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The first step

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Ireland's pathway towards a 100% renewable energy-system: The first step

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ABSTRACT

Ireland has an abundant supply of renewable energy, a dangerous reliance on imported fossil fuels, as well as very demanding energy and CO_2 targets to reach. All of these indicate that a major alternation to the current energy system is necessary, especially an increase in the utilisation of renewable energy. Consequently, this study presents the first step towards identifying how this transition may be achieved for the Republic of Ireland. The energy-systems-analysis tool, EnergyPLAN, was chosen for this investigation, as it accounts for all sectors that need to be considered for 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 alternatives were compared to identify the most effective method of increasing renewable energy penetration. The results in this paper illustrate the four scenarios of a 100% renewable energy system for Ireland: a biomass, hydrogen, electricity and combination scenario. However, these results have been completed based on numerous assumptions that will need to be investigated in future work, before a serious roadmap can be defined for Ireland's renewable energy transition.

INTRODUCTION

Currently 92.6% of the energy used for electricity generation in Ireland[1] is fossil-fuel based, and 59% of this energy is wasted due to transformation losses [1]. Also, approximately 85% of the fuel consumed in Ireland is imported, which is an extremely volatile situation in the current economic climate [2]. Considering these, and the fact that Ireland has an abundant renewable-energy resource [3], as well as an obligation from the European Commission to supply 16% of the total energy requirement from renewable resources by 2020 [4], 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, 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.

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

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.* [5] investigated the effects of more wind energy on the electricity grid in the Republic of Ireland and Northern Ireland. Gardner *et al.* argued that there is no technical limit on the wind penetration feasible, 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 [6] also analysed the costs associated with increasing the wind penetration in the Republic of 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.* [7] modelled the Irish electricity grid using the WILMAR energy model [8]. 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, 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[2] at a wind penetration of 42%. 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.

This is a common situation throughout energy planning as a lot of international research is focused on wind energy in the electricity sector [9-12]. In contrast the aim of this work is to analyse the entire energy-system which includes the electricity, heat and transport sectors, and identify the possibility of supplying these demands using all forms of renewable energy such as wind, wave, tidal, biomass and so forth. 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.* [13] investigated the feasibility of 100% RES on the island of Mljet, Croatia, Lund and Mathiesen [14] identified how Denmark could transfer to a 100% RES, and Lehmann proposed a 100% RES for Japan [15]. 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 [14].

METHODLODGY

To identify how Ireland can transform from a fossil-fuel based energy-system to a renewable energy-system, it is necessary to firstly model the Irish energy-system. Choosing the correct modelling tool was the first, and also one of the most important decisions that needed to be made for this study. As a result, a study was carried out to identify which tool would be most suitable. After an initial investigation, 6 models were shortlisted:

1. EnergyPLAN [16]
2. ENPEP [17]
3. HOMER [18]
4. LEAP [19]
5. WILMAR [8]

[2] In 2007, Ireland emitted 15.4 Mt of CO_2 due to electricity generation.

6. TIMES / MARKAL [20]

A detailed report of the various models which can analyse national energy-systems is currently being completed, and it will provide a detailed overview of the energy tools considered [21]. Therefore, this will not be discussed in detail here. Instead the two primary reasons that EnergyPLAN was chosen are outlined below:

1. 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 [14]. 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.
2. 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 [22], the optimum combination of various renewable-energy technologies in an energy system [23], the benefits of energy storage [24] and finally, the pathway towards a 100% renewable energy-system for Denmark [14, 25]. 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 Figure 1.

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. A number of key features about the EnergyPLAN model are:

1. It uses an hourly simulation over a period of one year.
2. It uses aggregated data i.e. all power-plants are modelled as a single power-plant, with a combined efficiency
3. The model uses analytical programming rather than iterations so the calculations are completed in a very short period of time
4. The model can identify the optimum technical-operation of the energy system as well as the optimal economic-operation. This is one of the key advantages of EnergyPLAN. A lot of energy models 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, the EnergyPLAN model is also able to model the energy system according to the costs if required, so a comparison can be made with and without existing infrastructures.

A more detailed description of the EnergyPLAN model and its applications can be found at [16].

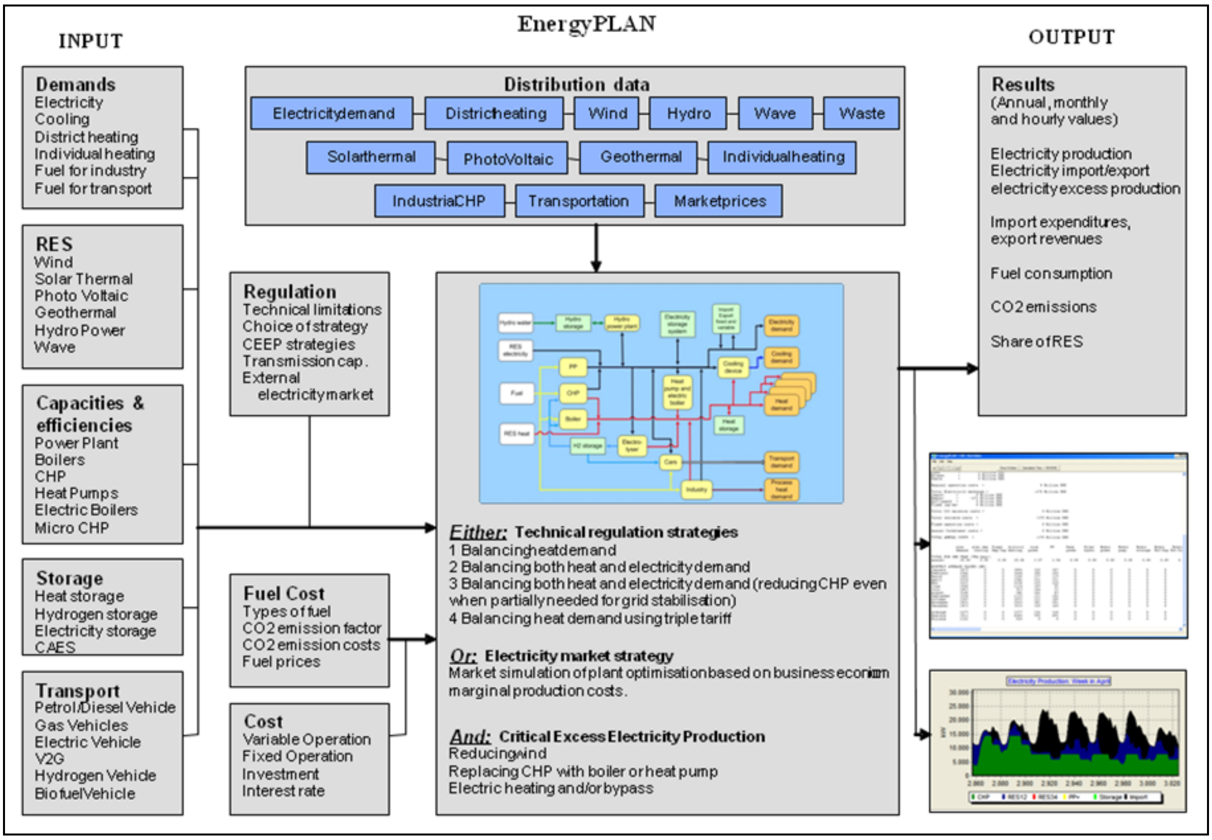

Figure 1. The structure of the EnergyPLAN model [26]

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 Connolly *et al.* [27]. Once the reference model was created and verified, an initial draft of a 100% RES for Ireland could 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. However, as this is only a first attempt, these assumptions would have to be validated to propose a concrete solution. They do however provide an indication of the future. Listed below are the assumptions used in three of the 100% renewable energy-systems investigated for Ireland:

Scenario 1: Biomass Energy System (BES)

The following changes were made to the 2007 Irish energy-system:

1. All electricity, heat and transport demands were maintained at 2007 levels
2. Energy storage is increased to 3,000 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 1,500 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)

Scenario 2: Hydrogen Energy System (HES)

The following changes were made to the 2007 Irish energy-system:

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 H_2 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 1,500 people
8. Introduce 251 MW (0.92 TWh) of tidal power
9. Introduce 3,000 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.

Scenario 3: Electricity Energy System (EES)

The following changes were made to the 2007 Irish energy-system:

1. All electricity, heat and transport demands were maintained at 2007 levels
2. Energy storage is increased to 3,000 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 1,500 people
6. Introduce 251 MW (0.92 TWh) of tidal power
7. Introduce 1,000 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 energy system, the capacity of wind power was adjusted incrementally to identify an ‘optimum’ solution. Wind power was chosen as the variable, due to the large potential resource currently available in Ireland. 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 capacities for each energy-system, the amount of wind energy, the CEEP, PES, biomass demand, and imported electricity required was monitored for an installed wind energy of 25% to 100% of electricity demand in each energy system. The graphs created for the BES are displayed in Figure 2 and Figure 3. All wind capacities with a CEEP or imported electricity greater than 2 TWh were disregarded as this was deemed unacceptably wasteful or dependent. From the options that remained a balancing coefficient, B, was created using the change in PES between each iteration, ΔPES, and the change in CEEP between each iteration, ΔCEEP:

$$B = \frac{\Delta PES}{\Delta CEEP} \tag{1}$$

The optimum solution occurred when B 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 1,000 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 1,000 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 balance 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 balancing coefficient results can be seen in Figure 4 where the optimum wind energy chosen was 9 TWh. A similar analysis was carried out for the HES, EES and COMBO.

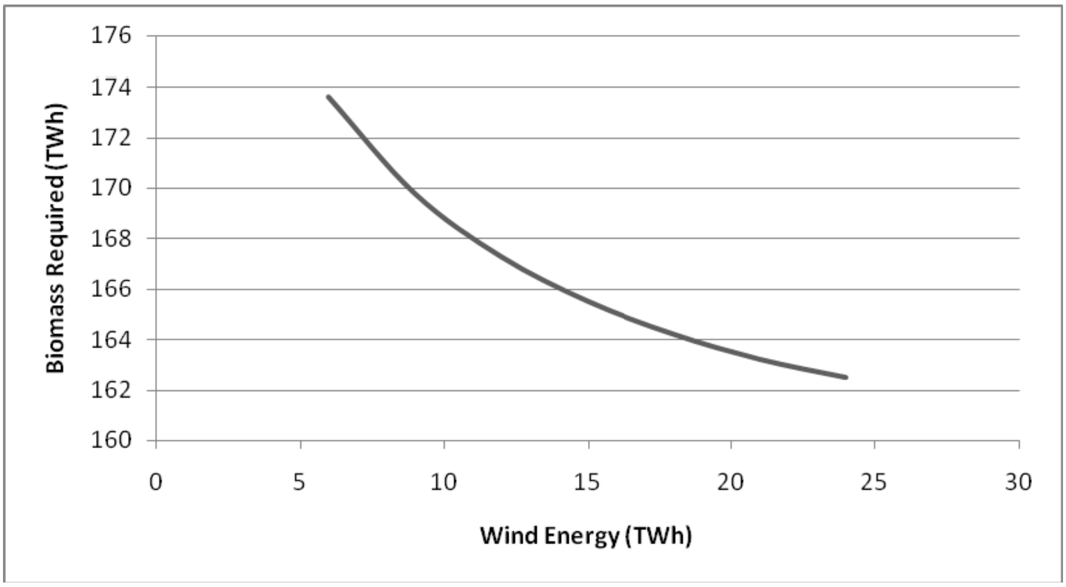

Figure 2: Biomass required for different wind capacities in the biomass energy-system

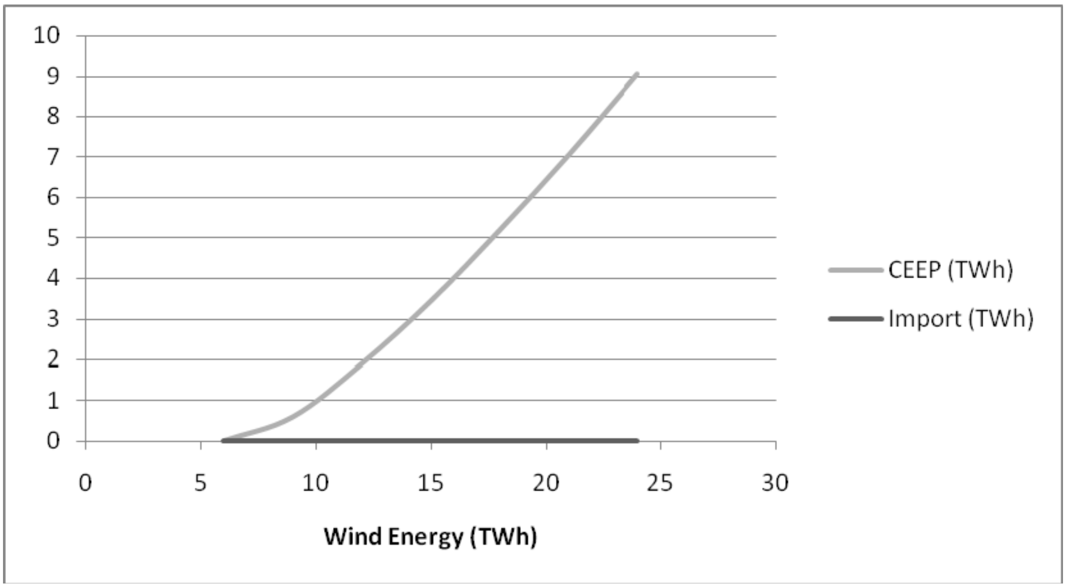

Figure 3: CEEP and imported electricity required for different wind capacities in the BES

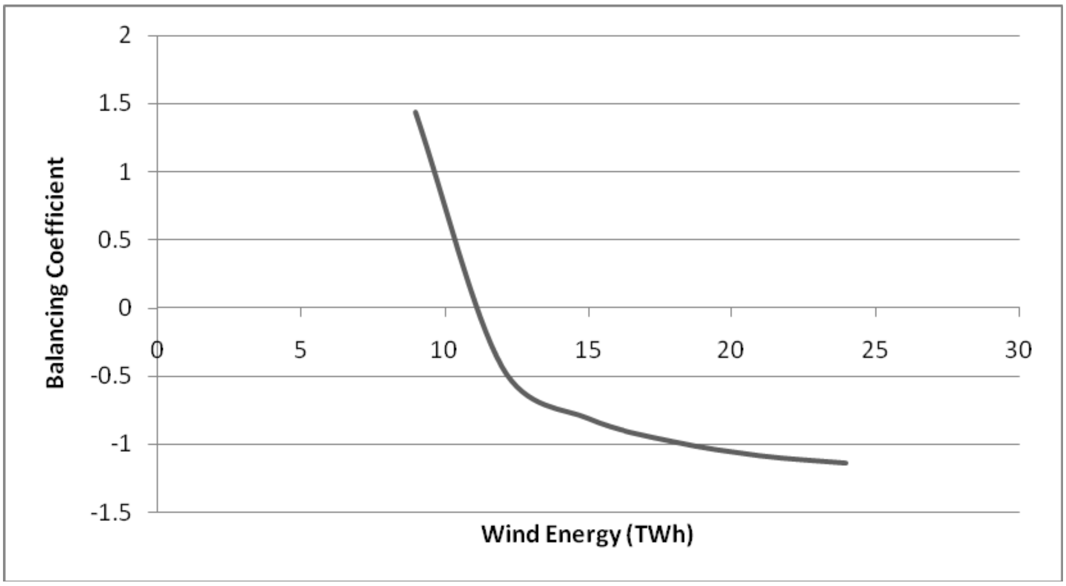

Figure 4: Balancing coefficient results for biomass energy-system

RESULTS AND DISCUSSION

Using the methodology defined above, the three scenarios displayed in Figure 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.

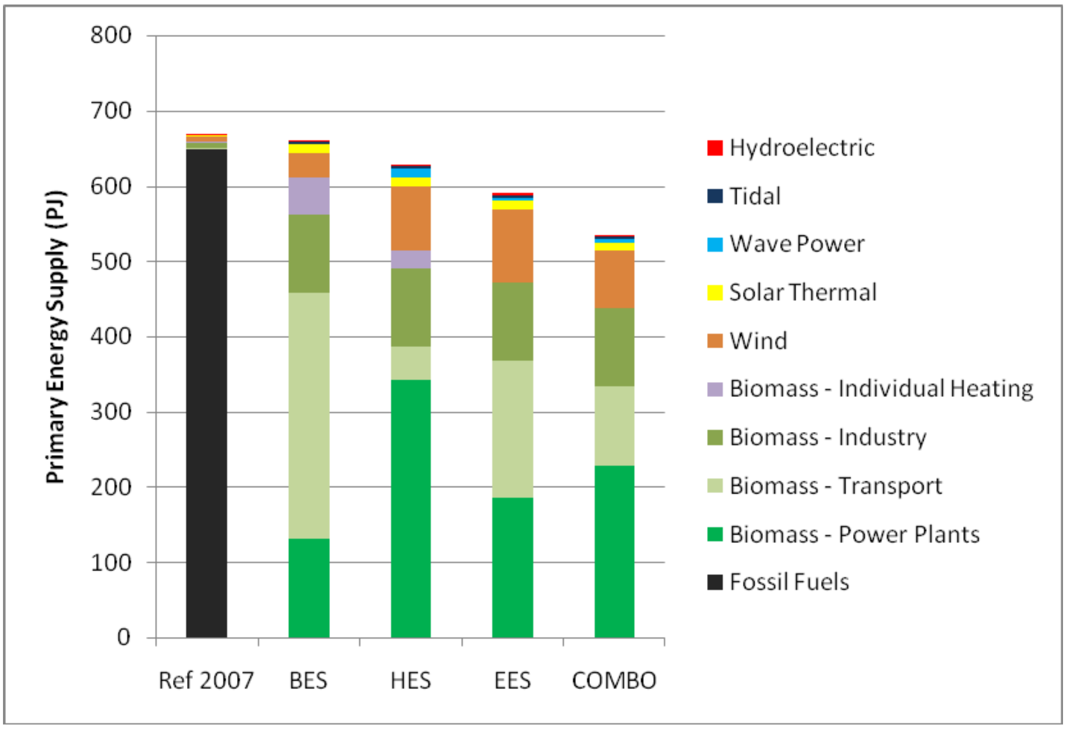

Figure 5: Reference, BES, HES, EES and COMBO energy-systems

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, H_2 micro CHP and transport as displayed in Figure 6. The EES uses a large amount of electricity for electric heating and transportation, while the electric vehicles can also act as large sink for excess renewable energy.

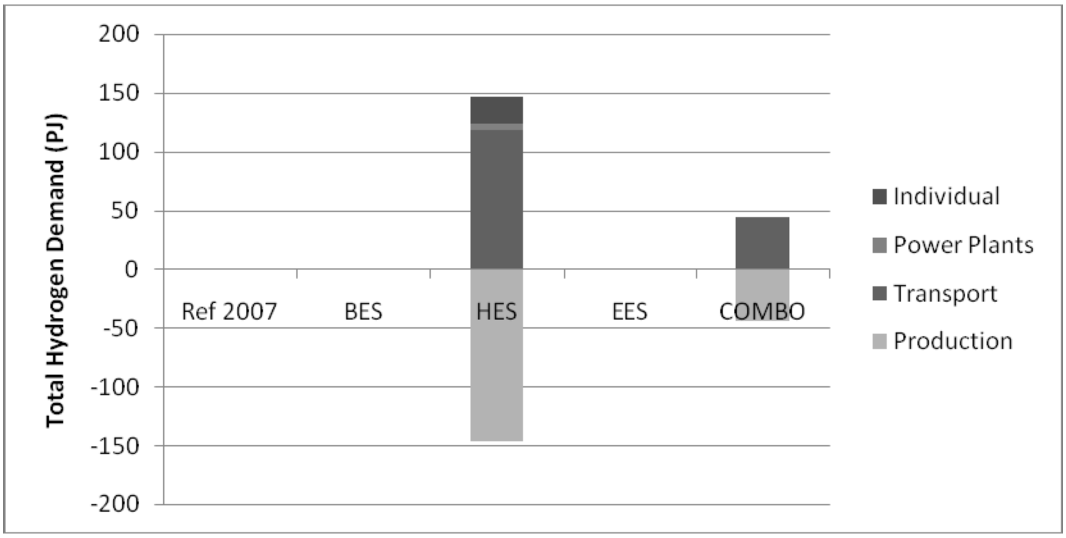

Figure 6: Use of hydrogen in reference, BES, HES, EES and COMBO

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 1,500 people
6. Introduce 251 MW (0.92 TWh) of tidal power
7. Introduce 1,000 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 Figure 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 [28]. 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 the challenge of 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.

FUTURE WORK

This study has identified four technically-feasible 100% RES for Ireland. 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. Nonetheless, the objective of this study is to illustrate that a 100% RES is feasible, and can be achieved from a technical perspective. 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 energy model. With this in mind, the following objectives have been set for the future work in this study:

1. To create a market optimisation in addition to the technical optimisation of the Irish energy-system using EnergyPLAN, so that the most economic transition to a 100% renewable energy-system can also be analysed.
2. To consult with experts within the relevant areas to obtain a more accurate and realistic illustration of the future Irish energy-system
3. To analyse the benefits of each alternative individually. A few examples are identified below:
    a. What are the effects of battery electric-vehicles (BEV), smart electric-vehicles (SEV) or vehicle-to-grid (V2G)?
    b. Is the transformation from condensing power-plants and individual boilers to CHP and district heating, more cost-effective than the introduction of large-scale electricity-energy-storage and electric heating?
    c. Is there an optimal combination of the renewable energy sources available in Ireland i.e. optimal combination of wind, wave, photovoltaic and tidal power?
    d. Are energy reductions more beneficial than extra capacity?
    e. How much biomass should be utilised for energy production?

   By analysing these issues individually, it is hoped that the sequence of steps on the pathway towards a 100% RES can be extracted, by identifying which steps are the most beneficial and which are the least.
4. To quantify the socio-economic benefits of the transition to a 100% RES such as job creation, increased export potential, improved balance-of-payment etc.

5. Finally, to create a realistic first step towards a 100% RES for Ireland by identifying what the objectives should be for a pre 100% renewable-energy Ireland, such as those that can be achieved by 2020 or 2030. This is once again similar to the methodology proposed by Lund and Mathiesen [14] who identified a 50% RES in Denmark by 2030.

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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