Implementing cleaner heating solutions towards a future low-carbon scenario in Ireland

Thellufsen, Jakob Zinck; Nielsen, Steffen; Lund, Henrik

Published in:
Journal of Cleaner Production

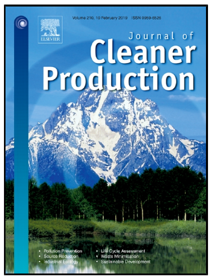
DOI (link to publication from Publisher):
10.1016/j.jclepro.2018.12.303

Publication date:
2019

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Thellufsen, J. Z., Nielsen, S., & Lund, H. (2019). Implementing cleaner heating solutions towards a future low-carbon scenario in Ireland. *Journal of Cleaner Production*, *214*, 377-388. https://doi.org/10.1016/j.jclepro.2018.12.303

Accepted Manuscript



Implementing cleaner heating solutions towards a future low-carbon scenario in Ireland

Jakob Zinck Thellufsen, Steffen Nielsen, Henrik Lund

PII:	S0959-6526(18)34034-4
DOI:	10.1016/j.jclepro.2018.12.303
Reference:	JCLP 15361
To appear in:	*Journal of Cleaner Production*
Received Date:	09 July 2018
Accepted Date:	29 December 2018

Please cite this article as: Jakob Zinck Thellufsen, Steffen Nielsen, Henrik Lund, Implementing cleaner heating solutions towards a future low-carbon scenario in Ireland, *Journal of Cleaner Production* (2018), doi: 10.1016/j.jclepro.2018.12.303

Implementing cleaner heating solutions towards a future low-carbon scenario in Ireland

Authors: Jakob Zinck Thellufsen*[a], Steffen Nielsen[b], Henrik Lund[c]

*Corresponding author

[a]Department of Planning, Aalborg University, Rendsburggade 14, 9000 Aalborg, Denmark

jakobzt@plan.aau.dk

[b]Department of Planning, Aalborg University, Rendsburggade 14, 9000 Aalborg, Denmark

steffenn@plan.aau.dk

[c]Department of Planning, Aalborg University, Rendsburggade 14, 9000 Aalborg, Denmark

lund@plan.aau.dk

Abstract

Studies show that energy efficiency should play a significant role towards achieving cost-efficient 100% renewable energy systems. One way to attain cleaner heating solutions for the future is to utilise waste heat from power plants and industry through district heating. In the European Union, approximately 50% of thermal energy is lost in conversion processes. This research paper investigates the potential for the implementation of district heating in a future energy system originally intended not to include district heating. The paper approaches the problem by utilising TIMES modelling to frame the initial future energy system. However, MARKAL/TIMES is not ideal to investigate the operation of different heating scenarios, due to a lack of hourly modelling. Hence, the study utilises EnergyPLAN to investigate the implementation of district heating as an alternative heating scenario to individual heating. EnergyPLAN allows for simulating the hourly operation of not only electricity systems but also heating systems. The study investigates the implementation of district heating in the CO2-80 scenario created with the Irish TIMES model. As the Irish CO2-80 scenario does not include district heating, this study uses EnergyPLAN to simulate an 80% reduction scenario, with and without district heating, to compare the operation of the two systems. A sensitivity analysis is included to reflect on the uncertainties of the study. The results show that a district heating solution is more fuel-efficient while more investment heavy, however the fuel savings more than compensates for the increased investments. In total, the district heating scenario is close to 300 M € cheaper in annual costs than the individual heating scenario for Ireland, and achieves a fuel efficiency increase of 3.5% in the whole energy system due to an efficiency increase in the heating sector. The article shows both the relevance of using multiple models, and the need to consider district heating in a future Irish energy system

Keywords: EnergyPLAN; MARKAL/TIMES; District heating; Energy Systems Analysis; Energy Systems Modelling

1 Introduction

The Heat Roadmap Europe studies found that over 50% of the thermal energy in the European Union in 2010 was lost during energy conversion processes, and thus emphasised the need to focus on increased energy efficiency [1]. In the transition to future renewable energy systems, an increase in energy efficiency seems very beneficial [2–4]. This benefit and potential have been shown in many studies, among others for Denmark [5], Europe [6], Turkey [7], the US [8] and Azerbaijan [9]. Increased energy efficiency can be achieved in several ways, for instance, lower consumption by the end user [10–14]; more fuel-efficient production, such as combined heat and power production [9]; and utilisation of waste resources like heat from industry [15,16], especially relevant in fourth-generation district heating [17].

The Heat Roadmap Europe studies [1,18,19] were done to identify how the heating sector in Europe can be designed to be more energy efficient. The studies investigated several heating options for Europe; one of the main conclusions is that by utilising energy efficiency measures like combined heat and power, industrial waste-heat, and district heating it is possible to change the heating sector in Europe [1,14,20]. The argument is that when comparing primary energy use to actual heating end use, as shown in Figure 1, the amount of energy wasted from electricity production and industrial processes could ideally fulfil the heating demands of Europe. Obviously, it is not that simple, since temperature levels matter [21,22] and not all heated buildings are situated in dense urban areas that potentially can be reached by district heating grids [23,24]. However, based on the spatial mapping in the second Heat Roadmap Europe study, district heating can theoretically cover 50% of the heating demand in Europe [1], highlighting the potential for more efficient energy utilisation.

It is important to mention that the availability of waste heat currently ties to the use of fossil fuels in industry and thermal power plants. In future 100% renewable energy systems, less waste heat from thermal power plants can be expected, as more renewable energy sources enter the energy system and replaces the thermal power plants. However, the thermal power plant capacity is still needed for regulation, and waste heat from industrial processes will still be available, and can be utilised efficiently in district heating [17]. Add to this, the flexible use of thermal storage in relation to heat pumps, where district heating has an important role to play in future renewable energy systems [6], even if they in many cases were or will be built based on the availability of waste heat. Furthermore, district heating can improve the local air quality compared to areas normally heated by individual boilers [25].

The heating systems in individual European countries are very diverse in terms of supply technologies [26,27]. In certain countries, like Denmark, Sweden, Finland, Estonia, Latvia and Lithuania, over 50% of consumers are connected to district heating systems [28], while in the UK, Switzerland, the Netherlands and France, less than 10% of consumers are connected to district heating systems[28]. These countries are predominantly heated by individual solutions, such as gas boilers or electric heating [26]. Figure 1 shows the cities in Europe with district heating systems; however, the figure does not show the size of these systems.

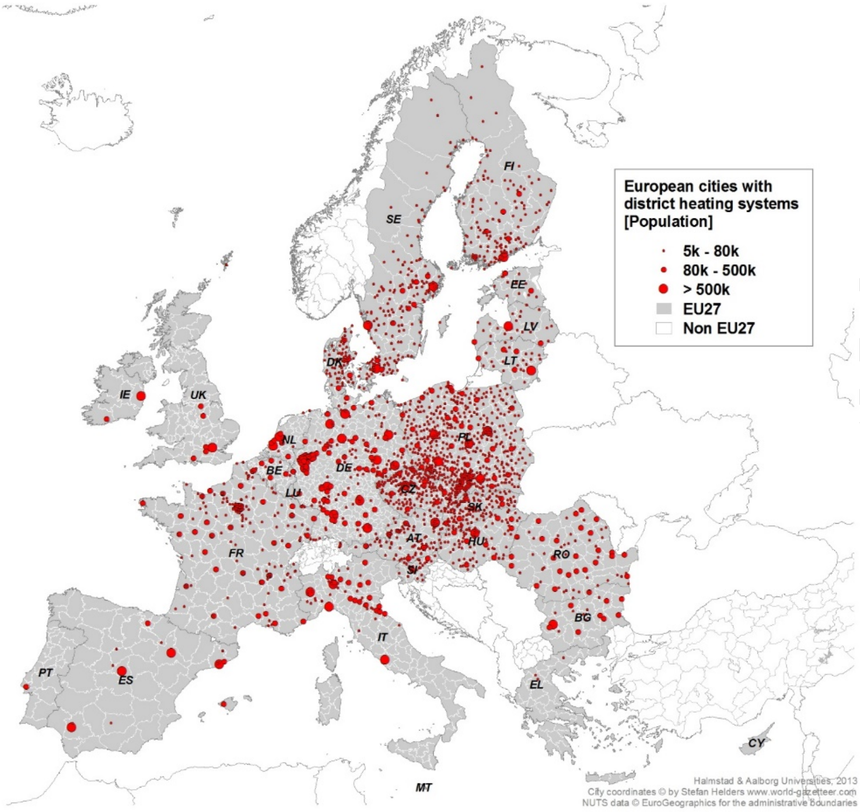


Figure 1. District heating systems in Europe in cities with over 5,000 inhabitants. [29]

While district heating has the benefit of utilising waste heat, it also carries the risk of being inefficient if the density of heat consumers is low [30] or if insufficient numbers of heat consumers are connected to the grid [30]. It is therefore necessary to make individual analyses of specific countries, since the heating demands, density of cities and other parameters vary depending on geographic location. This is partly accomplished in the studies for Heat Roadmap Europe 3 [19] and 4 [31].

Based on this knowledge, the goal of this paper is to investigate potential cleaner heating scenarios for countries with little tradition for district heating relying on individual boilers. District heating can improve air quality in urban areas [25,32] and expansion of district heating can lead to lower CO_2 emissions [33]. Specifically, the paper investigates Ireland. Ireland currently has very little district heating with less than 1% of the heat demand currently covered by district heating [34]. Currently, the main heating sources are individual electric boilers and individual gas boilers. However, a CODEMA analysis shows that potentially 75% of the heat demand in the Capital Dublin can be covered by district heating [35], and in total, the Heat Roadmap Europe studies show that there is a potential for 37% district heating nationally [1]. Furthermore, low-carbon scenarios for the future energy systems of Ireland have been modelled using the Irish TIMES model [36]. While district heating for Ireland has been investigated as part of Green Plan Ireland [37,38], this paper takes a different approach. Countries with no district heating can have well-established scenarios for transitioning to renewable energy systems or low carbon energy systems that do not take into account the possibility of district heating. Besides Ireland [39], examples are the UK [40], Japan [41] and the Netherlands [42]. One reason is that the tools used for the investigation of future scenarios in these countries currently do not consider district heating solutions, one example is the Irish TIMES model. The goal of this paper is therefore to investigate if district heating can be a feasible option for Ireland. This investigation has the intention of analysing the implementation of district heating in Ireland on an overall level, discussing if it can be a feasible solution. It does this within the framework of a well-established 2050 scenario for Ireland that does not include district heating. The study therefore contributes to the discussion of whether district heating can be a feasible option, even if it was not considered by the initial optimisation tool.

Specifically, the paper investigates the consequence of implementing district heating in the CO2-80 Scenario, which is a result form the Irish TIMES model. The CO2-80 Scenario suggests a technological pathway to reduce the carbon emissions in the Irish energy system by 80% in 2050 based on given technology cost This makes TIMES efficient at identifying a specific solution when many alternatives exists. Thus TIMES has the advantage of identifying initial suggestions for alternative energy systems. However, the Irish TIMES model currently is not able to model district heating. To model the district heating system, a two-model approach has been chosen. This means that instead of enabling the Irish TIMES model to consider district heating, EnergyPLAN is instead used to simulate the heating scenarios. Thus, the study uses EnergyPLAN to model the CO2-80 scenario as both a reference without district heating and an alternative scenario with district heating. EnergyPLAN is chosen due to its capabilities within heat modelling and hourly simulation of the heating system including chronically modelling of storage [11,12,43,44]. Other tools might provide similar benefits in other cases. These include EnergyPRO [45,46] and TRNSYS [47]. There are several examples of linking between TIMES and other energy system analysis tools to achieve this insight into system operation of the electricity system in a given scenario [48–52]. Using EnergyPLAN and TIMES can potentially provide similar insights into the operation of a district heating system, where TIMES identifies the layout of the overall energy system and EnergyPLAN is used to simulate different alternatives and the hourly operation of these. These insights are not achieved through the already-established linking procedures to other tools, as they focus on the electricity sector. The reasons why EnergyPLAN is used instead of implementing district heating as an option the Irish TIMES modelling are: 1) an hourly simulation of the heating system is still needed to sufficiently assess the consequences of different heating scenario. Thus, the two-model approach helps solving the problem better than if only one model was used. 2) It is a more flexible solution as it can be applied to other models that are not able to identify district heating solution. Thus, the paper serves as inspiration for other cases that might be based on different software than TIMES.

2 Methods

The primary method in this article is to identify how to link the two models, so that EnergyPLAN is able to interpret the inputs and outputs from the Irish TIMES model. The linking of the two models is necessary for the first part of the analysis, which investigates the reference scenario with only individual heating solutions. The second part of the analysis requires a change in the heating system, with a share of the individual heating being converted into district heating. As hourly operation of the district heating system is required, this analysis is made in EnergyPLAN.

2.1 TIMES and the Irish TIMES model

The Irish TIMES model is the Irish adaptation of the TIMES modelling framework. The TIMES (The Integrated MARKAL-EFOM System) modelling framework is developed and maintained by one of the International Energy Agency's Technology Collaboration Programmes, IEA-ETSAP (https://iea-etsap.org/). TIMES models are used by approximately 200 teams in 70 countries to build energy technology pathways that meet future energy service demands at least cost. The modeller can impose constraints to reflect policy targets (e.g. maximum levels of emissions, minimum levels of renewable energy). In this way, policymakers can learn about least-cost solutions to meet energy and climate targets; this is currently the greatest focus of TIMES modelling activities globally [53]. The fundamental mathematical basis for TIMES models is linear programming with practical equilibrium, and the models generally have perfect foresight for identifying the energy system based on linear optimisation [48,54].

TIMES models are generally used for medium- to long-term scenario development and analysis. This means that their main application is exploring how future energy systems develop over a long period (e.g. 20–50 years). This development is governed by the objective of finding the energy system that maximises the total (producer plus customer) surplus over the entire time horizon.

TIMES models comprise a large technology database (over 1,300 technologies) with current and future technical and economic parameters. Inputs include detailed information on the current energy system, future energy service demands (e.g. freight and passenger tonne kilometres, building useful energy requirements, etc.) for all sectors, and future fuel prices and available energy resources. Based on these inputs, TIMES models select energy technologies and their usage in each time period to provide the optimal least-cost energy system over the entire time horizon, for example to 2050 or 2100. Figure 2 presents a schematic diagram that shows this overall approach.

Due to the long time horizon applied in TIMES analyses, the tool is rarely used with an hourly time resolution. Instead, it splits a given year into a reduced number of time slices, typically between eight and twenty, to capture seasonal variation, weekdays and weekends, and morning, peak and night-time demands. The focus is clearly on the long term, which poses a challenge when trying to incorporate short-term operation issues facing the power or heating system, e.g. when there is a large share of variable non-synchronous renewable energy or energy storage [51].

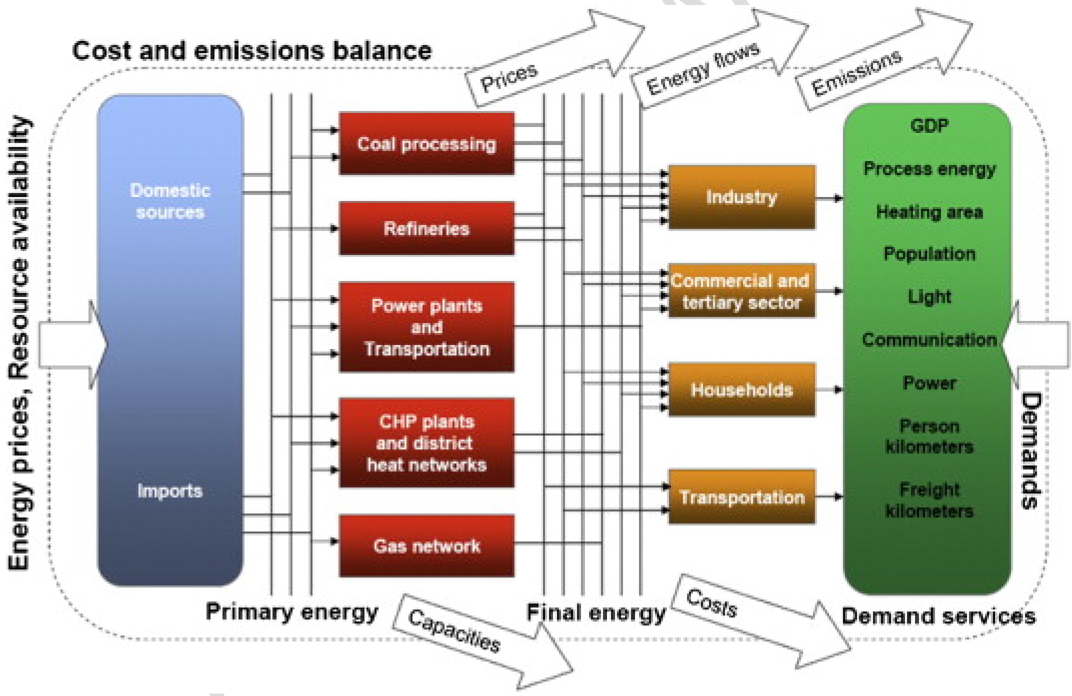


Figure 2. Overview of the TIMES tool. Arrows pointing out show the outputs from the model. [55]

The Irish TIMES model is specifically developed to investigate the transition of the Irish energy system. Based on the general structure of TIMES, this means it investigates long-term solutions, without hourly resolution modelling. Irish TIMES has an extensive database of technology, regarding both production technology and demand side technology, potentially usable in a future Irish energy system. However, the Irish TIMES model is currently not able to model district heating solution as an alternative the individual solutions.

Several scenarios has been made for Ireland using the model [36,39,56,57]. The baseline scenario in this study is the 2050 CO2-80 scenario. Section 3 describes the scenario more in detail.

2.2 EnergyPLAN and heat modelling

EnergyPLAN is a deterministic input-output model that simulates the yearly operation of an energy system on an hourly level [58,59]. It includes all sectors of the energy system and can link them with each other. This means it considers heating, cooling, electricity, transport and industry. Figure 3 shows the structure of EnergyPLAN.

EnergyPLAN models the heating sector as different demands. Primarily divided into individual heating and district heating. As Figure 3 shows, EnergyPLAN is able to account for waste heat from industry and heat from CHP plants within the district heating sector. The district heating modelling can be divided into three groups, 1) small district heating areas only with boilers; 2) small decentralized district heating areas with CHP; and 3) large centralized district heating areas with CHP. This allows for the utilisation of spatial data on heat demands by interpreting those into any of these three categories. EnergyPLAN is therefore capable of handling the differences in heat demands depending on location. It is also able to align with the electricity sector and identify production hours for heat pumps and how this balances with thermal storages. This provides a meaningful level of detail to the analysis, especially combined with the hourly simulation capabilities of EnergyPLAN and its ability to track the energy content of storages chronologically.

EnergyPLAN has in many cases been used to model the transition to future energy systems and to investigate countries' or cities' entire energy systems. Examples include Copenhagen [60], Aalborg [61], Frederikshavn [62,63], Denmark [64], Ireland [37,65] and Brazil [2]. It has also been used to test the implementation of various technologies, such as vehicle-to-grid [66], CAES [67], energy savings [11,12], heat pumps [68] and wind turbines [69]. In these cases, the aim was to investigate different options for fulfilling the heat demand in various energy systems. EnergyPLAN has historically been used to compare heat pumps with other solutions such as electrical boilers, district heating and individual fuel boilers [20,38,68]. The tool has also been used to quantify the potential utilisation of district heating [20,70,71]. Furthermore, it has been used for comparing district heating and heat savings [11]. Finally, the tool has been used for the design of heating systems in future renewable energy systems [5,38,72]; one of these cases is Green Plan Ireland. This makes EnergyPLAN suitable as a tool for investigating heating solutions in a least-cost scenario generated by the Irish TIMES model.

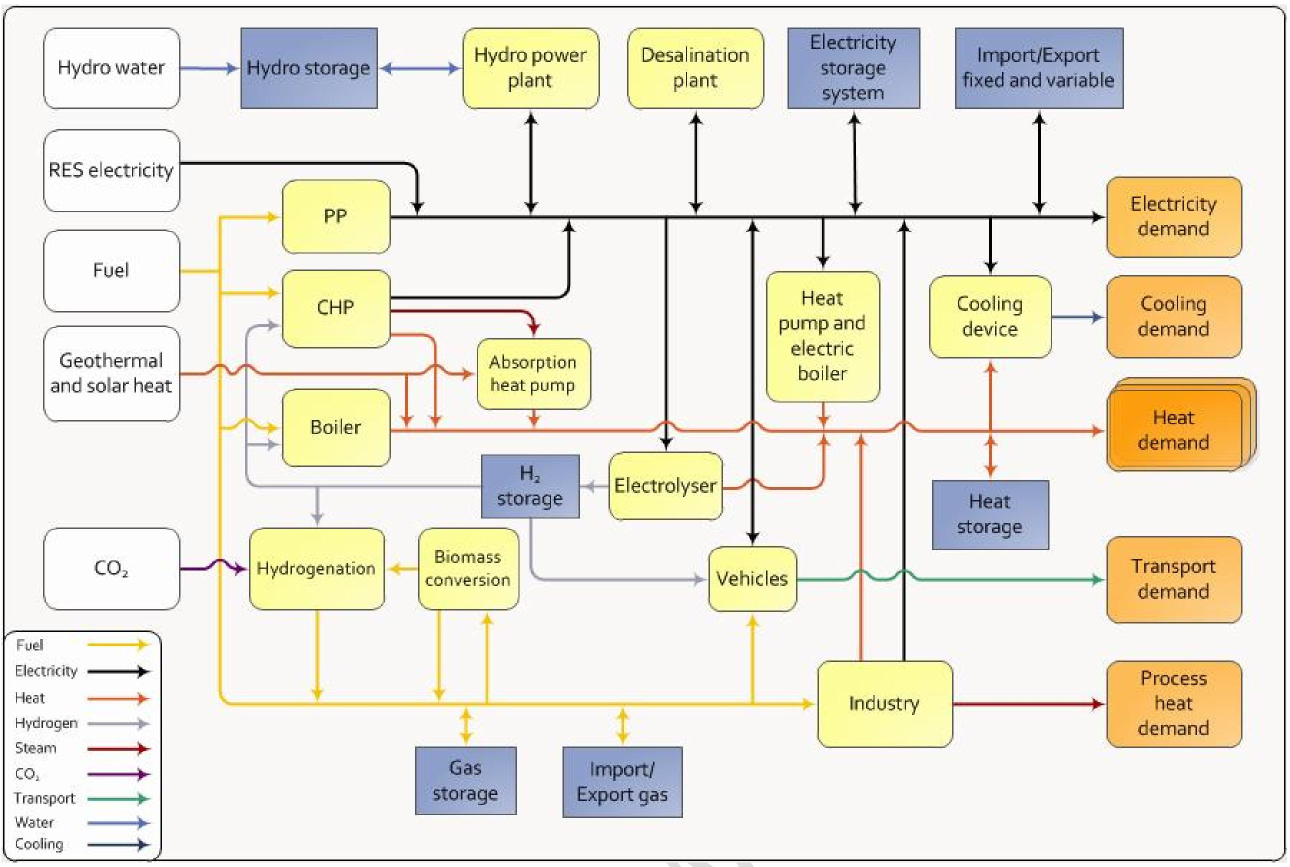


Figure 3. Overview of the EnergyPLAN model and its approach to an energy system. [58]

2.3 Linking Irish TIMES to EnergyPLAN

To accomplish the linking from Irish TIMES to EnergyPLAN to enable the investigation of heating scenarios in EnergyPLAN, the study suggests the following procedure, outlined in Figure 4.

The process of linking the tools follows a number of steps in order, whereby some steps generate data for the Irish TIMES model, some generate data for EnergyPLAN, and others are relevant for both tools. The steps can be replicated for transferring and linking other tools albeit some differences might occur. The steps are:

1) Define inputs needed to run the TIMES model. These include a model of the reference energy systems, available technologies from which TIMES will create the scenarios, and certain restrictions like targets for reductions of CO_2 emissions.
2) Define the common inputs needed for both TIMES and EnergyPLAN. These are primarily cost assumptions regarding both fuel prices and investment costs, lifetimes, and operation and maintenance costs of the technologies. Furthermore, assumptions regarding discount rates are important to define here as common variables for both TIMES and EnergyPLAN.
3) Run the TIMES model based on these assumptions.
4) Implement the outputs from the MARKAL/TIMES run into creating an EnergyPLAN model. The EnergyPLAN model should be based on the following outputs from the MARKAL/TIMES model:
    a. Demands for the energy sectors. Electricity demands, heating demands, transport demands and energy demands.

   b. Capacities for energy conversion technologies. Boilers, power plants, solar power, wind turbines and others.
   c. Efficiencies of the technologies in the scenario defined in the MARKAL/TIMES model.
5) Implement EnergyPLAN-specific inputs into the EnergyPLAN model. These are hourly distributions of demands and, potentially, technologies that a given MARKAL/TIMES model is not able to handle.
6) Simulate the EnergyPLAN system.
7) Outputs and results from EnergyPLAN.

In this case, the Irish TIMES scenario already existed, thus the majority of the work occurred in step four: creating the right interface between the TIMES outputs and the fixed structure of EnergyPLAN inputs. This paper illustrates one way of creating the interface for the heating scenarios for Ireland. The translation from TIMES to EnergyPLAN is specific for this paper. Nevertheless, it might serve as inspiration for others working with using multiple tools to approach energy planning problems.

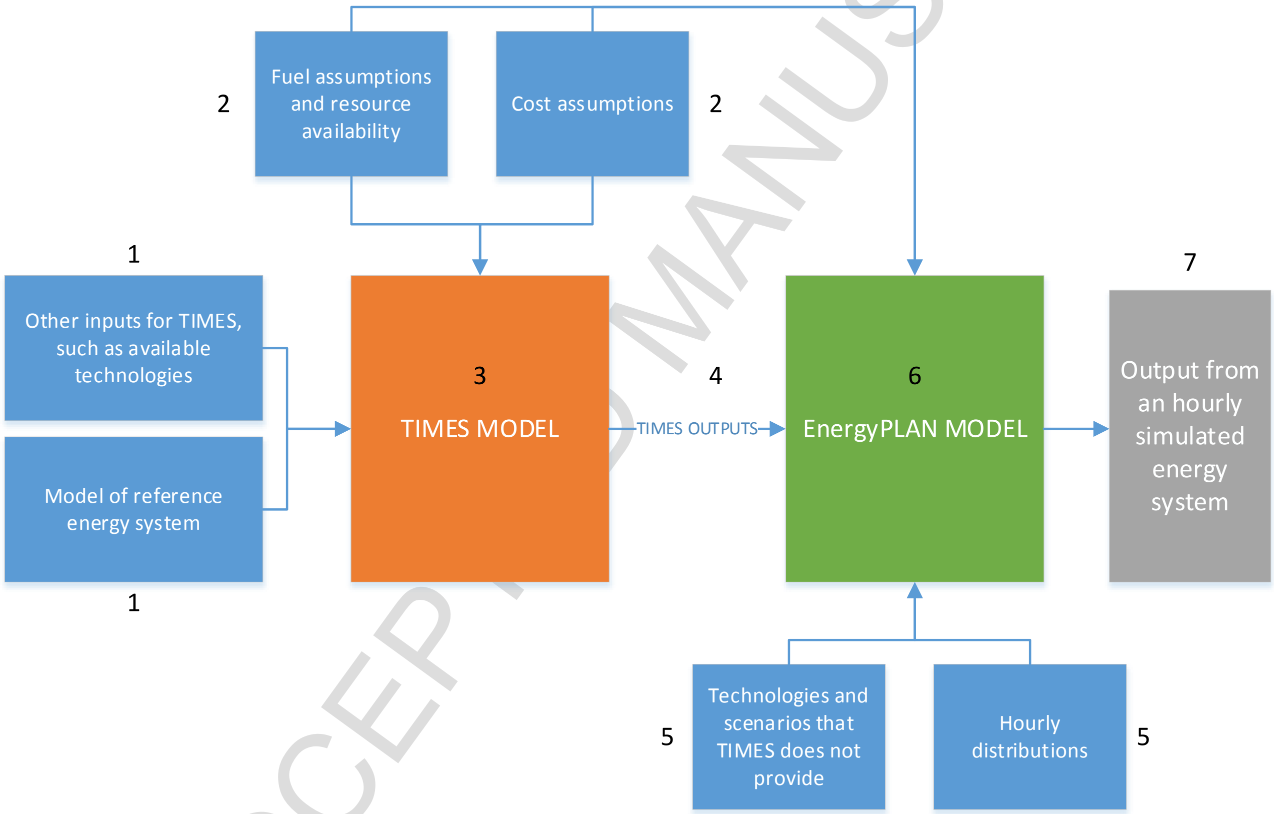


Figure 4. Scheme of the soft-linking procedure between the Irish TIMES model and the EnergyPLAN model.

3 Converting the CO2-80 Scenario from Irish TIMES to EnergyPLAN

This section points to the main assumptions behind the CO2-80 scenario from Irish TIMES and details how these are converted to fit the EnergyPLAN modelling framework. The Irish TIMES CO2-80 scenario background data is documented here. [73].

The intention of the Irish CO2-80 scenario is to identify low-cost scenarios for 80% reduction in carbon emissions in Ireland from 1990 to 2050. These are based on investment and price databases. The fuel costs are based on the World Energy Outlook 2012 report [73]. Since the constraint of the model is to identify low carbon scenarios, a marginal abatement cost is identified for the modelled year. In 2050, it results in a cost of 336 €/tonne CO_2, compared to 74 €/tonne CO_2 in 2020. The resulting energy system of the CO2-80 scenario from Irish times is shown in Figure 5.

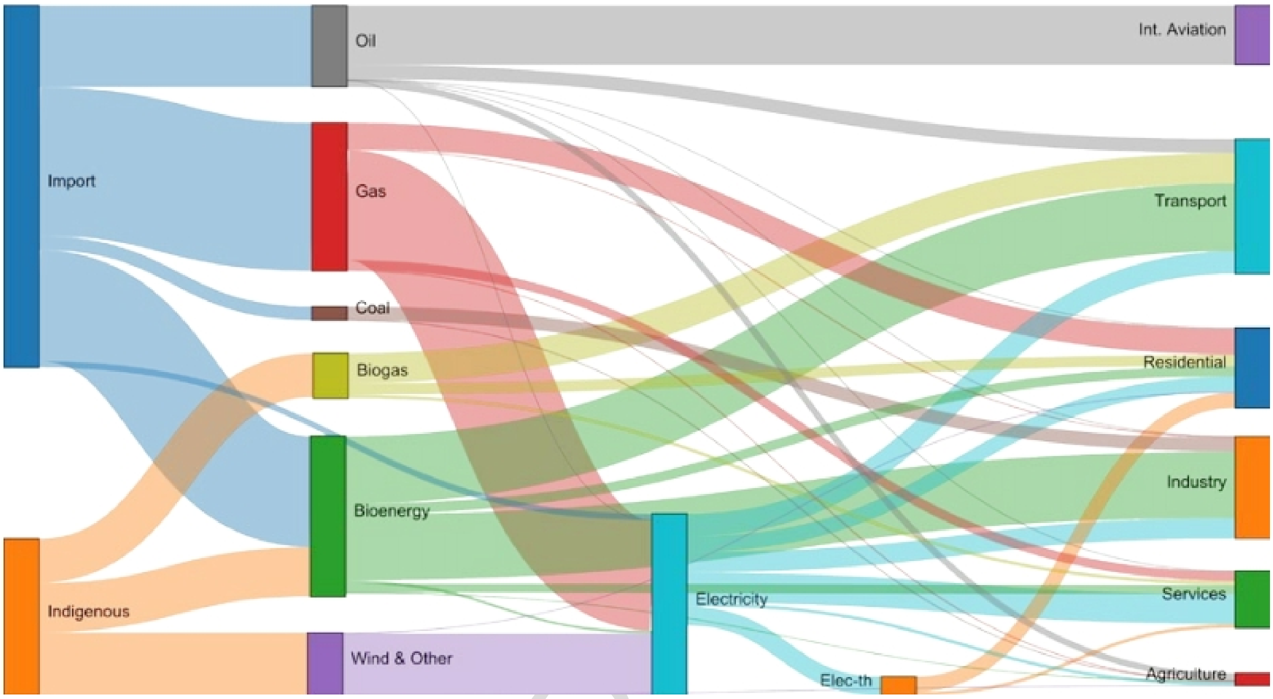


Figure 5. Sankey diagram of the energy consumption in the Irish CO2-80 scenario [73].

The Irish TIMES demand categories have to be summarised in the following four categories in EnergyPLAN: electricity, individual heating, industry and various, and transport. These aggregations are detailed in Table 1.

	Irish TIMES CO2-80	EnergyPLAN
General electricity demand [TWh]	26.34	26.34
Individual heating (fuel) [TWh]		
Oil		0.07
Commercial oil	0.07	
Residential oil	0.00	
Gas		14.96
Commercial gas	3.50	
Residential gas	7.12	
Biogas	4.34	
Biomass		6.00
Commercial biomass	2.90	
Residential biomass	3.11	

Electric heating		6.41
Commercial electric	1.11	
Residential electric	5.30	
Industry (fuel) [TWh]		
Coal	4.87	4.87
Oil		6.97
Industrial energy	0.05	
Industrial non-energy	6.92	
		0.40
Natural gas	0.04	19.88
Biomass	19.88	
Various/agriculture (fuel) [TWh]		
Coal	0.00	0.00
Oil	1.99	1.99
Natural gas	0.38	0.38
Biomass	0.35	0.35
Transport (fuel) [TWh]		
Jet fuel (fossil)	17.89	17.89
Diesel (fossil)		4.23
Diesel	3.44	
Heavy fuel oil	0.79	
Diesel (biofuel)	8.93	8.93
Diesel (electrofuel)	4.71	4.71
Petrol (fossil)		0.69
Gasoline	0.65	
Transport kerosene	0.04	
Petrol (biofuel)	10.54	10.53
Gas (biogas)	5.25	5.12
Electric		6.65
Battery	5.78	
Electric	0.87	

Table 1. Demand outputs in Irish TIMES and the demand inputs for EnergyPLAN.

The reference scenario is based on individual heating, utilising individual boilers. To identify the boiler efficiency for individual heating, the individual technology data sheet in the Irish TIMES model for the CO2-80 scenario is used. Table 2 indicates the identified efficiencies for the boilers in EnergyPLAN based on the available technology sheets.

	EnergyPLAN
Boiler efficiencies	
Oil	0.95
Natural gas	0.95
Biomass	0.81
Electric heating	1.00

Table 2. Efficiency outputs/inputs from TIMES and the resulting capacity inputs for EnergyPLAN for individual heating.

Based on the TIMES results, the power plants in the Irish system are divided into CCS and non-CCS power plants. Table 3 shows the transformation of system outputs from the Irish TIMES CO2-80 scenario into EnergyPLAN inputs for power plants. The table also shows the total amount of carbon captured in CCS. This amount includes both power plants and industry. The efficiencies are identified based on electricity production and fuel consumption, which means they are the annual average efficiency. To match the operation of the energy system, the oil consumption in power plants is slightly higher in EnergyPLAN than in the Irish TIMES model.

	Irish TIMES CO2-80	EnergyPLAN
Power plant capacity [MW]		
Non-CCS	1,581	1,581
CCS	1,525	1,525
Power plant electric efficiency		
Non-CCS	0.63	0.63
CCS	0.48	0.48
Power plant fuel [TWh]		
Non-CCS	0.09 oil | 6.85 gas	0.19 oil | 6.85 gas
CCS	23.66 gas	23.66 gas
Renewable energy capacity [MW]		
Onshore wind	5,341	5,340
Solar PV	2,153	2,150
River hydro	342	342
Total amount of CO_2 captured in CCS (power plants + industry) [Mton]		5.84
From electricity production	4.20	
From industry	1.64	

Table 3. Capacity and efficiency outputs/inputs from TIMES and the resulting capacity inputs for EnergyPLAN for power production.

Irish TIMES and EnergyPLAN have different approaches to the modelling of biogas as well as of biofuels and electrofuels for the transport sector. TIMES allows for the import of biofuels and biomass, while EnergyPLAN only considers the import of biomass for local biofuel plants. Thus, in EnergyPLAN, in this study, the biomass is calculated as being equal to the biofuel production, both for biodiesel and bio petrol.

The Irish TIMES CO2-80 scenario identifies two sources of biogas production: from biogas plants and as a waste product from biomass gasification. The EnergyPLAN model uses the specifications from the biorefinery process in the Irish TIMES model as the inputs for biomass gasification. Hence, it is necessary to tweak the efficiencies of biomass gasification to fit the outputs defined in TIMES.

Biogas is used in the transportation and heating sectors. To reflect this, EnergyPLAN accounts it as gas production and uses it in the respective gas for heating and gas for transport inputs. In the Irish TIMES CO2-80 scenario, the final DME electrofuel demand is 4.71 TWh. The EnergyPLAN representation assumes that the DME electrofuels are produced within Ireland and includes electrolysers and hydrogenation. Thus, based on the assumption of 80% efficiency of conversion from synthetic grid gas to DME, an efficiency of 80% and a hydrogen share of 36% for synthetic grid gas production, the EnergyPLAN inputs are defined. These efficiencies resemble the ones identified in [74].

Table 4 shows these inputs necessary to construct the biorefinery and biogas production in EnergyPLAN.

	Irish TIMES CO2-80	EnergyPLAN
Biodiesel plant [TWh]		
Biomass input	-	8.93
Biodiesel output	8.93	8.93
Bio petrol plant [TWh]		
Biomass input	-	10.53
Bio petrol output	10.53	10.53
Biogas [TWh]		
Biogas plant output	9.10	9.10
Waste biogas from gasification plant	0.37	0.37
Synthetic fuel production [TWh]		
- Biomass input for gasification plant	9.5	9.5
- Syngas demand from gasification plant	4.72	4.72
Hydrogen production [MW]		
Electrolysers for electrofuels	-	500
Biomass hydrogenation output [TWh]		
Synthetic grid gas for electrofuels	-	5.89
Electrofuel demand		
Diesel	4.71	4.71

Table 4. Inputs for the generation of biogas, biofuels and synthetic fuels.

In the Irish TIMES CO2-80 scenario, the energy system is set up to curtail wind and solar in hours of excess production (unless power-to-gas or energy storage are economically attractive alternatives) and when inertia constraints are not met. Distribution files are the same as used in Green Plan Ireland [38]. EnergyPLAN simulates the energy system based on minimising fuel consumption by regulating the combined heat and power plants in relation to both electricity and heat demands.

Figures 6 and 7 show the results of the comparison of the EnergyPLAN replication of the Irish TIMES CO2-80 scenario. Figure 6 compares the primary energy consumption, including fuel for aviation and exported industrial goods, while Figure 5 compares CO_2 emissions excluding emissions from international transport and exported industrial goods.

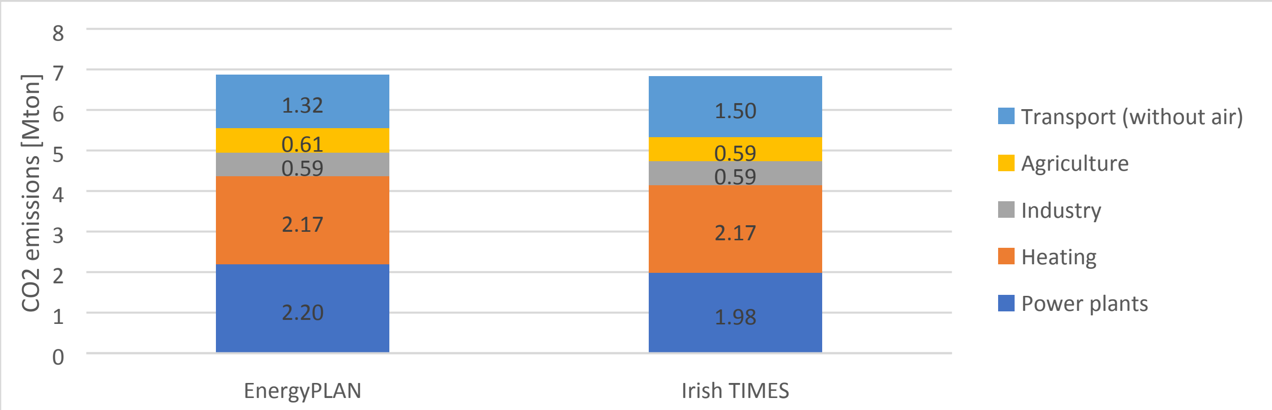


Figure 6. CO_2 emissions from the TIMES model and the EnergyPLAN model of the CO2-80 scenario, excluding CO_2 emissions from aviation and exported industrial goods.

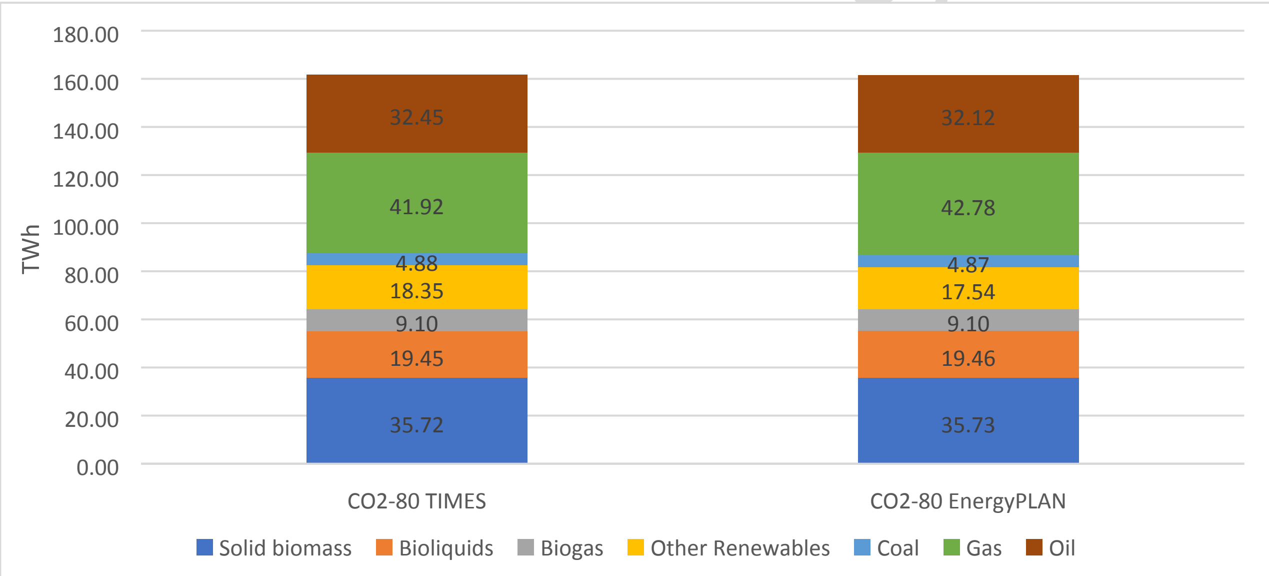


Figure 7. Primary energy consumption from the TIMES model and the EnergyPLAN model of the CO2-80 scenario, including fuel consumption for aviation and exported industrial goods.

Figure 6-7 show the performance of the reference scenario from Irish TIMES and that EnergyPLAN reaches similar performance in terms of primary energy and CO_2 emissions from the CO2-80 scenario. Both systems rely on the import of 2 TWh of electricity, also indicating that the system operation is similar.

4 Modelling a district heating scenario for Ireland

District heating for Ireland has been investigated in the Green Plan Ireland scenario [38] and for Dublin [35,75]. The present study uses the inputs from Green Plan Ireland to create the basis for the district heating scenarios implemented in this study. Green Plan Ireland has a different offset than TIMES CO2-80: it targets a 100% renewable energy scenario. Another major difference is that the TIMES CO2-80 scenario select carbon capture and storage on power plants as a least-cost pathway, whereas that technology has been ruled out for Green Plan Ireland. Since Green Plan Ireland not only uses power plants but also central, combined heat-and-power plants, some of the power plants from the CO2-80 scenario should be converted to combined heat-and-power plants. The annual costs reflect this change. In this study, the non-CCS power plants are converted to combined heat and power, while the CCS power plants remain as electricity-only producers. Another main difference is that the heat demand is different in the two models. Green Plan Ireland has a total heat demand of 28 TWh, whereas the CO2-80 scenario has a heat demand of 25.55 TWh, due to assumed efficiency measures at the individual household level in CO2-80 scenario. Thus, the heat demand from the TIMES scenario is used, but the share of converted heat demand is identified through Green Plan Ireland. This means that in total, 37% of the heating demand in Ireland is converted to district heating. The 37% is an assumption based on a spatial analysis of heat demand in Europe made in the Heat Roadmap Europe study [1]. It suggests that 50% of the heat demand in buildings are situated in areas with a heat density over 15 TJ/km^2. 33% of the heat demand in buildings are in areas with a heat density over 50 TJ/km^2. This results in that Green Plan Ireland suggests that 15% of the heat demand is converted to district heating from decentralised plants (smaller cities) and 22% of the heat demand is situated in centralised areas (larger cities).

In terms of cost assumptions, the main scenario applies the Irish TIMES cost assumptions for all the energy systems besides the district heating, in which the cost assumptions from Green Plan Ireland are used. Green Plan Ireland uses a district heating grid cost of 522 M€/TWh. This cost is based on the Danish Energy Agency's assumption for low temperature [17] district heating grids installed in already existing urban areas [76]. However, if current conventional temperatures in the district heating grid are desired, it is possible to reduce costs to 72 M€/TWh [76]; furthermore, the cost of a district heating grid may increase to up to 720 M€/TWh when implemented in rural areas or as low-temperature district heating in newly developed areas [76]. Thus, the price is highly sensitive to grid losses and the amount of energy transferred. These costs are based on a country where district heating is a common technology. The study therefore tests for these lower and higher grid costs. The costs reflect total costs for implementing the technology as a consumer.

The primary assumption for losses in the district heating grids is based on the Green Plan Ireland scenario and amounts to 10% in large urban areas and 15% in smaller cities and towns. These assumptions are also in line with the Danish Energy Agency's assumptions for district heating grids [76]. The assumptions for grid losses are also based on a low-temperature system. The losses may be higher in a traditional district heating system; thus, these are also included in the sensitivity analysis, where grid losses are increased to 20% and 25% of the heating demand in decentralised areas and 15% and 20% of the heat demand in centralised areas.

Thus, the study does take into account the uncertainty of the performance of the district heating grid implemented. It is hard to identify the actual grid losses since Ireland for now do not have an extensive district heating buildout. While energy efficiency is a natural companion to the transition to low temperature district heating, it is possible that low temperature heating can work in buildings and heating installations designed for the current generation of district heating [77,78]. This study therefore do not discuss the implementation of heat savings, but recognise its potential impact on the result.

Tables 5–6 show the technical inputs used for the district heating scenario. The district heating scenario converts approximately half of the individual gas boilers, and a small number of the individual electric and biomass boilers, to district heating. The total heat demand in Ireland comes from the Irish TIMES model, while the way it is distributed is based on the Green Plan Ireland scenario. The boilers are scaled to cover peak demands, while the sizes of the combined heat-and-power plants are identified through the Green Plan Ireland scenario. All the district heating technologies are new builds; however, the combined heat-and-power plants replace those power plants not utilising combined heat and power.

	Share of heat demand on DH	Grid loss	Heat demand [TWh]
Decentralised district heating	15%	15%	3.80
Centralised district heating	22%	10%	5.60
Individual gas boilers	-	-	7.10
Individual biomass boilers	-	-	3.65

363 Table 5. Heating demands in the district heating scenario.

	Electric capacity [MW]	Heat capacity [MW]	Electric efficiency	Heat efficiency
Decentralised combined heat and power	750	938	40%	50%
Centralised combined heat and power	1,581	872	58%	32%
Decentralised district heating boilers	-	1,000	-	90%
Centralised district heating boilers	-	1,500	-	90%

Table 6. Assumptions for combined heat-and-power plants and district heating boilers for the district heating scenario.

Tables 7–8 show the economic inputs for the individual heating scenario and the district heating scenario. Since the study only changes the composition of power plants and heating units, only these investment costs are included here, as the others remain fixed. The cost assumptions are total investments before discounts. The fixed operation and maintenance costs are estimated as a percentage of investment costs. These cost assumptions are based on the cost databases in the Irish TIMES model. As a baseline, power plants without CCS are assumed to cost 0.60 M€/MW.

	Investment cost [M EUR]	Fixed O&M [%]	Lifetime [years]
Power plants	3,106	2.9	26
District heating grids	-	-	-
Decentralised combined heat-and-power plants	-	-	-
Centralised combined heat-and-power plants	-	-	-
District heating boilers	-	-	-
Individual gas boilers	2,636	7	15
Individual bio boilers	2,018	3	15

Individual electric boilers	1,183	0	15
District heating substation	-	-	-

Table 7. Electricity and heating costs for the individual heating scenario.

	Total investment cost [M EUR]	Fixed O&M [%]	Lifetime [years]
Power plants	1,800	2.9	26
District heating grid	5,580	0.6	40
Decentralised combined heat-and-power plants	638	3	25
Centralised combined heat-and-power plants	1,265	3	25
District heating boilers	125	3	25
Individual gas boilers	1,309	7	15
Individual bio boilers	1,514	3	15
Individual electric boilers	998	0	15
District heating substation	1,029	1	20

Table 8. Electricity and heating costs for the district heating scenario.

Since there has been no thorough study of the specific district heating potential in all of Ireland, the study includes the following sensitivity analyses to assess the results:

- A discount rate of 3% instead of 5%.
- District heating grid investment costs of 72 M€/TWh. This equals a total investment of 770 M€.
- District heating grid investment costs of 720 M€/TWh. This equals a total investment of 7,718 M€.
- District heating pipe loss of 15% of heat demand in centralised district heating areas and 20% in decentralised district heating areas (higher grid loss step 1).
- District heating pipe loss of 20% of heat demand in centralised district heating areas and 25% in decentralised district heating areas (higher grid loss step 2).

5 Results

Based on the construction of the district heating scenario, it is possible to achieve results for the Irish energy system with and without district heating. It is important to note that neither of these systems are renewable energy systems. Both systems are low-carbon emission systems based on natural gas, biomass and variable renewable energy sources. While we believe a 100% renewable energy system is possible, in line with Green

Plan Ireland [38], the goal of this study is to investigate if district heating is feasible in a system originally designed without district heating. The outputs from the energy system built on individual heating solutions was already shown in chapter 2; with the results from the district heating scenario, it is possible to compare the two. Figure 8 shows the fuel consumption in the two systems, and Figure 9 shows the total annual costs for the two systems. From Figure 8 we can see that the implementation of district heating in the Irish CO2-80 energy system provides a more fuel-efficient solution for the entire system, with a reduction of 5 TWh in the fuel demand. This is a reduction of 3.5 % of the entire fuel demand. However, this has to be compared to the heating demand of 25.25 TWh, which in the reference system results in a fuel consumption of 21.03 TWh and 6.41 TWh for electric heating. Thus, the increase in efficiency of the heating sector is 18%. The district heating system achieves a more efficient use of gas, oil and biomass. Figure 9 shows the annual costs; from these results, district heating is a more cost-efficient solution than a system based on individual heating. The annual costs are quite similar, but the savings in fuel consumption manages to cover the increased investment costs for the district heating system.

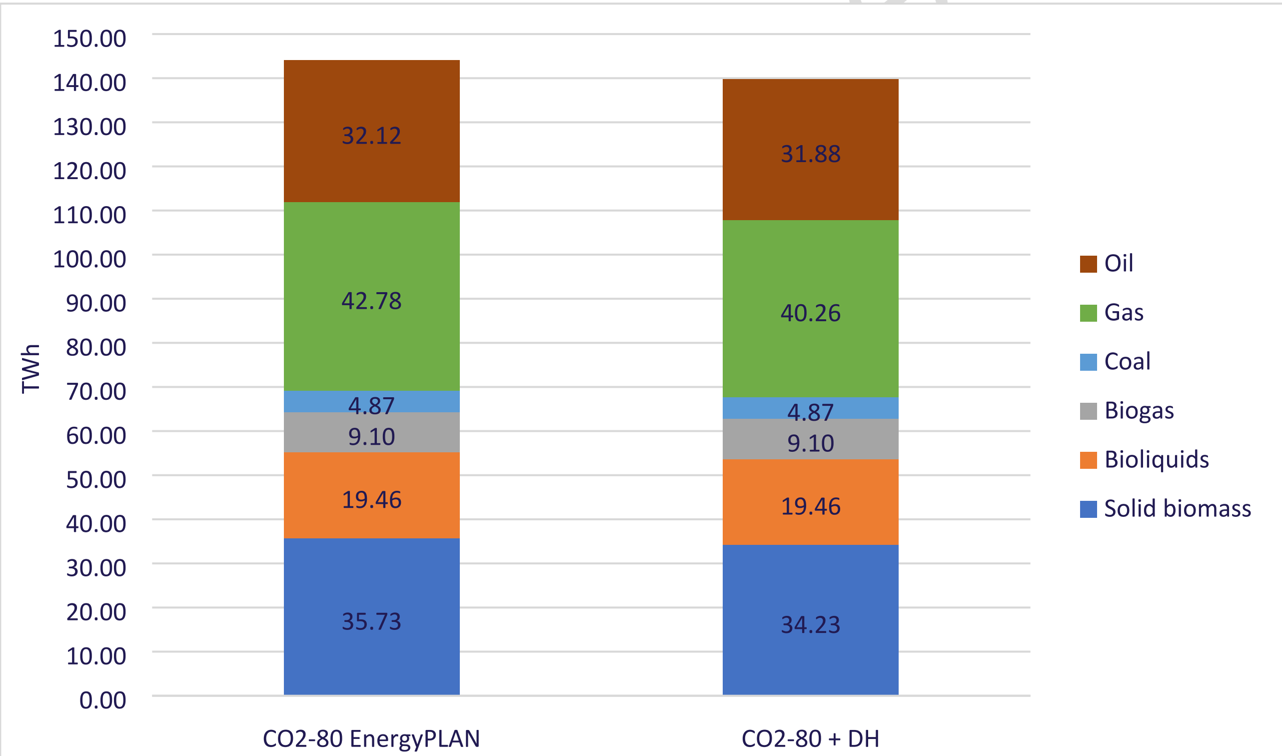


Figure 8. Fuel consumption in the CO2-80 scenario, comparing the reference scenario (CO2-80 EnergyPLAN) to the district heating scenario (CO2-80+DH).

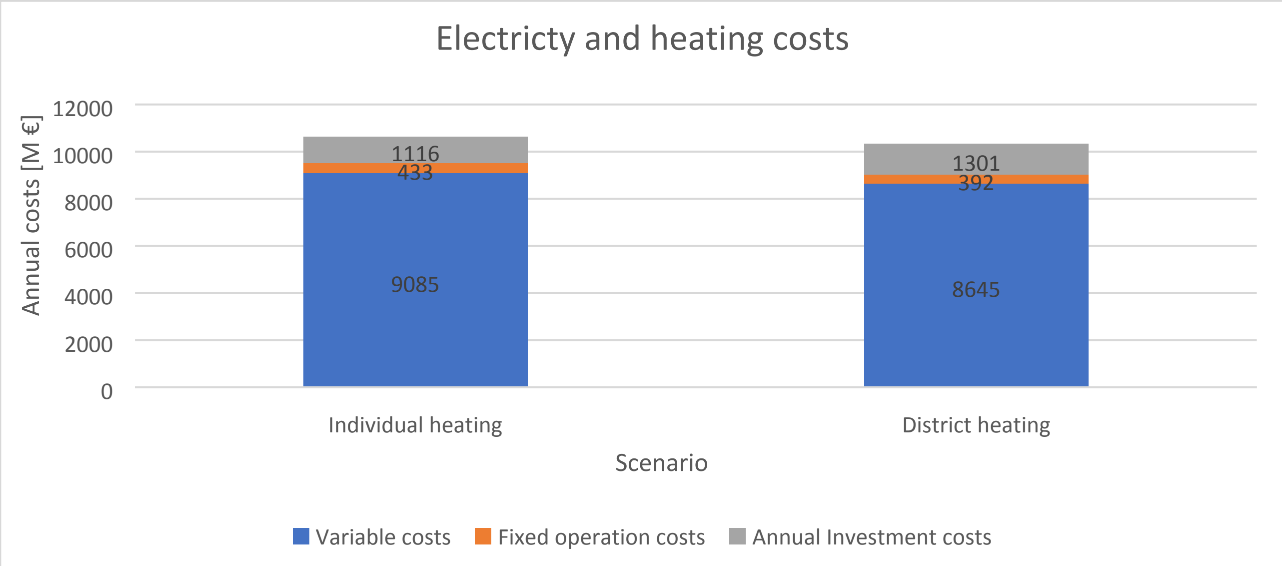


Figure 9. Annual discounted costs for the heating and electricity systems in the CO2-80 scenario with individual heating and district heating.

The results are based on assumptions regarding the implementation of a low-temperature district heating system in Ireland. Since the potential for district heating in Ireland has yet to be fully investigated, there are uncertainties related to these results. The investment costs might be more expensive or grid losses could be higher. The results from the sensitivity analysis, highlighted in chapter 3, are shown in Figures 10 and 11. Figure 10 shows the sensitivity at different grid costs, and higher grid losses with the assumption of a 3% discount rate. Figure 11 shows the same, but with a 5% discount rate.

Even though the differences are not great, the district heating version of the Irish CO2-80 system performs better than the system with individual heating in all cases. District heating provides a more efficient energy system at a lower cost in all cases. Current technology cost for medium temperature district heating, results in lower annual costs. An investment reduction does not change the energy production in the system, thus the fuel consumption stays the same. The same goes if higher investment costs for district heating grids are assumed. Even a 40% increase in investment costs for the district heating system does not result in the district heating system being more expensive than the individual heating system. The second primary sensitivity analysis regards the district heating grid losses. The increased grid losses results in slightly higher fuel demand for the district heating system, which increases the cost associated with the fuel consumption. However, due to the system design, an increase in losses from 15% to 25% in decentral areas and 10% to 20% in central areas only results in a fuel demand increase of 1.4 TWh over a year. This is still within the efficiency gains of the district heating system compared to the individual heating system. The final sensitivity analysis reflects on the sensitivity of the investment costs to the discount rate. Even if all results perform better than the reference CO2-80 scenario, the higher grid cost scenario is almost equal to the reference scenario. This however does mean that it is possible to see a case where high investment costs and high grid losses could result in a more expensive system than the reference scenario.

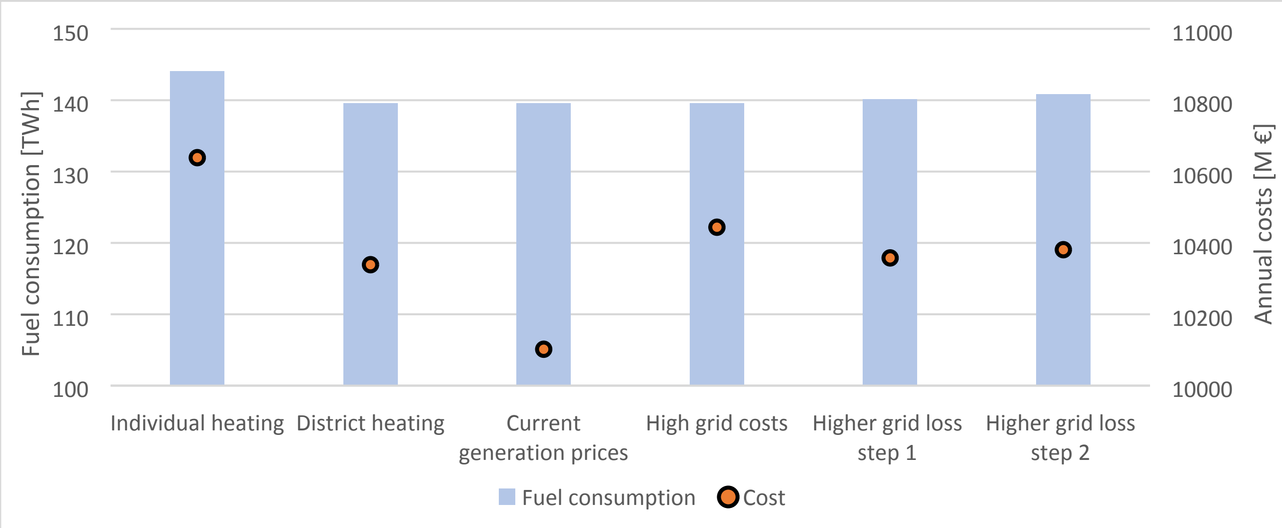


Figure 10. Sensitivity of fuel consumption and annual costs, all at a 3% discount rate.

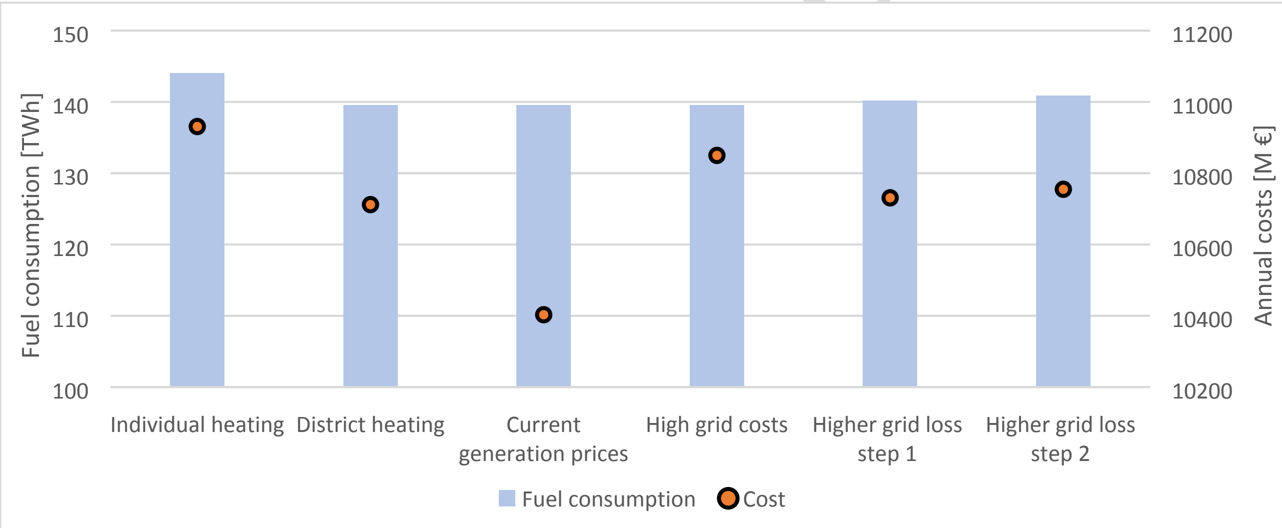


Figure 11. Sensitivity of fuel consumption and annual costs, all at a 5% discount rate.

6 Conclusion

The study identifies the possibility for implementing cleaner heating solutions in terms of district heating in a future low-carbon emission system for the Ireland. The study applies the Irish TIMES model to make a scenario for an 80% reduction in carbon dioxide. This is based on the current development of the Irish TIMES model, which is currently not able to conduct detailed analyses of district heating. Thus, EnergyPLAN is used to investigate not only for the operation of the heating system, but also for the feasibility of district heating in Ireland, compared to a scenario based on individual heating solutions. EnergyPLAN enables the hourly simulation of the heating system and therefore includes the operation of combined heat and power plants, boilers and storages in relation to the electricity system on a chronological basis over the year.

In the Irish CO2-80 scenario that was explored in this paper, the conversion of 37% of the Irish heat demand to district heating shows that the district heating option provides a solution that is more efficient than an individual heating solution. The inclusion of district heating and combined heat and power shows that the district heating solution has lower annual costs than the solution based on individual heating. To investigate the uncertainties related to district heating, the study analyses the sensitivity of the district heating scenario, but finds that in all cases the district heating solution outperforms the individual heating solution, both in terms of fuel efficiency and in terms of costs. It is important to note that these costs are based on the Danish technology catalogue, and as such reflect the total costs for district heating based on a country used to dealing with this technology. In reality, potentially higher installation costs might result in higher costs during the implementation phase in Ireland.

The cost for district heating also includes the installation of a district heating substation in the buildings connected to the district heating grids. These district heating substations replace individual boilers, and thus also replace the costs for individual boilers in buildings connected to the district heating grids. The cost here is again based on the Danish experience, so there may be differences in Ireland due to the unfamiliarity of the technology. In total, should these costs significantly higher than the Danish prices, and should the district heating grid not be able to reduce losses, a case could arise where district heating is not feasible in the given system.

The study suggests that district heating can play a role in increasing the efficiency of a low-carbon energy system for Ireland, and do it without increasing cost. However, it is important to note that the given district heating system suggested in this study is based on large amounts of thermal power plants, to deliver excess heat. This resource will not be available in a future 100% renewable energy system. Nevertheless, district heating can play a key infrastructural role in a 100% renewable energy system, due to its availability of large thermal storages in which hot water produced from excess electricity can be stored. Furthermore, there should still be excess heat from industrial processes available. It would therefore be an interesting further study, to implement the methodology described in this paper to a 100% renewable energy system identified using the TIMES model. This would further the discussion of the role of district heating in future renewable energy system.

7 Acknowledgments

The work presented in this article is a result of Jakob Zinck Thellufsen's research stay at University College Cork and was conducted in collaboration with Brian Ó Gallachóir, Paul Deane and James Glynn. The work is part of the Centre for IT–Intelligent Energy System in Cities (CITIES) and the RE-INVEST project, and it draws on knowledge from the 4DH research project. All these projects are funded by Innovation Fund Denmark.

[1] Connolly D, Mathiesen BV, Østergaard PA, Möller B, Nielsen S, Lund H, et al. Heat Roadmap Europe 2050: Second pre-study. 2013.

[2] Østergaard PA, Soares I, Ferreira P. Energy efficiency and renewable energy systems in Portugal and Brazil. Int J Sustain Energy Plan Manag 2014;2:1–6.

[3] Ben Amer-Allam S, Münster M, Petrović S. Scenarios for sustainable heat supply and heat savings in municipalities - The case of Helsingør, Denmark. Energy 2017;137:1252–63. doi:10.1016/J.ENERGY.2017.06.091.

[4] Quiquerez L, Lachal B, Monnard M, Faessler J. The role of district heating in achieving sustainable cities: comparative analysis of different heat scenarios for Geneva. Energy Procedia 2017;116:78–90. doi:10.1016/J.EGYPRO.2017.05.057.

[5] Mathiesen BV, Lund H, Hansen K, Ridjan I, Djørup SR, Nielsen S, et al. IDA's Energy Vision 2050: A Smart Energy System strategy for 100% renewable Denmark. Aalborg, Denmark: 2015.

[6] Connolly D, Lund H, Mathiesen BV. Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renew Sustain Energy Rev 2016;60:1634–53. doi:10.1016/j.rser.2016.02.025.

[7] Apak S, Atay E, Tuncer G. Renewable hydrogen energy and energy efficiency in Turkey in the 21st century. Int J Hydrogen Energy 2017;42:2446–52. doi:10.1016/j.ijhydene.2016.05.043.

[8] Noblet CL, Teisl MF, Evans K, Anderson MW, McCoy S, Cervone E. Public preferences for investments in renewable energy production and energy efficiency. Energy Policy 2015;87:177–86. doi:10.1016/j.enpol.2015.09.003.

[9] Vidadili N, Suleymanov E, Bulut C, Mahmudlu C. Transition to renewable energy and sustainable energy development in Azerbaijan. Renew Sustain Energy Rev 2017;80:1153–61. doi:10.1016/j.rser.2017.05.168.

[10] Truong NL, Dodoo A, Gustavsson L. Effects of energy efficiency measures in district-heated buildings on energy supply. Energy 2018;142:1114–27. doi:10.1016/j.energy.2017.10.071.

[11] Lund H, Thellufsen JZ, Aggerholm S, Wittchen KB, Nielsen S, Mathiesen BV, et al. Heat Saving Strategies in Sustainable Smart Energy Systems. Int J Sustain Energy Plan Manag 2015;4:3–16.

[12] Thellufsen JZ, Lund H. Energy saving synergies in national energy systems. Energy Convers Manag 2015;103:259–65. doi:10.1016/j.enconman.2015.06.052.

[13] Gustavsson L, Dodoo A, Truong NL, Danielski I. Primary energy implications of end-use energy efficiency measures in district heated buildings. Energy Build 2011;43:38. doi:DOI: 10.1016/j.enbuild.2010.07.029.

[14] Hansen K, Connolly D, Lund H, Drysdale D, Thellufsen JZ. Heat Roadmap Europe: Identifying the balance between saving heat and supplying heat. Energy 2016;115. doi:10.1016/j.energy.2016.06.033.

[15] Togawa T, Fujita T, Dong L, Fujii M, Ooba M. Feasibility assessment of the use of power plant-sourced waste heat for plant factory heating considering spatial configuration. J Clean Prod 2014;81:60–9. doi:10.1016/j.jclepro.2014.06.010.

[16] Andrews R, Pearce JM. Environmental and economic assessment of a greenhouse waste heat exchange. J Clean Prod 2011;19:1446–54. doi:10.1016/j.jclepro.2011.04.016.

[17] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH). Energy 2014;68:1–11. doi:10.1016/j.energy.2014.02.089.

[18] Connolly D, Mathiesen BV, Østergaard PA, Möller B, Nielsen S, Lund H, et al. Heat Roadmap Europe 2050: First pre-study 2013.

[19] Hansen K, Werner S, Möller B, Wilke OG, Bettgenhäuser K, Pouwels EW, et al. Enhanced Heating and Cooling Plans to Quantify the Impact of Increased Energy Efficiency in EU Member States. 2016.

[20] Connolly D, Lund H, Mathiesen B V., Werner S, Möller B, Persson U, et al. Heat roadmap Europe:

Combining district heating with heat savings to decarbonise the EU energy system. Energy Policy 2014;65:475–89. doi:10.1016/j.enpol.2013.10.035.

[21] Zhang Y, Gao X, Li B, Li H, Zhao W. Assessing the potential environmental impact of woody biomass using quantitative universal exergy. J Clean Prod 2018;176:693–703. doi:https://doi.org/10.1016/j.jclepro.2017.12.159.

[22] Kabalina N, Costa M, Yang W, Martin A, Santarelli M. Exergy analysis of a polygeneration-enabled district heating and cooling system based on gasification of refuse derived fuel. J Clean Prod 2017;141:760–73. doi:10.1016/j.jclepro.2016.09.151.

[23] Möller B, Nielsen S. High resolution heat atlases for demand and supply mapping. Int J Sustain Energy Plan Manag 2014;1:41–58.

[24] Nielsen S. A geographic method for high resolution spatial heat planning. Energy 2014;67:351–62. doi:10.1016/j.energy.2013.12.011.

[25] Ravina M, Panepinto D, Zanetti MC, Genon G. Environmental analysis of a potential district heating network powered by a large-scale cogeneration plant. Environ Sci Pollut Res 2017;24:13424–36. doi:10.1007/s11356-017-8863-2.

[26] Persson U, Möller B, Werner S. Heat Roadmap Europe: Identifying strategic heat synergy regions. Energy Policy 2014;74:663–81. doi:10.1016/j.enpol.2014.07.015.

[27] Werner S. International review of district heating and cooling. Energy 2017;137:617–31. doi:10.1016/j.energy.2017.04.045.

[28] Euroheat and Power. District Heating and Cooling Statistics 2015 2015:2013.

[29] Werner S, Persson U. District heating and Cooling database 2013.

[30] Frederiksen S, Werner S. District heating and cooling. Lund, Sweden: Studentlitteratur; 2013.

[31] Connolly D. Heat Roadmap Europe: Quantitative comparison between the electricity, heating, and cooling sectors for different European countries. Energy 2017;139:580–93. doi:10.1016/j.energy.2017.07.037.

[32] Ravina M, Panepinto D, Zanetti MC. DIDEM - An integrated model for comparative health damage costs calculation of air pollution. Atmos Environ 2018. doi:10.1016/j.atmosenv.2017.11.010.

[33] Guelpa E, Mutani G, Todeschi V, Verda V. Reduction of CO2emissions in urban areas through optimal expansion of existing district heating networks. J Clean Prod 2018. doi:10.1016/j.jclepro.2018.08.272.

[34] Euroheat and Power. Distrct Energy in Ireland 2017. https://www.euroheat.org/knowledge-centre/country-profiles/district-energy-ireland-2/ (accessed September 11, 2018).

[35] Gartland D. Dublin City Spatial Energy Demand Analysis. Dublin, Ireland: 2015.

[36] Chiodi A, Gargiulo M, Rogan F, Deane JP, Lavigne D, Rout UK, et al. Modelling the impacts of challenging 2050 European climate mitigation targets on Ireland’s energy system. Energy Policy 2013;53:169–89. doi:10.1016/j.enpol.2012.10.045.

[37] Connolly D, Lund H, Mathiesen BV, Leahy M. The first step towards a 100% renewable energy-system for Ireland. Appl Energy 2011;88:502–7. doi:10.1016/j.apenergy.2010.03.006.

[38] Connolly D, Mathiesen BV. A technical and economic analysis of one potential pathway to a 100% renewable energy system. Int J Sustain Energy Plan Manag 2014;1:7–28.

doi:doi.org/10.5278/ijsepm.2014.1.2.

[39] Chiodi A, Deane P, Gargiulo M, Ó Gallachóir B. The Role of Bioenergy in Ireland's Low Carbon Future – Is it Sustainable? J Sustain Dev Energy, Water Environ Syst 2015;3:196–216. doi:10.13044/j.sdewes.2015.03.0016.

[40] Barton J, Davies L, Dooley B, Foxon TJ, Galloway S, Hammond GP, et al. Transition pathways for a UK low-carbon electricity system: Comparing scenarios and technology implications. Renew Sustain Energy Rev 2018;82:2779–90. doi:10.1016/j.rser.2017.10.007.

[41] Esteban M, Portugal-Pereira J, Mclellan BC, Bricker J, Farzaneh H, Djalilova N, et al. 100% renewable energy system in Japan: Smoothening and ancillary services. Appl Energy 2018;224:698–707. doi:10.1016/j.apenergy.2018.04.067.

[42] Koelbl BS, van den Broek MA, Wilting HC, Sanders MWJL, Bulavskaya T, Wood R, et al. Socio-economic impacts of low-carbon power generation portfolios: Strategies with and without CCS for the Netherlands. Appl Energy 2016;183:257–77. doi:10.1016/j.apenergy.2016.08.068.

[43] Lund H, Ostergaard PA, Connolly D, Ridjan I, Mathiesen BV, Hbelplund F, et al. Energy Storage and Smart Energy Systems. Int J Sustain Energy Plan Manag 2016;11:2016–3. doi:10.5278/ijsepm.2016.11.2.

[44] Lund R, Mathiesen BV. Large combined heat and power plants in sustainable energy systems. Appl Energy 2015;142:389–95. doi:10.1016/j.apenergy.2015.01.013.

[45] Sorknæs P, Lund H, Andersen AN, Ritter P. Small-scale combined heat and power as a balancing reserve for wind – The case of participation in the German secondary control reserve. Int J Sustain Energy Plan Manag 2015;4:31–42.

[46] Mathiesen BV, Lund H, Hansen K, Ridjan I, Djørup S, Nielsen S, et al. IDA's Energy Vision 2050 - Technical data and methods. 2015. doi:10.1016/j.energy.2012.11.030.

[47] Arnaudo M, Zaalouk OA, Topel M, Laumert B. Techno-economic Analysis Of Integrated Energy Systems At Urban District Level – A Swedish Case Study. Energy Procedia 2018;149:286–96. doi:10.1016/j.egypro.2018.08.229.

[48] Deane JP, Chiodi A, Gargiulo M, Ó Gallachóir BP. Soft-linking of a power systems model to an energy systems model. Energy 2012;42:303–12.

[49] Deane JP, Gracceva F, Chiodi A, Gargiulo M, Ó Gallachóir B. Soft-Linking Exercises Between TIMES, Power System Models and Housing Stock Models. In: Giannakidis G, Labriet M, Ó Gallachóir B, Tosato G, editors. Informing Energy Clim. Policies Using Energy Syst. Model. Insights from Scenar. Anal. Increasing Evid. Base, Cham: Springer International Publishing; 2015, p. 315–31. doi:10.1007/978-3-319-16540-0_18.

[50] Deane JP, Gracceva F, Chiodi A, Gargiulo M, Gallachóir BPÓ. Assessing power system security. A framework and a multi model approach. Int J Electr Power Energy Syst 2015;73:283–97. doi:10.1016/j.ijepes.2015.04.020.

[51] Collins S, Deane JP, Poncelet K, Panos E, Pietzcker RC, Delarue E, et al. Integrating short term variations of the power system into integrated energy system models: A methodological review. Renew Sustain Energy Rev 2017;76:839–56. doi:10.1016/j.rser.2017.03.090.

[52] Welsch M, Deane P, Howells M, O Gallachóir B, Rogan F, Bazilian M, et al. Incorporating flexibility requirements into long-term energy system models - A case study on high levels of renewable

electricity penetration in Ireland. Appl Energy 2014;135:600–15. doi:10.1016/j.apenergy.2014.08.072.

[53] Vaillancourt K. Policy Analysis Tools for Global Sustainability : E4 systems tools and joint studies. 2013.

[54] Gargiulo M, Ó Gallachóir B. Long-term energy models: Principles, characteristics, focus, and limitations. Wiley Interdiscip Rev Energy Environ 2013;2:158–77. doi:10.1002/wene.62.

[55] Remme U. Overview of TIMES: parameters, primal variables & equations. Proc. ETSAP Work., vol. November 2, Brazil: 2007.

[56] Mulholland E, O'Shea RSK, Murphy JD, Ó Gallachóir BP. Low carbon pathways for light goods vehicles in Ireland. Res Transp Econ 2016;57:53–62. doi:10.1016/j.retrec.2016.10.002.

[57] Chiodi A, Donnellan T, Breen J, Deane P, Hanrahan K, Gargiulo M, et al. Integrating agriculture and energy to assess GHG emissions reduction: a methodological approach. Clim Policy 2015;3062:1–22. doi:10.1080/14693062.2014.993579.

[58] Lund H. EnergyPLAN Documentation Version 12. Aalborg, Denmark: 2015.

[59] Lund H. Renewable Energy Systems - A Smart Energy Systems Approach to the Choice and Modeling of 100% Renewable Solutions. 2nd editio. Academic Press; 2014.

[60] Mathiesen BV, Lund RS, Connolly D, Ridjan I, Nielsen S. Copenhagen Energy Vision 2050: A sustainable vision for bringing a capital to 100% renewable energy. Copenhagen, Denmark: 2015.

[61] Østergaard PA, Mathiesen BV, Möller B, Lund H. A renewable energy scenario for Aalborg Municipality based on low-temperature geothermal heat, wind power and biomass. Energy 2010;35:4892–901. doi:10.1016/j.energy.2010.08.041.

[62] Østergaard PA, Lund H. A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating. Appl Energy 2011;88:479–87. doi:10.1016/j.apenergy.2010.03.018.

[63] Lund H, Østergaard PA. Sustainable Towns: The Case of Frederikshavn – 100% Renewable Energy. Sustain. Communities, New York, NY: Springer New York; 2010, p. 155–68. doi:10.1007/978-1-4419-0219-1_11.

[64] Lund H, Mathiesen B V. Energy system analysis of 100% renewable energy systems-The case of Denmark in years 2030 and 2050. Energy 2009;34:524–31. doi:10.1016/j.energy.2008.04.003.

[65] Waenn A, Connolly D, Gallachóir BÓ. Investigating 100% renewable energy supply at regional level using scenario analysis. Int J Sustain Energy Plan Manag 2014;3:21–32.

[66] Lund H, Kempton W. Integration of renewable energy into the transport and electricity sectors through V2G. Energy Policy 2008;36:3578–87. doi:10.1016/j.enpol.2008.06.007.

[67] Lund H, Salgi G. The role of compressed air energy storage (CAES) in future sustainable energy systems. Energy Convers Manag 2009;50:1172–9. doi:10.1016/j.enconman.2009.01.032.

[68] Lund R, Ilic DD, Trygg L. Socioeconomic potential for introducing large-scale heat pumps in district heating in Denmark. J Clean Prod 2016:1–20. doi:10.1016/j.jclepro.2016.07.135.

[69] Lund H. Large-scale integration of wind power into different energy systems. Energy 2005;30:2402–12. doi:10.1016/j.energy.2004.11.001.

[70] Xiong W, Wang Y, Mathiesen BV, Lund H, Zhang X. Heat roadmap China: New heat strategy to reduce

energy consumption towards 2030. Energy 2015;81:274–85. doi:http://dx.doi.org/10.1016/j.energy.2014.12.039.

[71] Dyrelund A, Fafner K, Ulbjerg F, Knudsen S, Lund H, Mathiesen BV, et al. Varmeplan Danmark 2010. vol. 49. 2010.

[72] Lund H, Hvelplund F, Mathiesen BV, Østergaard PA, Christensen P, Connolly D, et al. Coherent Energy and Environmental System Analysis. 2011.

[73] Deane P, Curtis J, Chiodi A, Gargiulo M, Rogan F, Dineen D, et al. Technical support on developing low carbon sector roadmaps for IrelandLow Carbon Energy Roadmap for Ireland. 2013.

[74] Ridjan I, Mathiesen BV, Connolly D, Ridjan I, Mathiesen BV, Connolly D. SOEC pathways for the production of synthetic fuels. Department of Development and Planning, Aalborg University; 2013.

[75] Gaillot O, Walsh J, Weiss P, Clausen NO. District heating for Dublin. Dublin, Ireland: 2008.

[76] Energistyrelsen, Energinet.dk. Technology data for energy plants - individual heating plants and energy transport. 2013. doi:ISBN: 978-87-7844-940-5.

[77] Østergaard DS, Svendsen S. Experience from a practical test of low-temperature district heating for space heating in five Danish single-family houses from the 1930s. Energy 2018. doi:10.1016/j.energy.2018.06.142.

[78] Østergaard DS, Svendsen S. Space heating with ultra-low-temperature district heating - A case study of four single-family houses from the 1980s. Energy Procedia, 2017. doi:10.1016/j.egypro.2017.05.070.

Highlights

1) EnergyPLAN is capable of simulating energy systems identified in MARKAL/TIMES
2) EnergyPLAN and Markal/TIMES combined enables better analysis of heating scenarios
3) District heating can compete with individual heating in an Irish energy system