage capacity of 500 GWh. In total, nine storage capacities were considered which were, in GWh, 1.8 (reference), 3, 6, 12, 25, 50, 100, 250, and 500. After the MFWP was identified for each of these storage capacities, the hourly values were examined in each simulation to identify the pump and turbine capacity required to achieve this MFWP, which revealed a number of interesting trends.

The results in Fig. 7 indicate that as the storage capacity of a single PHES increases from the reference value of 1.8 GWh to 25 GWh, the MFWP increases rapidly from approximately 30% up to 40%. Afterwards, it slows down, taking about 125 GWh more to increase a further 10% up to 50% and over 350 GWh more to reach a wind penetration of 60%. Interestingly, the pump and turbine capacities required are very similar for the first 25 GWh, but diverge away from one another after that. By 500 GWh, the pump capacity required to reach a 60% wind penetration is approximately 4500 MW, which is around 66% larger than the 2700 MW turbine required. Similarly for a double PHES, the results in Fig. 8 indicate that it also increases the MFWP by 10% over the first 25 GWh. However, unlike a single PHES, the MFWP continues to increase at this rate up to a storage capacity of 100 GWh, when it reaches 80% of the total electricity demand. Subsequently, it takes an additional 150 GWh to rise a further 10% and finally, practically all of the electricity is provided using wind power with a storage capacity of 500 GWh. Once again, like the single PHES there is a clear divergence of capacities between the pump and turbine. However, this is even more severe for the double PHES facility as for each scenario considered the pump was approximately double the turbine capacity. After analysing the hourly operation of the systems simulated, it is clear that the pumping capacity is correlated to the excess electricity produced whereas the turbine is correlated to the power plant production it can replace. Therefore, as wind penetrations increase the pump size also increases so it can absorb more wind power which cannot be integrated onto the system. However, the turbine capacity doesn't increase this quickly, as the power plants it is replacing remain the same size. The relatively small increase in turbine capacity is thus due to the additional energy which is now stored in the PHES facility, as a result of the larger pump.

By comparing Figs. 7 and 8 (and as already discussed in Section 3.1), it is evident that a double penstock PHES can enable much higher MFWPs than a single penstock PHES. However, the results also indicate that the pump and turbine capacities required by the double PHES to achieve its MFWPs are much larger than the

[6] A sensitivity analysis has been carried out using various different definitions for the MFWP in Section 4.1.

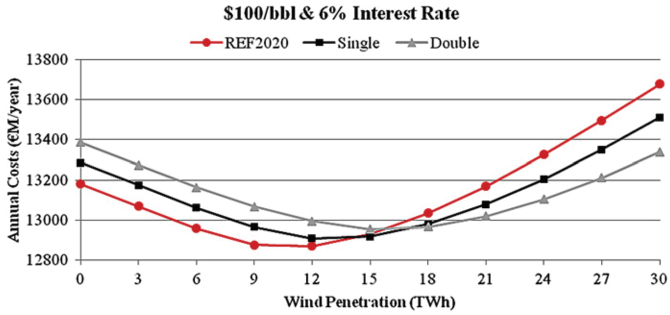

Fig. 6. Cost of Irish energy system in 2020 for the reference scenario, a 2500 MW/25 GWh single PHES, and a 2500 MW/25 GWh double PHES, for wind penetrations of 0–100% (0–30 TWh) of electricity demand, assuming fuel prices based on an oil price of $100/bbl and an interest rate of 6%.

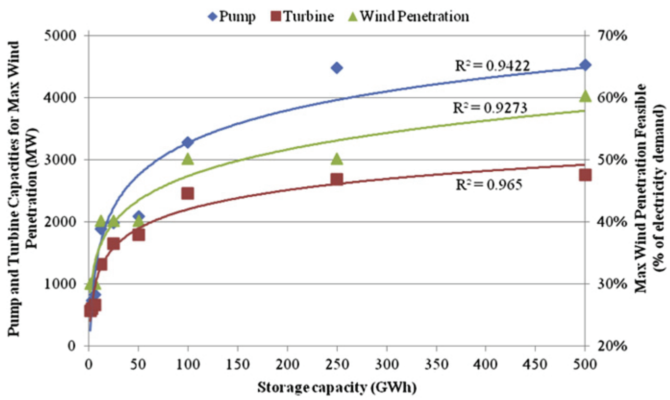

Fig. 7. Maximum feasible wind penetration on the 2020 Irish energy system when various single PHES storage capacities are added to the system with infinite power capacities. Also outlined are the corresponding pump and turbine capacities required to achieve the maximum feasible wind penetrations at each storage capacity.

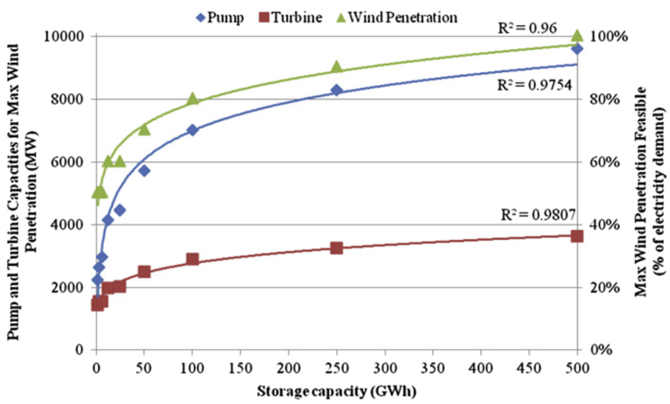

Fig. 8. Maximum feasible wind penetration on the 2020 Irish energy system when various double PHES storage capacities are added to the system with infinite power capacities. Also outlined are the corresponding pump and turbine capacities required to achieve the maximum feasible wind penetrations at each storage capacity.

Table 5
Pump and turbine capacities assumed when evaluating the economic viability of a single and double PHES system for various storage capacities.

Single PHES			Double PHES		
Pump	Turbine	Ratio ($C_{Pump}/C_{Turbine}$)	Pump	Turbine	Ratio ($C_{Pump}/C_{Turbine}$)
272	292	Reference	272	292	Reference
600	500	1.2	642	292	2.2
900	750	1.2	1650	750	2.2
1200	1000	1.2	2750	1250	2.2
1500	1250	1.2	3850	1750	2.2
1800	1500	1.2	4950	2250	2.2
2400	2000	1.2	6050	2750	2.2
3000	2500	1.2	7150	3250	2.2
3625	2500	1.45	8250	3750	2.2
4250	2500	1.7			

capacities required by the single PHES. These findings created uncertainty in relation to the economics of a single and double PHES. In Fig. 6, it was shown that the higher wind penetrations due to a double PHES did not justify the larger initial investment required when the same PHES capacities are considered. However, the capacity analysis indicates that the turbine capacities required for a double PHES can be almost half those required for the pump and also, the double PHES can achieve very high wind penetrations at smaller storage capacities compared to the single PHES. Consequently, a second cost assessment was carried out to analyse the implications of these findings.

3.4. Cost at various capacities

Based on the ratios identified between the pump and turbine capacities in Section 3.3, a selection of pump-turbine combinations (which are outlined in Table 5) were chosen to assess the operating costs over a range of different PHES storage capacities. These pump-turbine capacities were simulated for all 9 storage capacities considered and in each simulation the wind penetration was varied from 0–100% in steps of 10% on the 2020 Irish energy system. Subsequently, the cheapest wind penetration was identified for each combination of the PHES capacities, which is illustrated in Fig. 9 for a single PHES and in Fig. 10 for a double PHES.

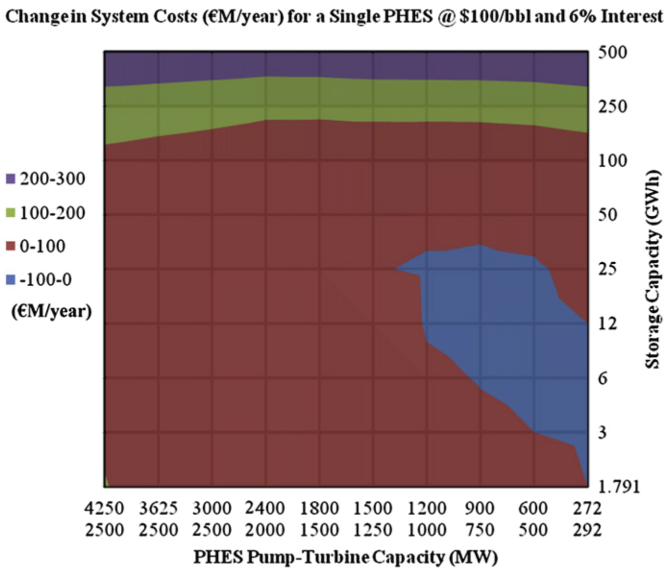

Fig. 9. Change in energy system costs when various single PHES capacities from Table 5 are added to the 2020 Irish energy system compared to the reference, assuming fuel prices corresponding to $100/bbl and an interest rate of 6%.

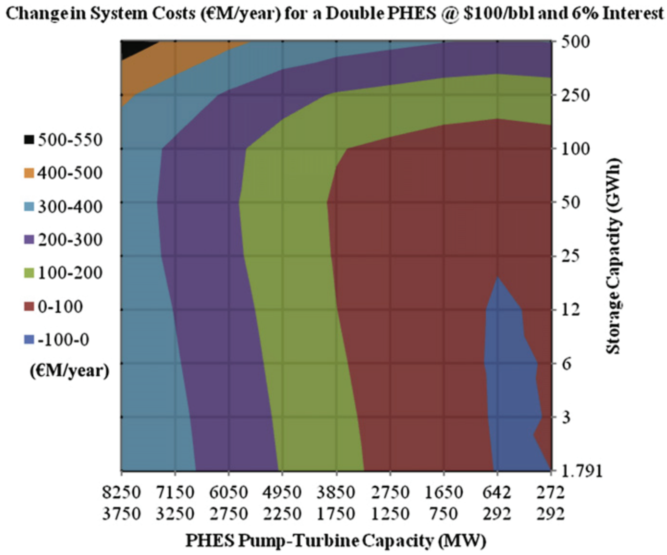

Fig. 10. Change in energy system costs when various double PHES capacities from Table 5 are added to the 2020 Irish energy system compared to the reference, assuming fuel prices corresponding to $100/bbl and an interest rate of 6%.

From the results, it is evident that the sizing of a PHES has dramatic implications on the overall operating costs of the system. Contradictory to the results identified in Fig. 6, the results in both Figs. 9 and 10 indicate that PHES could reduce the overall operating costs of the Irish energy system. However, the scale of these cost reductions are quite small and as such, Fig. 11 indicates that the cheapest scenario for both a single and a double PHES only reduced the operating costs by approximately €9 M/year and €3 M/year respectively. Hence, there were no significant economic gains from the addition of PHES. Finally, it is also clear from Figs. 9 and 10 that the total operating costs of the system can be increased dramatically if the PHES capacities are not optimised for the system in question, especially for a double PHES. Therefore, it can be concluded that wind and PHES are capable of reducing the operating costs of the Irish energy system, but under 2020 predictions the scale of these reductions and the risk associated with increasing the operating costs, PHES is not yet an attractive alternative. Finally, to further investigate the validity of these conclusions, a sensitivity analysis was completed on a range of key parameters.

4. Sensitivity analysis

The key parameters assessed in this sensitivity analysis include the definition used in Section 3.3 to define a MFWP, changes in the

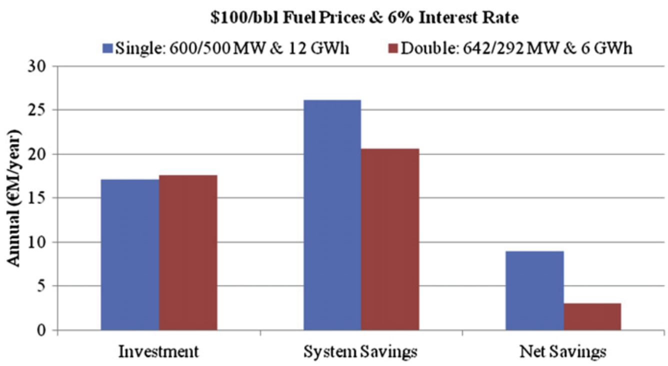

Fig. 11. The investment and savings for the single and double PHES capacities which provided the largest reduction in system costs (40% wind penetration for both), when analysed using fuel prices corresponding to $100/bbl and an interest rate of 6%.

wind energy produced, a lower interest rate on investments, an increase in fuel prices, and a lower investment cost for the double PHES facility.

4.1. Different criteria for capacities

Firstly, the relationship between the pump and turbine capacities outlined in Section 3.3 was recalculated based on a number of different criteria. In this study, the MFWP occurred when the total annual CEEP surpassed 5% of wind energy produced. For the sensitivity analyses, this was recalculated based on 10%, 15%, 20%, and 25% of wind as well as 2%, 4%, 6%, 8%, and 10% of total electricity. All of these criteria produced a similar trend to that observed in Section 3.3, although the magnitude of the MFWP did change depending on the magnitude which was deemed acceptable. In addition, a COMP coefficient, which was developed in [41] to define the MFWP based on a trade-off between increasing CEEP and decreasing PES, was also used and once again a similar pattern was identified. Therefore, it was concluded that the definition of a MFWP may alter the magnitude of pump and turbine required, but the diverging trend between pump and turbine capacities as the MFWP increases is consistent. Overall, the limiting factor used in this study, which was a maximum CEEP equivalent to 5% of wind, is a very austere definition and hence many of the others would most likely increase the savings associated with additional energy storage.

4.2. Wind generation

There are two aspects to wind which were analysed in this sensitivity analysis: hourly distribution and total annual generation. The hourly wind distribution data in this study was based on historical data recorded in Ireland from the year 2009 [53]. To ensure that this particular wind distribution was not responsible for the conclusions made in this study, the results were repeated based on hourly wind data recorded in Ireland from the year 2007. Using this data, there was no significant change in the trends identified in this study. Also, changes in the total annual electricity generation from wind were assessed. As the installed wind capacity in Ireland has increased by an average of 35% each year between 1999 and 2009, it is difficult to conclude what variation occurs for in total wind production from one year to the next using historical data. However, by analysing Danish wind data from 2003 to 2008[7] [54], it is evident that the total wind power produced from the same capacity of wind turbines can vary by up to 20% from one year to the next. Therefore, this has been used as a proxy in this study. The annual operating costs were recalculated based on an expected wind production which produced an actual wind production of ±20% for three different scenarios: the REF2020 scenario with no additional PHES, the REF2020 system with a 2500 MW 25 GWh single PHES facility, and finally the reference REF2020 scenario with a 2500 MW 25 GWh double PHES facility. As expected, Fig. 12 indicates that a 20% increase in the expected wind production will reduce the annual operating costs for each scenario while a 20% decrease in wind production will inflate costs. Due to the insignificant role of additional PHES below a wind penetration of 9 TWh (30%), the change in annual costs is the same for all three scenarios up until this point. Afterwards, the reference scenario shows the least variation in costs, followed by the single PHES, and the double PHES shows the largest deviation in annual operating costs due to a change in annual wind production. However, for all three scenarios the increase in costs for a +20% wind production is very similar to the corresponding decrease in costs due to a −20% production. In fact, in all scenarios simulated the increase in annual operating costs was never greater than the corresponding reduction in annual

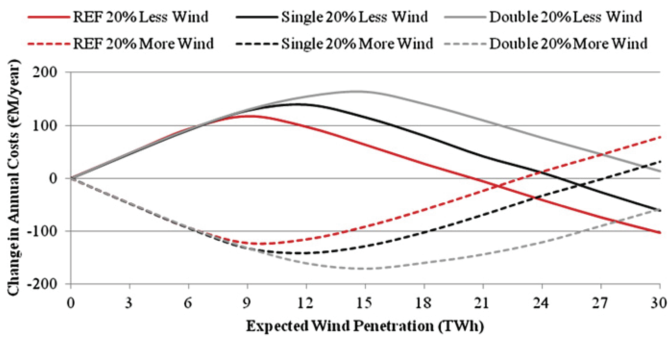

Fig. 12. Change in annual costs (using a 6% interest rate and $100/bbl fuel prices) for an expected wind production of 0–30 TWh (0–100%) for the 2020 reference scenario on its own, with a single 2500 MW 25 GWh PHES, and with a double 2500 MW 25 GWh PHES.

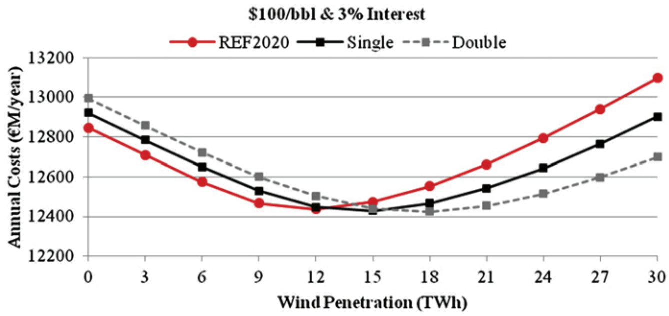

Fig. 13. Cost of Irish energy system in 2020 for the reference scenario, a 2500 MW/25 GWh single PHES, and a 2500 MW/25 GWh double PHES, for wind penetrations of 0–100% (0–30 TWh) of electricity demand assuming fuel prices based on an oil price of $100/bbl and an interest rate of 3%.

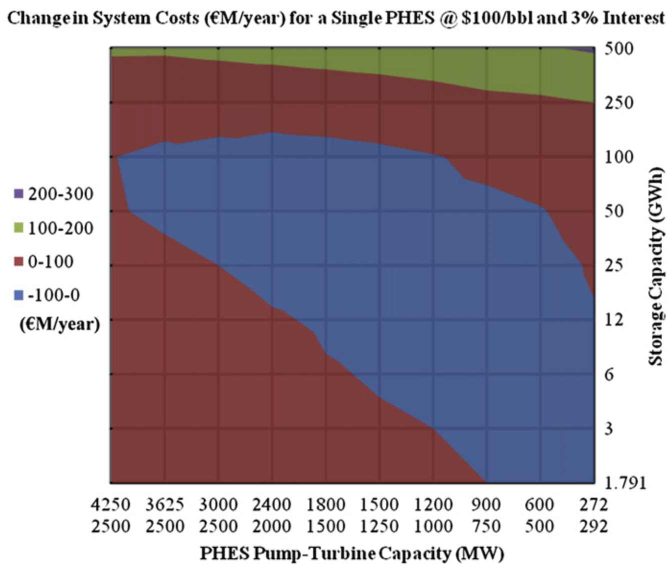

Fig. 14. Change in energy system costs when various single PHES capacities from Table 5 are added to the 2020 Irish energy system compared to the reference, assuming fuel prices corresponding to $100/bbl and an interest rate of 3%.

[7] The installed wind capacity in Denmark was practically the same from 2003 to 2008, as the maximum and minimum capacity recorded for each of these years was 3116 MW and 3163 MW.

operating costs. This indicates that over the 40 year lifetime of a PHES facility, the additional costs that occur during years of low annual wind production should be cancelled out by years of savings in years of high annual wind production.

4.3. Interest rate of 3%

The economic calculations in this study were based on an interest rate of 6%, but it could be argued that a 3% interest rate is more applicable due to the 40 year lifetime of PHES and the societal gains from utilising more wind energy. Therefore, the costs were recalculated using a 3% interest rate instead, which are outlined in Fig. 13 for the 2500 MW, 25 GWh facility. As the initial investment costs for wind power and PHES are relatively high, a comparison between Figs. 6 and 13 indicates that a 3% interest would significantly improve the economic feasibility of a wind-PHES system in Ireland. This is even more apparent for the double penstock PHES, which could enable a wind penetration of approximately 60% using a 3% interest rate at a similar cost to the REF2020 scenario, which only has a wind penetration of 40%. Based on the trend identified here, the costs were also recalculated for the range of PHES capacities discussed in Sections 3.3 and 3.4. As outlined in Figs. 14–16, with an interest rate of 3% the optimum capacities for both a single and double penstock PHES could reduce the overall operating costs of the Irish energy system by approximately €25 M/year and €35 M/year respectively in 2020. In addition, the size of the PHES facility which provides the most economical scenario has increased significantly to 1800/1500 MW and 50 GWh for the single PHES and to 2750/1250 MW and 50 GWh for the double PHES.

4.4. Fuel price of $150/bbl

By 2020, global fuel prices are expected to reach an oil price equivalent of $100/bbl [49]. However, as already experienced in the past, fuel prices can be extremely unpredictable due to many political and supply concerns [55]. To demonstrate the consequences of a fuel price increase, the results were recalculated based on an oil price of $150/bbl and an interest rate of 6%, with corresponding prices for other fuels outlined in Table 4. The results from the analysis were very similar to those observed for an interest rate

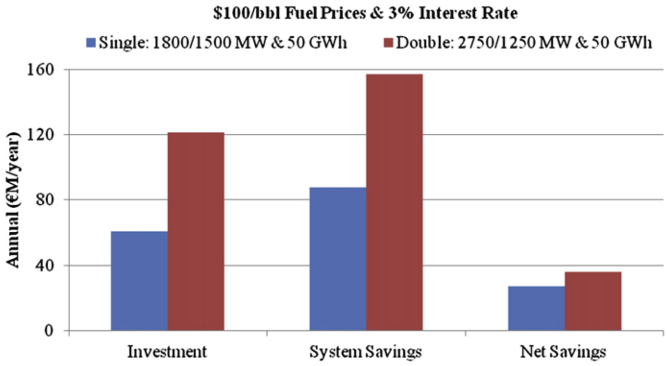

Fig. 16. The investment and savings for the single and double PHES capacities which provided the largest reduction in system costs for fuel prices corresponding to $100/bbl and an interest rate of 3%.

of 3% and fuel prices corresponding to $100/bbl of oil. Once again a 2500 MW and 25 GWh double penstock PHES could enable a 60% wind penetration at a similar cost to a 40% wind penetration on the reference scenario, similar to the results presented in Fig. 13. Also, the optimum capacities for the single and double PHES were the same when using $150/bbl and 6% as those identified when using $100/bbl and 3%, which was 1800/1500 MW and 50 GWh for the single PHES and 2750/1250 MW and 50 GWh for the double. Once again, the reductions in operating costs in 2020 were €25 M/year and €35 M/year for the single and double respectively. The only key difference between the results was the scale of initial investments required. At a 3% interest rate and $100/bbl the initial investment costs for the single and double PHES were €60 M/year and €120 M/year respectively. However, at 6% and $150/bbl the investment costs were €85 M/year and €170 M/year, thus increasing the risk associated with constructing PHES.

4.5. Double PHES investment costs

To complete this economic assessment, it was assumed that the double penstock PHES (€1 M/MW) would cost twice as much to

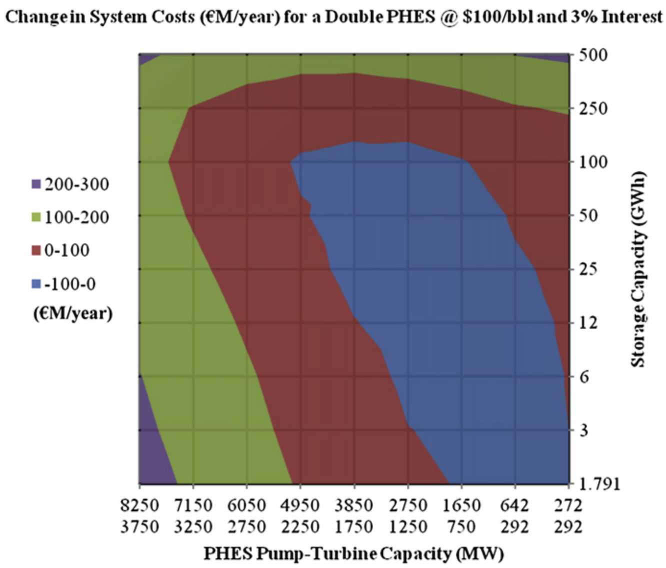

Fig. 15. Change in energy system costs when various double PHES capacities from Table 5 are added to the 2020 Irish energy system compared to the reference, assuming fuel prices corresponding to $100/bbl and an interest rate of 3%.

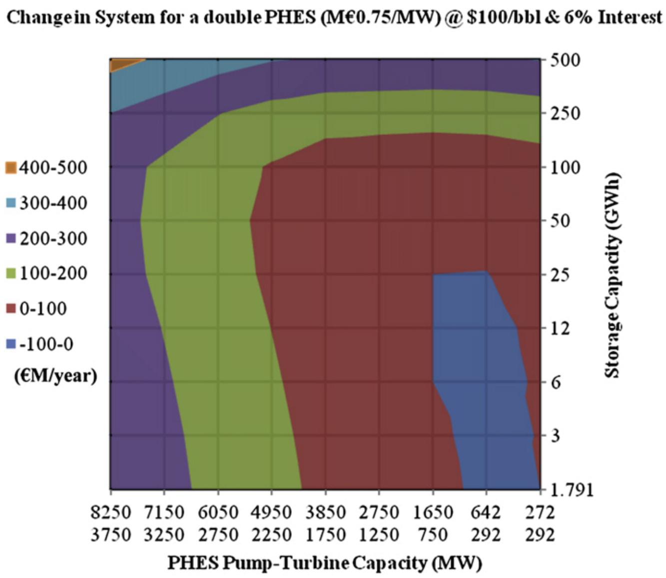

Fig. 17. Change in energy system costs when various €0.75 M/MW double PHES capacities from Table 5 are added to the 2020 Irish energy system compared to the reference, assuming fuel prices corresponding to $100/bbl and an interest rate of 6%.

Table 6
Capacity and cost assumptions for the alternative scenarios considered on the 2020 Irish energy system.

Alternative	Size	Unit	Costs per unit (€M)	Lifetime (years)	Fixed O&M (% of investment)	Total costs (€M/year)	Ref
Heat pumps	**135**	**MW_e**	**1.2**	**15**	**0.6**	**17.5**	[56]
CHP						**17.6**	
Convert PP	125	MW_e	0.80	30	2.00	9.3	[47,56]
Thermal storage	1	GWh	1.34	20	1.00	0.13	[57]
Peak boilers	125	MW_{th}	0.15	20	3.00	2.2	[56]
Network	15	km	2.00	40	1.00	2.3	[58]
Central heating	1500[a]	Conversions	0.0054	40	0.90	0.6	[56]
Heat exchangers	15,000	Customers	0.00275	40	0.90	3.11	[56]
Single PHES						**17.1**	
Pump	330	MW_e	0.25	40	1.5	6.7	[46,47]
Turbine	210	MW_e	0.25	40	1.5	4.2	[46,47]
Storage	10.2	GWh	7.50	40	1.5	6.2	[3]
Double PHES						**17.6**	
Pump	370	MW_e	0.50	40	1.5	15.07	[46,47]
Turbine	0[b]	MW_e	0.50	40	1.5	0.00	[46,47]
Storage	4.2	GWh	7.50	40	1.5	2.57	[3]

[a] Equates to 10% of total customers.
[b] Capacity required is already installed in Ireland.

construct compared to the single PHES (€0.5 M/MW). This assumption was based on the additional penstock, transmission, housing, and communication systems that would be necessary in a double PHES. However, no evidence was found to support this assumption and therefore the results were analysed for a double PHES investment cost of €0.75 M/MW also. Fig. 17 indicates that if a double PHES can be constructed at €0.75 M/MW, then it would become economically viable over a larger range of capacities than those reported in Section 3.4. However, the results do not change as dramatically as those already displayed for a lower interest rate of 3% and for higher fuel prices corresponding to $150/bbl (see Fig. 15). To conclude, it is important that the uncertainty surrounding the PHES construction costs is considered when assessing the results in this study, but the implications of these seem less severe than those reported for the interest rate and the fuel prices.

4.6. Summary

To recap briefly, this sensitivity analysis has verified that the optimum pump and turbine capacities diverge as wind penetrations increase. Also, the wind distribution does not alter the results significantly and although any reduction in the total annual electricity generation from wind would increase the operating costs, this is equivalent to the savings identified due to a corresponding increase in annual wind generation. Finally, the economic viability of PHES in conjunction with wind power is significantly enhanced by offering a 3% interest rate for the initial investment required or if global fuel prices reach $150/bbl. Under both of these scenarios and based on the costs assumed in Table 3, a double PHES system would enable a 60% wind penetration on the Irish energy system at the same cost as a 40% wind penetration in the reference scenario. In addition, the uncertainty surrounding the additional investment required for a double penstock PHES is important to consider when assessing the results in this section, although the sensitivity analysis indicates that the interest rate and fuel price assumptions have a greater impact on the results. Finally, before concluding that PHES is a suitable alternative for Ireland, it must also be compared to alternative technologies that could also be utilised.

5. Comparison to alternatives

As outlined in Section 3.4, for $100/bbl the cheapest single and double penstock capacities both corresponded to an investment of approximately €17 M/year. Therefore, the results from the PHES analysis were compared to the same investment in two other technologies: domestic heat pumps (HP) and the creation of a district heating network utilising a new combined heat and

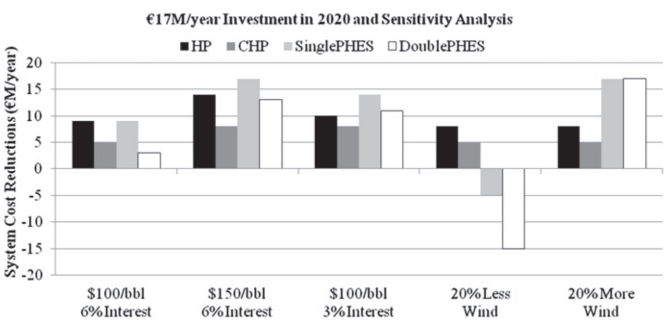

Fig. 18. Annual system cost reductions compared to reference when approximately €17 M/year is invested in domestic heat pumps, a CHP system with district heating, as well as the optimum single and double PHES facilities from Section 3.4. All capacity and cost assumptions are outlined in Table 6 and a wind penetration of 40% was used as it was the most economical for each alternative.

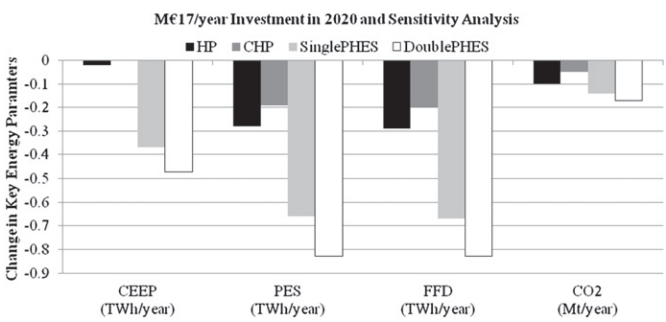

Fig. 19. Change in key energy parameters compared to reference when approximately €17 M/year is invested in domestic heat pumps (HP), a CHP system with district heating (CHP), as well as the optimum single and double PHES facilities from Section 3.4. All capacity and cost assumptions are outlined in Table 6 and a wind penetration of 40% was used as it was the most economical for each alternative.

power (CHP) plant. The capacities, costs, and investments required for these alternatives are outlined in Table 6.

As displayed in Fig. 18, under predicted 2020 fuel prices of $100/bbl and a 6% interest rate, an investment of €17 M/year in domestic heat pumps provides the same savings for the Irish energy system as an optimum single PHES unit. The CHP alternative provided larger savings than the optimum double penstock PHES, but it was not as cost-effective as the optimum single PHES for 2020. However, it should be stressed that the PHES capacities have been optimised in this paper, while the CHP capacities are just estimates based on the heating demands that have to be met [58]. Once again, the sensitivity analysis discussed previously was repeated on these alternatives. As outlined in Fig. 18, an increase in fuel prices to $150/bbl or a reduced interest rate of 3% will improve the savings associated with all four alternatives. Although the single PHES is the most economical alternative when this occurs, it is the double PHES which is the most sensitive to changes in fuel prices and interest rates, which is most likely due to the additional wind energy it enables. Finally, each of the scenarios were analysed for a 20% reduction and increase of total annual wind energy generation. As already outlined in Section 4.2, PHES is very sensitive to changes in the total annual electricity generation from wind, which is evident once again in Fig. 18. In contrast, the cost savings related to the HP and CHP scenarios are practically the same for the reference as those calculated for a ±20% change in annual wind generation.[8] Consequently, the results indicate that even if optimum capacities of PHES are identified, there are alternatives that are as cost-effective under predicted 2020 conditions and which are less sensitive to changes in fuel prices, interest rates, and annual wind production.

Nonetheless, when assessing energy alternatives, it is not only important to consider their economic implications, but also the affect which they have on energy consumption. Displayed in Fig. 19 are the changes in a number of key energy parameters when each of the alternatives proposed are introduced to the 2020 Irish energy system. From these results it is evident that PHES improves Ireland's security of supply more than the HP or CHP scenarios. To do this, PHES reduces CEEP by enabling the integration of more wind power and thus correspondingly reduces the PES, fossil fuel demand (FFD), and CO_2 emissions. Comparing the alternatives, it is clear that PHES reduces the FFD more than the HP or CHP scenarios. Therefore, it could be argued that the additional cost of PHES is worth the larger reductions in FFD, due to the socio-economic benefits for Ireland such as increased security of supply and less CO_2 emissions. These benefits were considered in the results by using a predicted CO_2 cost of $50/t, but since this is a global guideline [49] and Ireland is the 12th largest net importer of energy in the world (relative to consumption) [59], this assumption may not be sufficient to reflect these benefits. In summary, PHES may not be the most economical alternative for 2020, but its additional socio-economic benefits could be worth the additional cost.

6. Conclusions

To conclude, this paper has outlined that wind power and PHES can be used together to reduce the operating costs of the Irish energy system. However, under the conservative assumption that societal benefits (such as less pollution, improved health, increased job creation, and a better balance of payment) are accounted for with a predicted CO_2 price of $50/t, the savings calculated are too small based on a conventional 6% interest rate and the predicted fuel prices for 2020 to warrant an investment in PHES, especially as it could also increase the operating costs. However, if the interest rate for assessing PHES is reduced to 3% to reflect its lifetime of 40 years and the socio-economic benefits of additional wind, then PHES can enable up to 20% additional wind in Ireland without increasing the annual operating costs of the energy system. Equally, if global fuel prices increase to a level which reflects $150/bbl of oil, then the same outcome will occur.

More specifically in relation to PHES, the analysis identified a divergence between the pump and turbine capacities required for PHES when it is used to integrate increasing amounts of wind power. As wind penetrations increase, the pumping capacity required also increases so the PHES can soak up excessive wind production, but the turbine capacity doesn't increase as quickly because the power plant production which it is replacing remains the same. The slight increase in turbine capacity required is primarily related to the additional energy available in the PHES due to the increased pumping capacity. Finally, a single penstock and double penstock operating strategy have been analysed throughout this study to assess if the additional capacity required for a double penstock system is offset by the additional wind penetrations feasible. The results suggest that as wind penetrations increase, the double penstock system is a more economical alternative and it enables Ireland to utilise more indigenous wind energy. However, it is also more sensitive to changes in fuel prices, interest rates, and total annual wind production. The double penstock operating strategy also illustrated how ancillary services can be provided when integrating wind power onto modern electric grids. Although PHES is used in this study to create a flexible supply and demand portfolio in Ireland for the integration of wind, other alternatives could be used in a similar way such as electric vehicles, the electrification of heat, thermal storage, and many more. Hence, alternatives were briefly investigated towards the end of this research also.

The two alternative technologies to PHES which were assessed in this study were domestic heat pumps and a district heating network with CHP. After comparing the operating costs of the Irish energy system with these alternatives to those obtained with PHES, it was evident that domestic heat pumps are just as economical as an optimum PHES in Ireland based on projected fuel prices for 2020 and an interest rate of 6%. In addition, the savings associated with domestic HP are not as sensitive to changes in fuel prices, interest rates, or annual wind productions as PHES and thus, would be a more attractive investment (although this study did not investigate the consequences of variations in the annual heat demand). In addition, the PHES capacities proposed have been optimised over the course of this study, but the HP and CHP capacities proposed are only estimates based on the demands that have to be met. Conversely though, the single and double PHES systems can integrate more indigenous renewable energy as well as provide larger reductions in PES, FFD, and CO_2 than the HP and CHP scenarios. Therefore, these additional socio-economic benefits associated with PHES may be worth the additional cost. As a result, a more detailed analysis of these alternatives is necessary, Irish specific energy-planning costs and indices which reflect the socio-economic benefits of indigenous renewable energy production need to be established, and it is essential that numerous alternatives across all sectors of an energy system are considered when evaluating solutions for the future.

There are also a number of limitations which need to be considered when interpreting the results of this study. Firstly, it is clear that PHES is a key asset for wind energy as it enables the grid to operate securely while also incorporating high wind penetrations. However, in the future, wind turbines and decentralised plants could make a more significant contribution to grid stabilisation and hence the value of PHES could be diminished. Also, the EnergyPLAN

[8] It should be noted that this sensitivity analysis did not assess fluctuations in the annual heat demand that occur due to hot and cold years, which could affect the results in the HP and CHP scenarios.

tool used in this study is a scenario tool that simulates an energy system on an hourly basis, which does not account for the dispatch of individual power plants or the current flow on individual power lines. Therefore, a more detailed energy tool will be required to fully establish the implications of using different grid constraints on the Irish energy system. This type of study would also provide another essential comparison between the alternatives considered i.e. the role out of domestic heat pumps could require less transmission upgrades than the construction of large centralised PHES facilities. Overall, the ultimate necessity for the future which can be drawn from this study is the demand for more detailed analyses of a wide range of alternatives for an energy system, as significant savings can be realised using existing technologies especially by integrating the electricity, heat, and transport sectors.

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Appendix H

Connolly D, Lund H, Mathiesen BV, Finn P, Leahy M. Practical operation strategies for pumped hydroelectric energy storage (PHES) utilising electricity price arbitrage. Submitted to the Journal of Energy Policy.

Energy Policy 39 (2011) 4189–4196

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Practical operation strategies for pumped hydroelectric energy storage (PHES) utilising electricity price arbitrage

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ARTICLE INFO

Article history:
Received 19 January 2011
Accepted 14 April 2011
Available online 7 May 2011

Keywords:
Pumped hydroelectric
Energy storage
Electricity market

ABSTRACT

In this paper, three practical operation strategies (24Optimal, 24Prognostic, and 24Hsitrocial) are compared to the optimum profit feasible for a PHES facility with a 360 MW pump, 300 MW turbine, and a 2 GWh storage utilising price arbitrage on 13 electricity spot markets. The results indicate that almost all (~97%) of the profits can be obtained by a PHES facility when it is optimised using the 24Optimal strategy developed, which optimises the energy storage based on the day-ahead electricity prices. However, to maximise profits with the 24Optimal strategy, the day-ahead electricity prices must be the actual prices which the PHES facility is charged or the PHES operator must have very accurate price predictions. Otherwise, the predicted profit could be significantly reduced and even become a loss. Finally, using the 24Optimal strategy, the PHES profit can surpass the annual investment repayments required. However, over the 5-year period investigated (2005–2009) the annual profit from the PHES facility varied by more than 50% on five out of six electricity markets considered. Considering the 40-year lifetime of PHES, even with low investment costs, a low interest rate, and a suitable electricity market, PHES is a risky investment without a more predictable profit.

1. Introduction

Many studies have analysed and compared a wide range of energy storage alternatives for future energy systems based on electricity (Connolly and Leahy, 2010; Ekman and Jensen, 2010; Gonzalez et al., 2004; Ibrahim et al., 2008; Kaldellis et al., 2009; Kondoh et al., 2000), heat (Connolly and Leahy, 2010; Lund and Clark, 2002; Mathiesen and Lund, 2009), and even transport (Kempton and Tomic, 2005; Lund and Kempton, 2008). Among other things, these studies indicate that pumped hydroelectric energy storage (PHES) is the most utilised and mature large-scale energy storage technology currently available for electricity (Connolly and Leahy, 2010; Ekman and Jensen, 2010; Gonzalez et al., 2004; Ibrahim et al., 2008), but its major drawback is the lack of suitable sites (Ekman and Jensen, 2010; Ibrahim et al., 2008; Kaldellis et al., 2009; Kondoh et al., 2000). However, recent reports show that there is over 7 GW of new PHES plants planned in the EU alone (Deane et al., 2010), there are more suitable PHES sites available than conventionally assumed (Connolly and MacLaughlin, 2010; Connolly et al., 2010; Spirit of Ireland, 2009; Yang and Jackson, 2011), and PHES can enable higher wind penetrations at lower costs onto some conventional power systems (Benitez et al., 2008; Kapsali and Kaldellis, 2010; Perez-Diaz et al., 2010). Hence, PHES will have a large role in future electricity grids. Therefore, this study investigates if it is possible to profit from a PHES facility on existing electricity markets.

A detailed description of PHES's operation, its parameters, existing facilities, and proposed sites is available from the American Society of Civil Engineers (1996), Connolly and Leahy (2010), and Deane et al. (2010). In a deregulated electricity market, an energy storage facility is typically defined as a merchant unit, which maximises its profits subject to technical constraints, or as a system asset, which is managed by the system operator to assist in maintaining system security and in reducing operational costs (Nyamdash et al., 2010). As a merchant unit, an energy storage facility will earn most of its revenue from the sale of electricity to the market (Loisel et al., 2010; Nyamdash et al., 2010). Hence, this work investigates how an energy storage facility can operate to maximise its revenue from the purchase of low-cost off-peak electricity and the sale of high-cost peak electricity on the market.

Previous studies have also assessed the economic viability of energy storage as a merchant unit. Furusawa et al. (2007) analysed energy storage as a demand side management tool

Abbreviations: EA, Ex-ante (predicted day-ahead) electricity prices in Ireland; EP2, Ex-post (final) electricity prices in Ireland; PHES, pumped hydroelectric energy storage

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doi:10.1016/j.enpol.2011.04.032

Nomenclature

Symbols

C_P capacity of the PHES pump (MW)
C_S capacity of the PHES storage (GWh)
C_T capacity of the PHES turbine (MW)
I_P investment cost of pump (M€/MW)
I_S investment cost of storage (M€/GWh)
I_T investment cost of turbine (M€/MW)
I_{Annual} total annual repayments for PHES investment (M€)
K constant (see Eq. (3))
MAXhour hour that contains the maximum electricity price (h)
MC_P marginal operating cost of pumping for the PHES facility (€/MWh)
MC_{prod} marginal operating cost for the PHES facility (€/MWh)
MC_G marginal operating cost of generating for the PHES facility (€/MWh)
MINhour hour that contains the minimum electricity price (h)
$O\&M_{Fixed}$ fixed operation and maintenance costs (% of investment)
$\overline{P}$ average price over the next 24 h (€/MWh)
P_{buy} buying price for the PHES pump (€/MWh)
P_{Max} available pump capacity at the minimum price hour (MW)
P_{sell} selling price for the PHES turbine (€/MWh)
T_{Max} available turbine capacity at the maximum price hour (MW)
i interest rate (%)
n lifetime of PHES facility (years)
ΔP price difference (€/MWh)
η_P efficiency of the PHES when pumping (%)
η_G efficiency of the PHES when generating (%)

utilising electricity prices for domestic scale consumers. Sioshansi et al. (2009) investigated the arbitrage value of small-scale energy storage for the PJM market in the USA, while Walawalkar et al. (2007) analysed the potential of sodium sulphur batteries and flywheel energy storage systems in New York state's electricity market. Kazempour et al. (2009b) completed an economic comparison between emerging (sodium sulphur battery) and traditional (PHES) electric energy storage technologies assuming perfect pricing foresight one week in advance. Lund and Salgi (2009) along with Lund et al. (2009) analysed various operating strategies and the corresponding profits from a compressed air energy storage on the Danish electricity market, Kazempour et al. (2009a) created a scheduling tool for a group of hydro plants supplemented by a PHES facility, Figueiredo and Flynn (2006) optimised the size of two specific PHES plants in Alberta, Canada, based on electricity arbitrage profits. Muche (2009) developed a model based on the German electricity market which included future price-based unit commitment planning when evaluating PHES. This study outlined the importance of considering the scope of future actions when evaluating PHES. Finally, Kanakasabapathy and Swarup (2010a, 2010b) created a bidding strategy for PHES based on day-ahead market prices, but assumed that pumping always takes place before generation, which may not be suitable for all electricity markets.

To compliment these studies, the objectives of this work are to identify the maximum feasible profit that a PHES facility can achieve on an electricity market with perfect pricing foresight for 1 year, to compare this to a range of realistic operating strategies which could be put into practise, and to investigate the economic viability of a PHES facility utilising price arbitrage on various electricity markets.

2. Methodology

In total four different operation strategies were created for energy storage on a liberalised electricity market, which are called 'Optimal', '24Historical', '24Prognostic', and '24Optimal'. The Optimal operation strategy tries to find the maximum theoretical operational income given an hourly time series of electricity prices over a 1-year period. The algorithm can be summarised by repeating the following steps (this is analytically illustrated in the Appendix):

1. Identify the hour of the maximum electricity price (MAXhour) in the spot market price series. Such hour is given priority when operating the turbine. (In the following iterations, hours already identified are disregarded and the hour of the remaining maximum price is picked).
2. In this step, the hours before and after MAXhour are examined to identify the earliest hour before MAXhour and the latest hour after MAXhour where the pump can operate. This range constitutes the time space in which recharging/discharging is possible.
   a. Before MAXhour: If the pump is going to operate before MAXhour, then there must be space within the reservoir at the time the pump is operated so energy can be stored for discharging during MAXhour. If the reservoir is full, then the pump could not operate and hence, the earliest hour before MAXhour which the pump can operate is the hour after the last time the storage was full.
   b. After MAXhour: If the pump is going to operate after MAXhour, then there must be energy in the reservoir so that it can be used by the turbine during MAXhour. If the reservoir is empty, then there would be no energy for the turbine to use at MAXhour which could be replaced by the pump at a later date. Hence, the latest hour after MAXhour which the pump can operate is the hour before the storage is emptied.
   c. The range can very well constitute only the MAXhour itself, in which case the plant will not operate.
3. Identify the minimum electricity price, MINhour, within the range defined in step 2. Such hour is given priority when operating the pump. (In the following iterations, hours already identified are disregarded and the hour of the remaining minimum price is picked.)
4. Calculate the marginal operating cost (MC_{prod}) using Eq. (1) based on the minimum price (P_{buy}) found in step 3. If the maximum electricity price (P_{sell}) found in step 1 is higher than the marginal production cost (MC_{prod}), the calculation proceeds to step 5.

$$MC_{prod} = MC_G + [(P_{buy} + MC_P)/(\eta_P * \eta_G)] \quad (1)$$

5. Determine the "operation bottlenecks" in the range between the maximum and minimum prices. In the case that 1 h of pump operation is compensated for by exactly 1 h of turbine operation there is no bottleneck. Otherwise, the turbine and/or the pump may have to partly load and the bottleneck is identified as the minimum of the following four considerations:
   a. Available turbine capacity at the maximum price hour.
   b. Available pump capacity at the minimum price hour.

c. The minimum free storage space if the pump operation takes place before the turbine operation.
d. The minimum storage content in case the pump operation succeeds the turbine operation.

6. Operate the turbine at the hour of maximum price and the pump at the hour of minimum price by the capacity determined in step 5 and update the storage content. In case the turbine has reached its full capacity, the hour is disregarded in the following iterations. Similarly, in case the pump has reached its full capacity.
7. Iterate back to step 1 until the period of 1 year is completed.

In practise, energy storage plants will not be able to implement the above-mentioned Optimal operation strategy since the fluctuations of spot market prices in the coming hours and days are not known for a whole year. Therefore, three additional strategies were created, which could be utilised by an energy storage operator:

1. 24Historical strategy: Decisions on buying and selling electricity are solely based on the knowledge of the average price over 12 historical and 12 future prices.
2. 24Prognostic strategy: Decisions on buying and selling electricity are based on the average price of the upcoming 24 h. Such a strategy requires the presence of good price prognoses.
3. 24Optimal strategy: Operation of the energy storage facility is optimised using the same procedure as the optimal strategy, but it optimises the energy storage for the next day only. After optimising the first day, the procedure then repeats itself until the entire year is complete. Once again, such a strategy requires the presence of good price prognoses.

The concept behind the historical and prognostic strategies is to take the average price of a user-specified period and bid on the market correspondingly. The bid on the market occurs so that the price difference between the buying and bidding prices is equally distributed around the average price. The price is updated on an hourly basis, as opposed to a fixed average over a specified period. This implicitly assumes that the system operator can update market bids on an hourly basis, which distinguishes the 24Prognostic and the 24Optimal strategies, as the latter uses a fixed 24-h time period, i.e. the next day. The concept of the prognostic and historical strategies for a 24-h period is demonstrated in Fig. 1. Here, the centre line represents the price average for the upcoming 24-h period (i.e. 24Prognostic strategy), which is updated every hour for the next 24 h. Based on that, the buying and selling prices are defined.

The PHES operates if the selling price, P_{sell}, is large enough to cover the cost of buying electricity, P_{buy}, along with the losses incurred during pumping, η_P, and generating, η_G, as well as the variable *O&M* costs incurred during pumping MC_P, and generation, MC_G. Therefore, considering Eq. (1), for the PHES to operate the smallest electricity arbitrage that can occur is

$$P_{sell} = \frac{P_{buy}}{\eta_P \eta_G} + \frac{MC_P}{\eta_P \eta_G} + MC_G \tag{2}$$

Assuming that K is a constant that includes the variable operational costs for the pump and turbine:

$$K = MC_P + \eta_P \eta_G MC_G \tag{3}$$

The minimum distance, ΔP, between the buying/selling lines and the average price, $\overline{P}$, is, respectively

$$\Delta P = \overline{P} - P_{buy} \tag{4}$$

$$\Delta P = P_{sell} - \overline{P} \tag{5}$$

Therefore, the minimum distance required between the buying/selling lines and the average price can be calculated analytically based on the following equation:

$$\Delta P = \frac{\overline{P}(1-\eta_P \eta_G) + K}{1 + \eta_P \eta_G} \tag{6}$$

Two deterministic modelling tools have been used to analyse the operation of a PHES facility on an hourly basis over 1 year. The first tool is called EnergyPLAN (Aalborg University, 2010) and it was developed by Lund et al. (2009) to evaluate two practical operation strategies for compressed air energy storage, which were called '24Historical' and '24Prognostic'. Here, the EnergyPLAN tool is used to model these two strategies when applied to PHES. In addition, a new operating strategy called '24Optimal' has been developed in MATLAB. Finally, the 'Optimal' strategy which was also developed in Lund et al. (2009), was simulated in both tools to model PHES and subsequently, their results were compared to ensure they were both operating in the same way.

Using each of the strategies defined above, the profit feasible using electricity price arbitrage for a PHES facility with the parameters outlined in Table 1 was identified for each of the 13 electricity markets displayed in Table 2. Previous studies have indicated that these are the typical capacities of existing PHES facilities (American Society of Civil Engineers, 1996; Deane et al., 2010), while other studies have illustrated that these capacities can also be constructed in the future (Connolly and MacLaughlin, 2010; Connolly et al., 2010). Also, using a pumping capacity of 360 MW and a turbine capacity of 300 MW enables the PHES

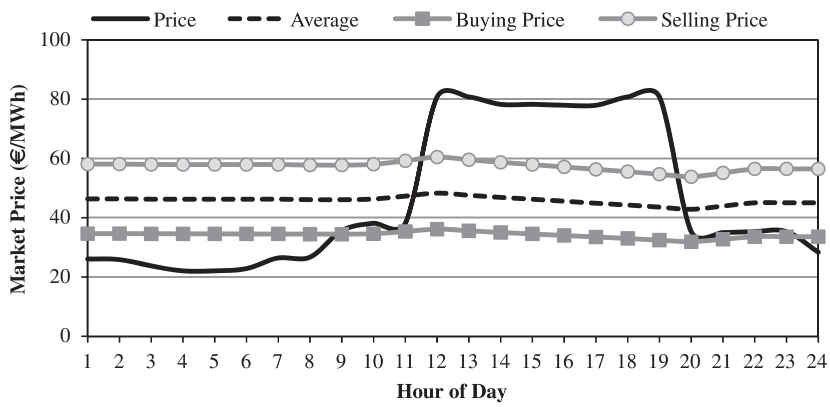

Fig. 1. This graph illustrates the average, buying, and selling prices for the 24Prognostic strategy, which is updated every hour for the next 24 h. The same concept is used for the 24Historical strategy, but 12 historical hours and 12 future hours are used to define the average, buying, and selling price.

facility to both charge and discharge for approximately 6 h and hence, the facility can take advantage of daily low and high prices which typically occur on an electricity market.

Table 1
Capacity assumptions for the PHES facility.

PHES parameter	Value (unit)
Pumping capacity	360 (MW)
Turbine capacity	300 (MW)
Storage capacity	2000 (MWh)
Pumping efficiency[a]	92 (%)
Generating efficiency[a]	92 (%)

[a] American Society of Civil Engineers (1996).

3. Results and discussion

Firstly, the profit for the energy storage facility was identified using all four operating strategies for each of the electricity markets, as displayed in Fig. 2. It is clear that the profit feasible varies dramatically from one market to the next due to the varying degrees of electricity price arbitrage on each market. This is caused by a range of issues which affect the market price such as the varying market structures, regulations, demands, and plant portfolios. Analysing the implications of these on the market price is beyond the scope of this study and hence, it could be examined in future research. Regardless of the profit obtained, however, it is evident from the results that the 24Optimal strategy can obtain almost all of the profit that is feasible from each market: on average the 24Optimal strategy obtained 97% of the profit which

Table 2
Electricity market data used for analysing the profit feasible from the PHES facility described in Table 1.

Electricity market operator	Region	Symbol	Link
Australian Energy Market Operator	New South Wales, Australia	AU	http://www.aemo.com.au
Energy Exchange Austria	Austria	AA	http://en.exaa.at
Elexon[a]	Britain	GB	http://www.elexon.co.uk
Alberta Electric System Operator	Alberta, Canada	CAA	http://ets.aeso.ca
Independent Electricity System Operator	Ontario, Canada	CAO	http://www.ieso.ca
Single Electricity Market Operator	Island of Ireland[b]	IE	http://www.sem-o.com
Gestore Mercati Energetici	Italy	IY	http://www.mercatoelettrico.org
Electricity Authority	New Zealand, North Island	NZN	http://www.ea.govt.nz
Nordpool Spot	Nordic region[c]	NP	http://www.nordpoolspot.com
Operador do Mercado Ibérico de Energia	Portugal	PL	http://www.omip.pt
Operador del Mercado de Electricidad	Spain	SP	http://www.omel.es
ISO New England	New Hampshire, New England, USA	USANE	http://www.iso-ne.com
New York ISO	Capital–F, New York, USA	USANY	http://www.nyiso.com

[a] Based on the market index price.
[b] Based on final EP2 prices.
[c] Includes Denmark, Finland, Norway, and Sweden.

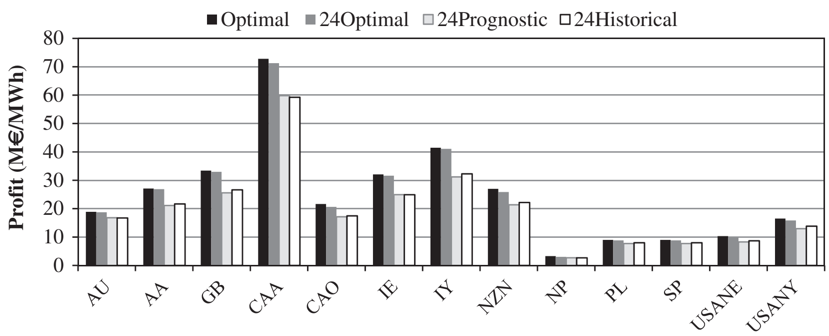

Fig. 2. Profit for 2008 on each of the electricity markets (see Table 2) considered for all four optimisation strategies with a 2 GWh storage capacity.

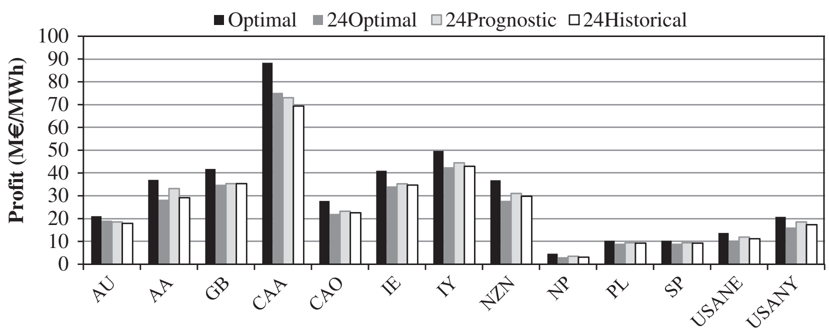

Fig. 3. Profit for 2008 on each electricity market (see Table 2) considered for all four optimisation strategies with an 8 GWh storage capacity.

was identified using the Optimal strategy. In comparison, the 24Prognostic and 24Historical strategies achieved 81% and 83%, respectively, of the Optimal strategy profits. However, it is likely that this large proportion of maximum profits achieved by the 24Optimal strategy is related to the 6-h charge/discharge cycle of the PHES facility considered (see Table 1). To illustrate this, the results were recalculated for a storage capacity of 8 GWh instead of 2 GWh. As displayed in Fig. 3, the profits achieved for an 8 GWh PHES facility using the 24Optimal strategy are only 82% of those achieved when the Optimal strategy is used. In addition, the 24Prognostic and 24Historical returned higher profits for the 8 GWh by achieving an average of 87% and 83% of the Optimal profits, respectively. However, as PHES are typically constructed with a charge/discharge cycle of approximately 6–8 h (American Society of Civil Engineers, 1996), the 24Optimal strategy is very applicable to most existing PHES facilities. This is significant as the 24Optimal strategy shows that PHES units with charge/discharge cycles of approximately 6 h do not need an intra-day market to maximise their profits from electricity arbitrage, but instead they only need accurate electricity prices 1 day in advance.

Although some markets, such as Nordpool, already provide exact electricity prices 1 day in advance, other markets do not. For example, the day-ahead market in Ireland only provides indicative prices called that Ex-Ante (EA) prices. Four days after the day of trading, final prices, called Ex-Post2 (EP2) prices, are produced, which include the cost of balancing the system. Therefore, if the 24Optimal strategy was utilised on the Irish market, the energy storage facility would be optimised using indicative EA prices, but charged the final EP2 prices. As outlined in Fig. 4, when the 24Optimal strategy is optimised and charged based on the final EP2 prices, it makes the most profit. Also, although the profits from the PHES facility are reduced when the facility is optimised and charged based on predicted EA prices, the least profit occurs when the energy storage facility is optimised based on predicted EA prices, but charged the final EP2 prices (i.e. the current situation).

After closer inspection of the price distributions, two primary reasons were identified for this profit reduction. Firstly, some extreme events can occur during the year where the predicted prices can change dramatically during the operation of the PHES. As outlined in Fig. 5, between hours 2060 and 2168 in 2008, the electricity price was predicted to be relatively low at approximately €60/MWh and hence, the PHES facility decided to operate the pump. However, the actual price was very high at approximately €260/MWh and as a result, instead of making a predicted profit that day of ~€25,000, the facility made a loss of ~€200,000.

Secondly, less extreme reductions in the daily profit are also experienced due to the relationship between predicted EA prices and final EP2 prices. As displayed in Fig. 6, prices that are predicted to be low are more likely to increase, while prices that are predicted to be large are more likely to decrease (Finn et al., 2010). Therefore, the hours when the PHES is pumping are more likely to increase and thus increase costs, while the hours when the PHES is generating are more likely to decrease and thus decrease income. In conclusion, for a PHES to maximise its profits, the operator needs to obtain the final electricity price in advance or else have very accurate price predictions.

Next, the profits identified for the PHES facility using the 24Optimal strategy were compared with the annual investment costs required using and the assumptions outlined in Table 3 along with Eq. (7), which consists of the total investment costs I, the installed capacities C, lifetimes n, an interest rate i, and the annual fixed $O\&M$ costs as a percentage of the total investment. As Deane et al. (2010) outlined in a review of existing and proposed PHES facilities around the world, there is no 'general' cost for a PHES

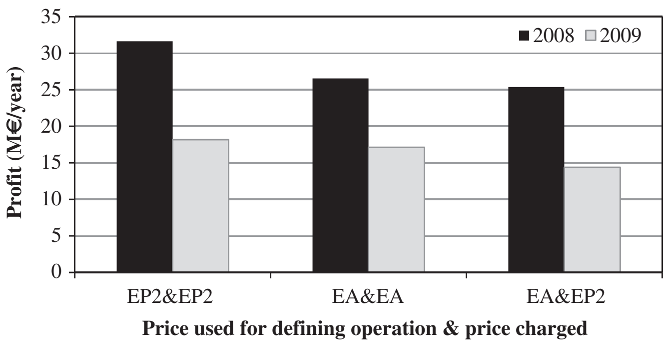

Fig. 4. PHES facility profit using the 24Optimal strategy on the Irish electricity market when it is optimised and charged different prices in 2008 and 2009.

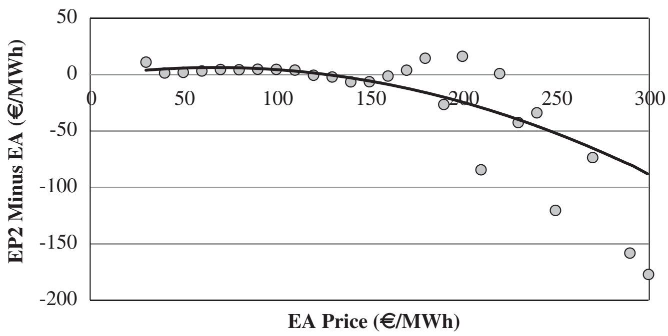

Fig. 6. Average price difference between predicted EA prices and final EP2 prices on the Irish electricity market in 2008.

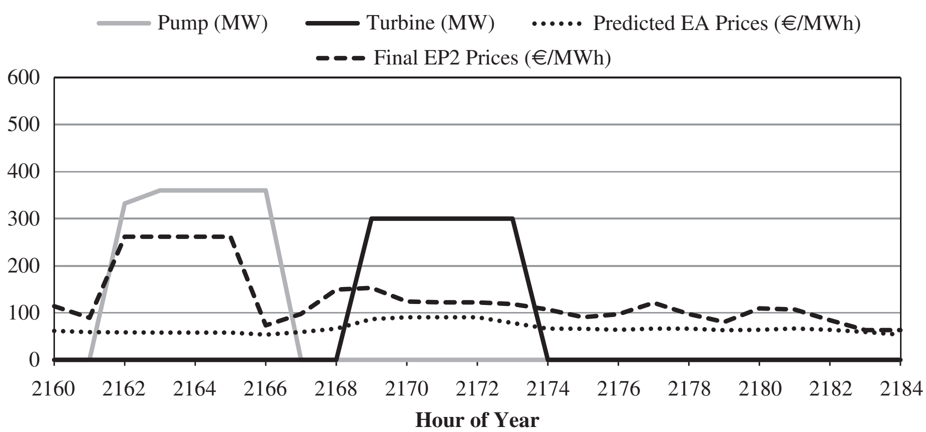

Fig. 5. Pump and turbine operation based on predicted Irish market prices in 2008.

facility as it is very site dependant: the authors concluded that the investment costs could vary from 0.47 to 2.17 M€/MW. Therefore, to account for this variability, a low and high investment scenario was investigated based on this data. In addition, this analysis was carried out over a 5-year period and hence, it was only completed for the electricity markets which provided the price data necessary. Finally, as the lifetime of PHES is approximately 40 years (and up to 100 years for some components), the annual investment cost will be sensitive to the interest rate. Therefore, an interest rate of 3% and 6% was also used for both the high and the low investment costs.

$$I_{Annual} = (I_P C_P + I_T C_T + I_S C_S)\left\{\left[\frac{i}{1-(1+i)^{-n}}\right] + O\&M_{\text{Fixed}}\right\} \quad (7)$$

As displayed in Fig. 2 previously and Fig. 7 below, the profit feasible varies considerably from one electricity market to the next. However, Fig. 7 also indicates that the profit on the same market can vary substantially from year to year. For five of the six markets analysed, the total profit varied by over 50% over the 5-year period analysed, which makes PHES a risky investment. In addition, Fig. 7 emphasises the importance of locating a suitable site for constructing the PHES facility. If the initial investment costs are low and the PHES facility is constructed in a suitable market, then the profit fluctuations will not result in significant losses. However, as a PHES facility has a typical lifetime of approximately 40 years, it is likely that any potential investor would need some additional profit stability. A low interest rate is one policy which could improve the long-term feasibility of PHES. When the interest rate is increased from 3% to 6% on the initial investment, the annual repayments correspondingly increase by approximately 40%. If the initial investment costs are high, then this equates to approximately M€17 extra investment each year. However, even though a low interest rate would improve the economics of PHES, the results indicate that a suitable electricity market and low investment costs are still the most significant factors.

Finally, there are a number of limitations that should be considered when assessing the results discussed in this paper. Firstly, the implications of the PHES facility on the historical markets prices used were not accounted for. If a PHES was installed, it is likely that low electricity prices would increase due to an increased demand from the PHES pump, and high electricity prices would decrease due to the generation provided from the PHES pump. However, due to the complexity of modelling the implications of a PHES unit on historical market prices as well as the relatively small scale of the PHES unit considered (compared to the size of the markets), the results in this study are still indicative of the expected profit from a PHES unit using price arbitrage. In addition, although a fixed *O&M* cost was considered in the economic calculations, the simulations here assumed that the PHES site was available for the entire year when maximising its profit on the electricity market. There could be a reduction in the profits feasible from electricity arbitrage, depending on the downtime of the PHES in the year. Lastly, the profit calculations in this study only considered the energy market. The PHES facility could make additional profit on the regulating, capacity, and ancillary services markets, if they exist and depending on the regulations specified in each market.

Table 3
Low and high cost assumptions for the PHES facility.

PHES parameter	Cost	Unit
Common economic assumptions		
Variable *O&M* costs	1.5[a]	€/MWh
Fixed *O&M* costs	1.5[b]	% of investment
Lifetime	40[a,b]	Years
Interest rate	6[c]	%
Low investment assumptions		
Pump investment[d]	0.235[a, e]	M€/MW
Turbine investment[d]	0.235[a, e]	M€/MW
Storage investment	7.884[a]	M€/GWh
High investment assumptions		
Pump investment[d]	1.085[e]	M€/MW
Turbine investment[d]	1.085[a, e]	M€/MW
Storage investment	15.77[a]	M€/GWh

[a] Gonzalez et al. (2004).
[b] Danish Energy Agency (2005).
[c] EirGrid (2009).
[d] This is 50% of the pump-turbine costs reported, which have been halved to reflect the pump and turbine costs separately.
[e] Deane et al. (2010).

4. Conclusions

The results indicate that the 24Optimal operation strategy is the most profitable practical method of dispatching a typical PHES facility. Under this strategy the PHES is optimised based on the day-ahead electricity prices and by doing so, almost all (∼97%) of the profits feasible can be obtained when the charge and discharge cycles are each approximately 6 h, which is typical for an existing PHES plant. This indicates that long-term foresight of electricity prices is not essential for most PHES facilities to

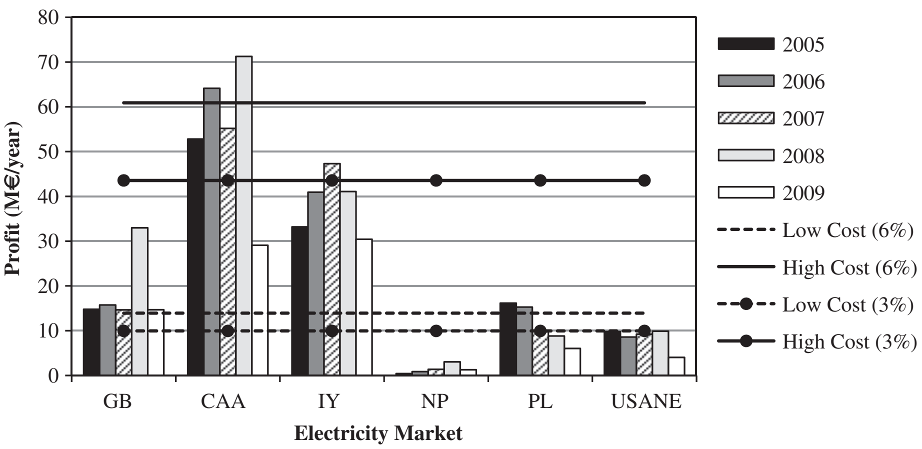

Fig. 7. PHES profit using 24Optimal strategy on electricity markets with available data for 2005–2009, along with high (M€2.17/MW) and low (M€0.47/MW) annual investment costs based on 3% and 6% interest rates.

maximise their profits using electricity price arbitrage. However, a further analysis based on the Irish electricity market indicated that for the 24Optimal strategy to be effective, the day-ahead electricity prices must be the actual prices which the PHES facility is charged or the PHES operator must have very accurate price predictions. Otherwise, the predicted profit could be significantly reduced and even become a loss. Finally, using the 24Optimal strategy, the PHES profit from energy arbitrage on some electricity markets can surpass the annual investment repayments required. However, the annual profit from the PHES facility varied by more than 50% on five out of six electricity markets considered over the 5-year period analysed: 2005–2009. Therefore, even with low investment costs, a low interest rate, and a suitable electricity market, a PHES facility is still a risky investment in most markets without a more predictable profit or some additional revenue, which could come from ancillary services, capacity payments, or a balancing market.

Appendix. Description and flow chart of 'Optimal' strategy

1. Find "MAXhour" remaining in the time series.
2. Range = time between "last hour before MAXhour when storage was full" and "first hour after MAXhour when storage is empty".
3. Find "MINhour" in range.

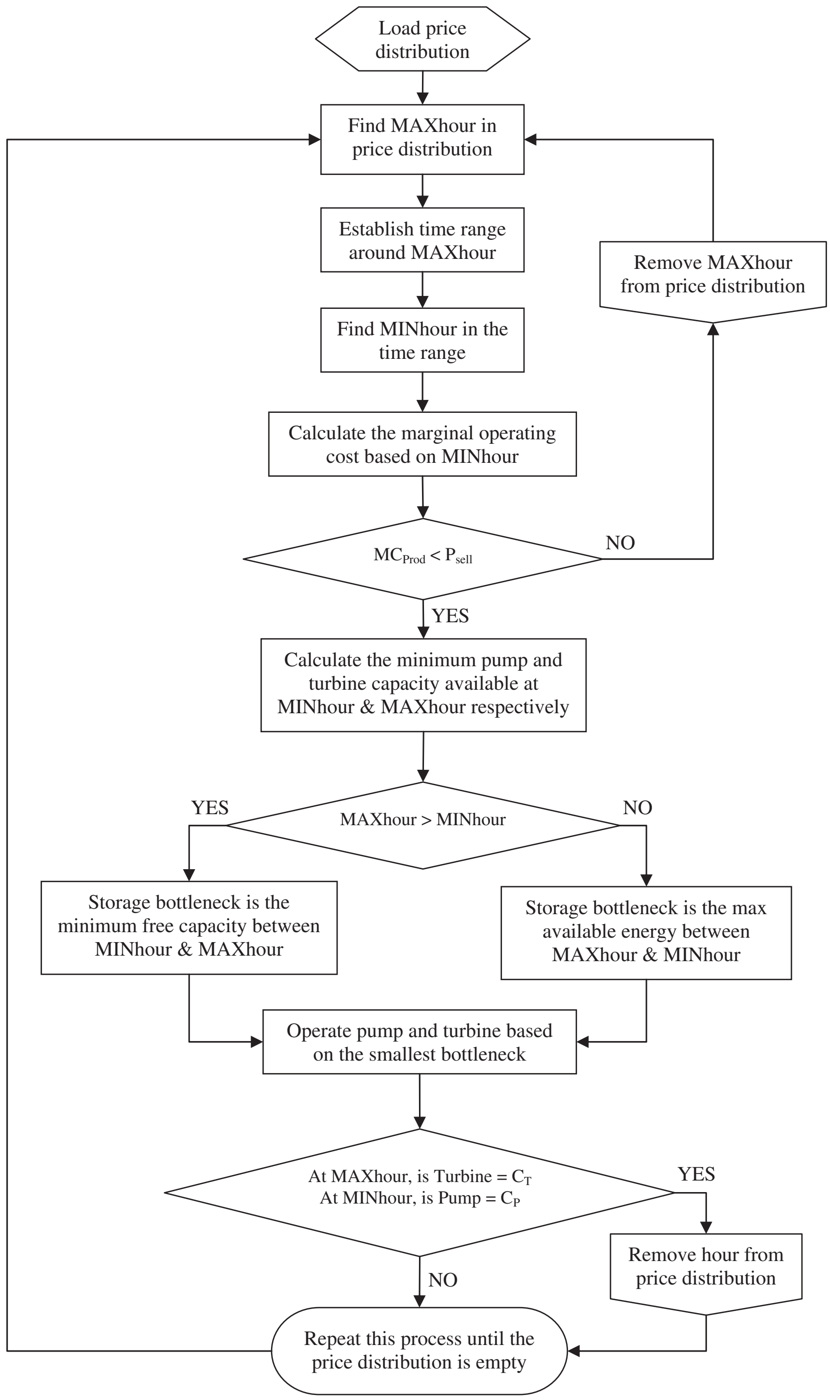

Fig. A1

4. $MC_{prod} = MC_G + [(P_{buy} + MC_P)/(\eta_P * \eta_G)]$
   If $MC_{prod} > P_{sell}$, then eliminate MAXhour and go back to step 1.
   If $MC_{prod} < P_{sell}$, then go to step 5.
5. Determine the "operation bottlenecks" in the range between the maximum and minimum prices.
   (a) T_{Max} = Available turbine capacity at the maximum price hour.
   (b) P_{Min} = Available pump capacity at the minimum price hour.
   (c) If MAXhour > MINhour, then
   (i) storage_free = Storage Capacity–Max Storage Between MINhour and MAXhour.
   (ii) bottleneck = minimum(T_{Max}, P_{Min}, storage_free).
   d. If MINhour > MAXhour, then
   (i) storage_left = Minimum storage between MAXhour and MINhour.
   (ii) bottleneck = minimum(T_{Max}, P_{Min}, storage_left).

   Once the bottleneck has been identified, then the energy storage can operate accordingly.
6. If turbine operation at MAXhour = C_T, then eliminate MAXhour.
   If pump operation at MINhour = C_P, then eliminate MINhour.
7. Iterate back to step 1 until the period of 1 year is completed.

See Fig. A1 for description and flow chart of 'Optimal' strategy.

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Appendix I

Connolly D, Lund H, Mathiesen BV, Leahy M. The first step towards a 100% renewable energy-system for Ireland. Applied Energy 2011;88(2):502-507.

Applied Energy 88 (2011) 502–507

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

The first step towards a 100% renewable energy-system for Ireland

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ARTICLE INFO

Article history:
Received 7 September 2009
Accepted 8 March 2010
Available online 25 March 2010

Keywords:
100% Renewable energy-system
Biomass
Hydrogen
Electric heating
Ireland

ABSTRACT

In 2007 Ireland supplied 96% of the total energy demand with fossil fuels (7% domestic and 89% imported) and 3% with renewable energy, even though there are enough renewable resources to supply all the energy required. As energy prices increase and the effects of global warming worsen, it is essential that Ireland begins to utilise its renewable resources more effectively. Therefore, this study presents the first step towards a 100% renewable energy-system for Ireland. The energy-system analysis tool used was EnergyPLAN, as it accounts for all sectors of the energy-system that need to be considered when integrating large penetrations of renewable energy: the electricity, heat, and transport sectors. Initially, a reference model of the existing Irish energy-system was constructed, and subsequently three different 100% renewable energy-systems were created with each focusing on a different resource: biomass, hydrogen, and electricity. These energy-systems were compared so that the benefits from each could be used to create an 'optimum' scenario called combination. Although the results illustrate a potential 100% renewable energy-system for Ireland, they have been obtained based on numerous assumptions. Therefore, these will need to be improved in the future before a serious roadmap can be defined for Ireland's renewable energy transition.

1. Introduction

On a global scale in recent years the affects of climate have become more apparent, new fossil fuel reserves have become scarce, and energy prices have reached all-time highs. Meanwhile in Ireland,[1] approximately 93% of the energy used for electricity generation in Ireland is fossil-fuel based, with 59% of this energy wasted due to transformation losses [1]. Also, approximately 89% of the total fuel consumed in Ireland is imported, which is an extremely volatile situation in the current economic climate [1]. In contrast to fossil fuels, Ireland has an abundant renewable energy resource [2,3] and hence under European Commission regulations, Ireland must supply 16% of the total energy requirement from renewable resources by 2020 [4]. With this in mind, it is essential that Ireland identifies the most effective transition from a fossil-fuel to a renewable energy-system (RES). Therefore, the aim of this work is to evaluate how Ireland can make this transition to a RES. Also, as the Irish energy-system is very similar to those that exist in most developed countries [5], the results obtained in this investigation reflect the changes necessary in a number of other energy-systems also. In addition, the Irish energy-system is an excellent laboratory for experimenting with new technologies as it is a relatively small country with 4.4 million people, it is an island which makes it specifically attractive for the implementation of alternative transport technologies such electric vehicles, and it has an abundant resource of renewable energy in the form of wind, wave, tidal, solar and biomass [2,3].

To date, a number of analyses have been carried out on the feasibility of integrating renewable energy onto the Irish electric grid. In 2003, Gardner et al. [6] investigated the effects of more wind energy on the electricity grid in Ireland and Northern Ireland, concluding that there is no technical limit on the wind penetration feasible, but instead costs are the limiting factor. Therefore, Garner et al. identified the most costly aspects of increasing the wind penetration as transmission reinforcement, wind curtailment, capital costs and operating costs. In 2004, ESB National Grid [7] also analysed the costs associated with increasing the wind penetration in Ireland, but in addition this report also investigated the effects of large wind-penetrations on conventional generation. The report concluded that increasing the wind penetration in Ireland from 0% to 11.7% would increase the total generation costs by €196 million, and would minimally affect baseload plant. However, peaking and mid-merit power plants would be affected as the wind penetration increases due to their more frequent start-ups, increased ramping, and lower capacity factors. Finally, in 2007, Meibom et al. [8] modelled the Irish electricity grid using the WILMAR energy tool [9]. The objective was to identify the effects of large wind-penetrations on the island of Ireland in relation to overall

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[1] Ireland refers to the Republic of Ireland only unless otherwise specified.

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doi:10.1016/j.apenergy.2010.03.006

operation, costs and emissions. Meibom et al. concluded that a wind penetration of 42% was feasible on the island of Ireland by 2020, overall operation costs will be reduced with a wind penetration of 42% compared to the current situation, and also, the CO_2 emissions from electricity generation will be reduced to 15 Mt at a wind penetration of 42%.[2] In summary, a number of studies have been carried out in Ireland on the integration of renewable energy. However, these studies are primarily focused on wind generation in the electricity sector.

Focusing on wind energy in the electricity sector is a common situation throughout energy planning [10–13]. In contrast the aim of this work is to analyse the entire energy-system, which includes the electricity, heat and transport sectors, to identify the possibility of supplying these demands using all forms of renewable energy such as wind, wave, solar, tidal, and biomass. Although not as common as analysing the effects of large wind-penetrations in the electricity sector, a number of studies have also been completed in this area: Krajacic et al. [14] investigated the feasibility of 100% RES on the island of Mljet, Croatia, Lund and Mathiesen [15] identified how Denmark could transfer to a 100% RES, while Lehmann proposed a 100% RES for Japan [16]. In conclusion, as it is clearly necessary for Ireland to integrate more renewable energy onto its energy-system, and the integration of renewable energy into the entire Irish energy-system has never been comprehensively analysed previously, the aim of this work is to identify the feasibility of a 100% RES for Ireland, using the methodology proposed by Lund and Mathiesen [15].

2. Methodology

To identify how Ireland can transform from a fossil-fuel based energy-system to a renewable energy-system, the first step is to create a model of the Irish energy-system. Therefore, a study was carried out to identify which tool would be most suitable for this investigation. A detailed report of the various tools considered has been completed [17] and therefore this will not be discussed in detail here. Instead the two primary reasons that EnergyPLAN was chosen are discussed. Firstly, EnergyPLAN considers the three primary sectors of any national energy-system: electricity, heat and transport. To date Ireland has no integration within its energy-system and therefore, the electricity, heat and transport sectors of the Irish energy-system are completely segregated. However, the integration of the three sectors is crucial in order to achieve large-scale penetrations of renewable energy, which has been outlined in [15]. Therefore, in order to meet Ireland's energy targets outlined previously, it will be imperative that Ireland begins to integrate its energy-system more. With this in mind, the EnergyPLAN model had a key advantage over a number of others considered. Secondly, EnergyPLAN has already been used to complete several studies that would be beneficial if applied to Ireland. These include studies analysing the effects of large wind-penetrations [18], the optimum combination of various renewable energy technologies in an energy-system [19], the benefits of energy storage [20] and finally, the pathway towards a 100% renewable energy-system for Denmark [15,21]. These are typical of the studies that will identify how Ireland can work towards its 2020 energy targets and beyond.

EnergyPLAN is a deterministic input/output model. General inputs are the demands, renewable energy sources, energy station capacities, costs, and a number of optional regulation strategies. Outputs are energy balances and the resulting annual productions, fuel consumption, import/export of electricity and the total costs including income from the exchange of electricity. The structure of the EnergyPLAN model is illustrated in Fig. 1 [22]. The main purpose of EnergyPLAN is to assist in the design of national or regional energy-planning strategies on the basis of technical and economic analysis, resulting from the implementation of different energy-systems and investments. It uses an hourly simulation over a period of 1 year as well as aggregated data, i.e. all power plants are modelled as a single power-plant, with a combined efficiency. EnergyPLAN also uses analytical programming rather than iterations so the calculations are completed in a very short period of time. Finally, EnergyPLAN can identify the optimum technical operation of the energy-system as well as the optimal economic-operation, which is one of its key advantages. A lot of energy tools are capable of optimising an energy-system based on costs. However, EnergyPLAN can optimise the energy-system based on the technical operation of its components. This is very useful as it eliminates the constraints imposed by existing financial-infrastructures when analysing future alternatives. Furthermore, EnergyPLAN is able to model the energy-system according to the costs if required. A more detailed description of the EnergyPLAN model and its applications can be found at [23].

In order to ensure the model was simulating the Irish energy-system correctly, a reference model was created representing the year 2007. Details of the inputs used and the assumptions made to create the reference model are discussed in detail in [24] where it was concluded that EnergyPLAN was providing an accurate simulation of the Irish energy-system. Once the reference model was proved accurate, an initial draft of a 100% RES for Ireland could then be created. In total, four 100% renewable energy scenarios were made for Ireland in this study:

1. *Biomass energy-system (BES)*: a 100% renewable energy-system based on biomass.
2. *Hydrogen energy-system (HES)*: a 100% renewable energy-system using hydrogen.
3. *Electricity energy-system (EES)*: a 100% renewable energy-system maximising the use of renewable generated electricity.
4. *A combination of each (COMBO)*: a 100% renewable energy-system based on the results from the BES, HES and EES scenarios.

For each scenario a number of assumptions were made about the future energy demands and production units required. Although these assumptions would have to be validated further before an accurate solution is proposed, they do provide an indication of the trends that can be expected. Listed below are the assumptions used in three of the 100% renewable energy-systems investigated for Ireland:

Assumptions for the biomass energy-system (BES).

1. All electricity, heat and transport demands were maintained at 2007 levels.
2. Energy storage is increased to 3000 MW and 15 GWh.
3. Eliminate existing electric heating.
4. Supply 10% of individual heating with solar thermal.
5. Supply 35% of individual heating with biomass boilers: accounts for all home in rural areas.
6. Supply 55% of individual heating using district heating: accounts for heating demand in all towns and cities with more than 1500 people.
7. Introduce 251 MW (0.92 TWh) of tidal power.
8. The entire fuel demand in industry is supplied using biomass.
9. All transportation fuel is supplied by biofuels, including jet fuel. Biomass is converted to bio-ethanol at a ratio of 1:1.35 (for private cars and jet fuel) and to biodiesel at a ratio of 1:1 (for road freight).

[2] In 2007 Ireland emitted 15.4 Mt of CO_2 due to electricity generation.

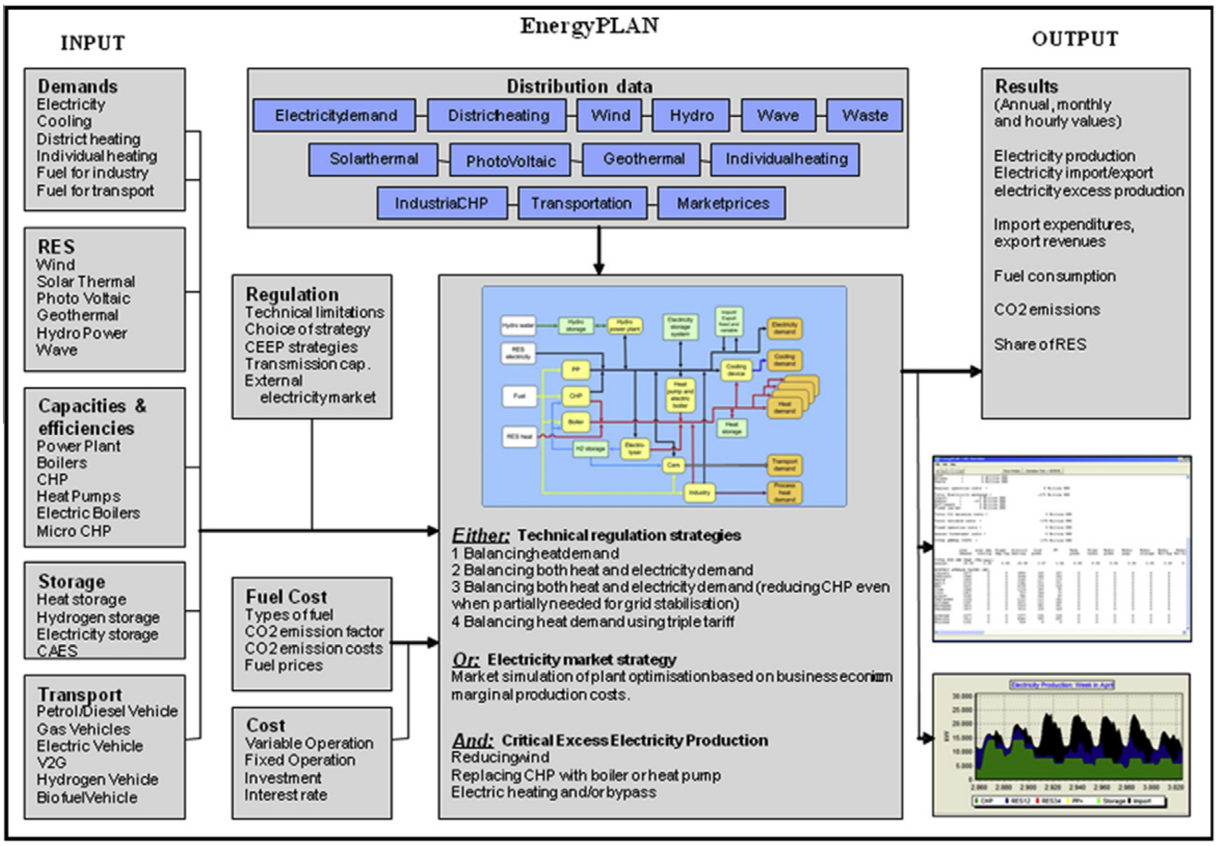

Fig. 1. The structure of the EnergyPLAN model [22].

Assumptions for the hydrogen energy-system (HES).

1. All electricity, heat and transport demands were maintained at 2007 levels.
2. An electrolyser of 10,000 MW and storage of 240 GWh is added to produce, store and provide hydrogen to the power-plant, transport and heating sectors.
3. Supply 10% of individual heating with H2 micro CHP.
4. Supply 10% of individual heating with solar thermal.
5. Supply 10% of individual heating with heat pumps.
6. Supply 15% of individual heating with biomass boilers.
7. Supply 55% of individual heating using district heating: accounts for heating demand in all towns and cities with more than 1500 people.
8. Introduce 251 MW (0.92 TWh) of tidal power.
9. Introduce 3000 MW (3.33 TWh) of wave power.
10. The entire fuel demand in industry is supplied using biomass.
11. Transportation fuel is primarily supplied by hydrogen: all private cars and jet fuel is replaced by hydrogen, while 50% of road freight is fuelled by hydrogen and 50% biodiesel.

Assumptions for the electricity energy-system (EES).

1. All electricity, heat and transport demands were maintained at 2007 levels.
2. Energy storage is increased to 3000 MW and 15 GWh.
3. Supply 10% of individual heating with solar thermal.
4. Supply 35% of individual heating with heat pumps: accounts for all home in rural areas.
5. Supply 55% of individual heating using electric heating: accounts for heating demand in all towns and cities with more than 1500 people.
6. Introduce 251 MW (0.92 TWh) of tidal power.
7. Introduce 1000 MW (1.11 TWh) of wave power.
8. The entire fuel demand in industry is supplied using biomass.
9. All road transportation is fuelled by electricity and biomass: the private car fleet is fuelled by 80% electricity and 20% bio-ethanol (which can include electric, hybrid or bio-ethanol cars). All road freight is fuelled using biodiesel and all jet fuel is supplied using bio-ethanol.

Once these assumptions were reflected in the model of the Irish energy-system, the capacity of wind power was increased incrementally to identify an 'optimum' solution. The 'optimum' solution was defined as that which enabled the largest utilisation of wind power. Wind power was chosen as the variable due to the large potential resource currently available in Ireland: there is enough onshore wind alone to supply 130% of Ireland's electricity demand [3]. As the wind power capacity increases, the amount of excess electricity produced also increases: this is referred to as critical excess electricity production (CEEP). In addition, as more wind generated electricity is added to the system, the primary energy supply (PES) of the system varies: typically falling as wind power is added, reaching a minimum, and then increasing again as wind power begins to have a negative impact on the system. To identify the 'optimum' wind capacities for each energy-system, the amount of wind energy, CEEP, PES, biomass demand, and imported electricity required was measured for an installed wind energy of 25–100% of electricity demand in each energy-system (in steps of 3 TWh/10.5% of reference electricity demand). The graphs created for the BES are displayed in Figs. 1, 2 and 3.

All wind capacities with a CEEP or imported electricity greater than 2 TWh were disregarded as this was deemed unacceptably wasteful. From the options that remained a compromise

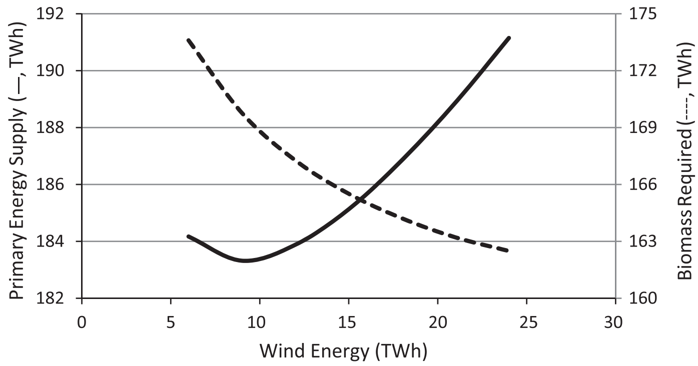

Fig. 2. PES and biomass required for different wind capacities in the biomass energy-system.

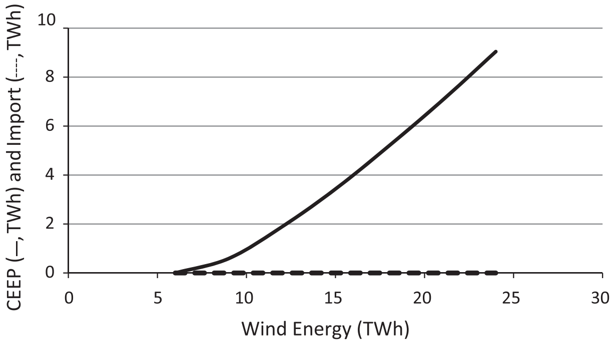

Fig. 3. CEEP and imported electricity required for different wind capacities in the biomass energy-system.

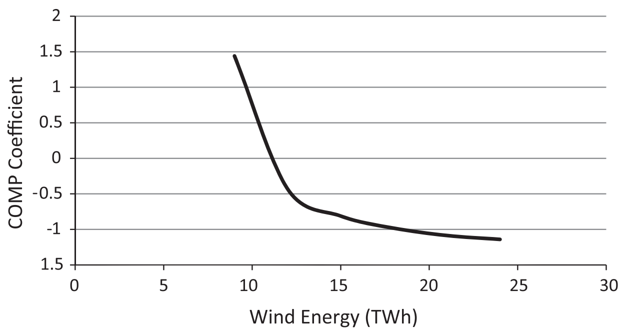

Fig. 4. Coefficient results for the biomass energy-system.

coefficient, COMP, was created using the change in PES between each iteration, ΔPES, and the change in CEEP between each iteration, ΔCEEP:

$$\mathrm{COMP} = \frac{\Delta \mathrm{PES}}{\Delta \mathrm{CEEP}} \qquad (1)$$

The optimum solution occurred when COMP was reduced to 1, i.e. the reduction in the primary energy supply was the same as the increase in excess electricity that could not be used. For example, if the addition of 1000 MW of wind energy caused the primary energy supply of the system to reduce by 3 TWh, and the excess electricity in the system to increase by 0.5 TWh, then the installed wind capacity was increased further. If however, after the next 1000 MW of wind was added, the primary energy supply was reduced again by a further 1 TWh, but the excess electricity produced was increased by 2 TWh, then this was deemed unproductive for the system and the scenario was rejected. Using this methodology, a compromise could be met between the benefits (i.e. reduced primary energy supply) and drawbacks (i.e. excess electricity production) of additional wind energy in the system. The COMP coefficient results for the BES can be seen in Fig. 4 where the optimum wind energy chosen was 9 TWh. A similar analysis was carried out for the HES, EES and COMBO.

3. Results and discussion

Using the methodology defined above, the three scenarios displayed in Fig. 5 were created. From the outset it is evident that all three scenarios (BES, HES and EES) have a lower primary energy supply than the reference. This is primarily due to the introduction of more efficient systems such as CHP and district heating in the BES and HES, as well as fuel cell transportation in the HES, and electric vehicles in the EES. Of the three alternatives, the EES has the lowest primary energy supply at 590 PJ, while the BES has the highest at 660 PJ. This is due to the large amount of biomass required to replace fossil fuels in the transport sector. In addition, unlike hydrogen and electricity cars, bio-ethanol vehicles do aid the penetration of large wind energy. The PES of the HES was also very similar to the BES at 629 PJ. This illustrates that a hydrogen economy is also very demanding on resources, especially in comparison to the EES. The main reason for this decrease in PES in the EES is the efficient use of electricity. In the HES, electricity is transformed to hydrogen which is typically transformed back to electricity at a later stage. This results in a very inefficient system. In contrast, the EES uses electricity directly so the losses are reduced, primarily in the transport sector.

The biomass consumption varies considerably within each scenario also, in terms of total consumption and also in terms of its specific uses. As expected, the BES uses the most biomass at 611 PJ, which is 92.5% of the PES. In the HES and the EES the biomass consumption is much less than the BES at 513 PJ and 472 PJ, respectively. However, the use of biomass in both the HES and the EES is very different. The HES uses a large amount of biomass in the power plants, to create electricity to produce hydrogen for heating and transportation. In contrast, the EES uses a lot of biomass directly in the transport sector.

Also from these results, it is evident that the biomass energy-system can utilise very little wind energy compared to the HES and the EES. In total, the BES was only able to integrate 10.4 TWh of renewable generated electricity, whereas the HES was able to integrate 29 TWh and the EES 29.7 TWh. This is due to the much larger electricity demands and energy storage capacities available in the HES and the EES. The HES uses a lot of electricity to generate hydrogen which can then be stored for use in power plants, H2 micro CHP and transport as displayed in Fig. 6. The EES uses a large amount of electricity for electric heating and

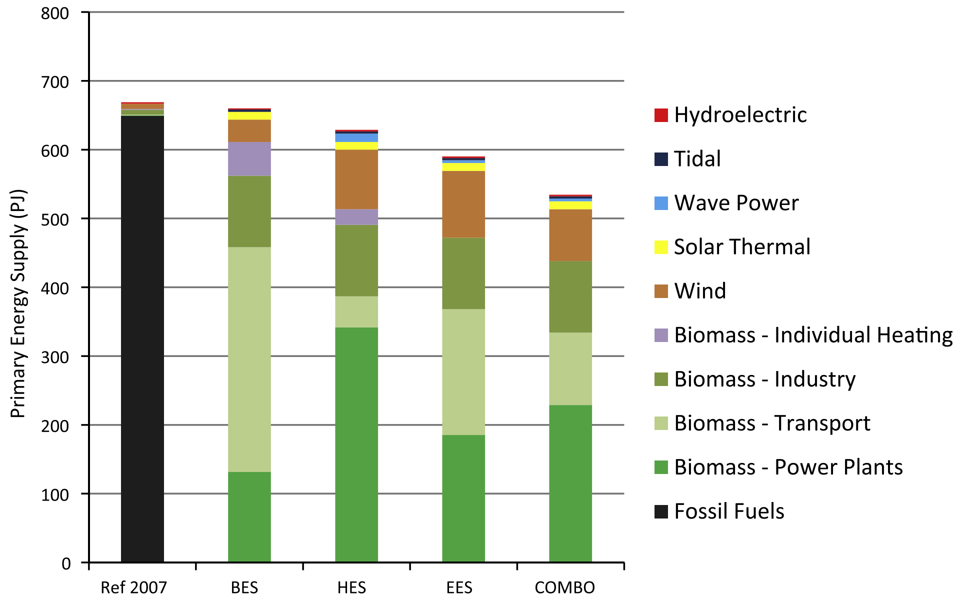

Fig. 5. Primary energy supply in reference, BES, HES, EES and COMBO energy-systems.

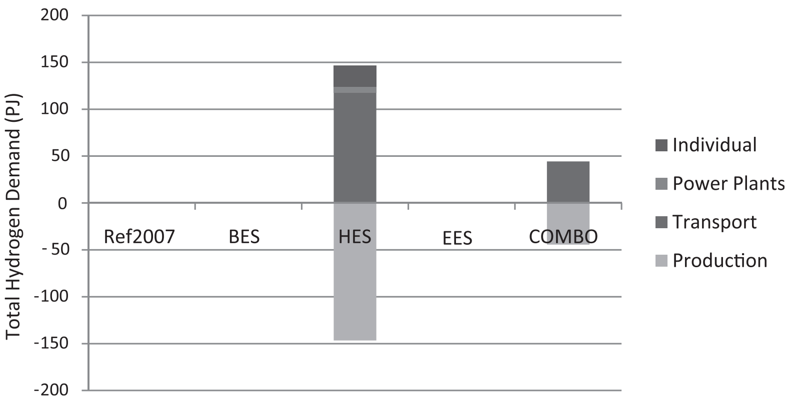

Fig. 6. Use of hydrogen in reference, BES, HES, EES and COMBO energy-systems.

transportation, while the electric vehicles can also act as large sink for excess renewable energy.

Based on the results from the BES, HES and ESS a COMBO scenario was created with the following characteristics:

1. All electricity, heat and transport demands were maintained at 2007 levels.
2. No energy storage is added: enough is provided by the electric vehicles in the transport sector.
3. Supply 10% of individual heating with solar thermal.
4. Supply 35% of individual heating with heat pumps: accounts for all home in rural areas.
5. Supply 55% of individual heating using district heating: accounts for heating demand in all towns and cities with more than 1500 people.
6. Introduce 251 MW (0.92 TWh) of tidal power.
7. Introduce 1000 MW (3.33 TWh) of wave power.
8. The entire fuel demand in industry is supplied using biomass.
9. Transportation is fuelled by electricity, hydrogen and biomass. The private car fleet is fuelled by 80% electricity and 20% bio-ethanol, road freight is supplied by 50% bio-ethanol and 50% hydrogen, and jet fuel is supplied using 50% hydrogen and 50% bio-ethanol.

The objective was to combine the efficient use of biomass in the BES scenario with the efficiency of rural heating in the EES for the electricity and heat sectors. Therefore, CHP and district heating was used instead of electric heating in the EES, while heat pumps were maintained as the primary heat technology in rural areas. For the transport sector, the efficiency of electric vehicles was maintained for private transport, and a mix of hydrogen and biomass was used for road freight and aviation fuel. From Fig. 5, it is evident that this results in the most efficient energy-system of all. The PES is reduced by 20% to 534.5 PJ and 23.7 TWh of renewable generated electricity is used. Finally, the biomass required in the COMBO scenario is reduced to 438 PJ, which is 71% of the biomass demand in the BES. This is also 59.6% of the potential biomass resource in Ireland, although this is a total potential and not a residual potential, i.e. it does not account for land that may be unavailable to avoid effecting food production or other industries [25]. Therefore, even though the biomass requirement in the COMBO scenario is low, it still might be too much depending on the residual biomass that is available in Ireland.

In addition to the issues discussed above, it is also worth noting that energy savings and conservation were not considered in detail in this paper. It was assumed that energy demands would remain the same as 2007: this may be too low as energy demands are likely to increase in the future, or it may be too high as it may be possible to reduce demands below 2007 levels depending on the energy savings feasible. Therefore, in future work energy conservation will need to be considered in more detail, when identifying the least-cost 100% renewable energy-system for Ireland.

In summary, this work illustrates that an Irish energy-system with district heating, heat pumps and a transportation mix of electricity, hydrogen and biomass, is the most efficient and resource-friendly method of converting Ireland to a 100% renewable energy-system. However, this analysis was carried out from a technical and resource perspective and not an economic perspective which may alter the results. Although the results obtained in this study are not ideal, they do illustrate the options available to Ireland in achieving a 100% renewable energy-system. In conclusion, this study also illustrates the importance of designing an effective energy-system, as the same demand can be supplied with much less energy if the energy-system is designed correctly.

4. Future work

The objective of this study was to illustrate the implications of a 100% RES for Ireland using various alternatives available. However, as mentioned previously the assumptions used to create these alternatives are crude, and the combinations of technologies used to supply the demands are not the optimum. Therefore, it is hoped that this work can motivate a larger interest in identifying accurate predictions for the future of the Irish energy-system, specifically among experts within each of the relevant areas and hence improve the overall accuracy of the models created. Also, this study focused on the technical implications of the different energy-systems considered. Therefore, the socio-economic and business-economic issues will also need to be considered within future studies. Finally, the overall objective of all future studies will be to define a realistic pathway towards a 100% RES for Ireland, by identifying what the targets should be for a pre 100% renewable-energy Ireland, such as those that can be achieved by 2020 or 2030. This is similar to the methodology proposed by Lund and Mathiesen [15] who identified a 50% RES for Denmark in 2030, and a 100% RES for Denmark in 2050.

5. Conclusions

In summary, this paper is the very first step in the attempt to identify a pathway towards a 100% renewable energy-system for Ireland. It is anticipated that the Irish experience will also illustrate how other energy-systems with large amounts of condensing plant and fluctuating renewable energy, can also make the transition towards a 100% renewable energy-system. From this first step, it is evident that a 100% renewable energy-system is not only feasible in Ireland, but that there are numerous methods of achieving this. In addition, with detailed planning for the future, drastic reductions in the energy required can be achieved by implementing the correct combination of technologies. As a result, this study illustrates that it is crucial to thoroughly investigate as many alternatives as possible, before major reforms or commitments are made in relation to the future of the Irish energy-system.

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