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# A technical and economic analysis of one potential pathway to a 100% renewable energy system

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**ABSTRACT**

This paper outlines how an existing energy system can be transformed into a 100% renewable energy system. The transition is divided into a number of key stages which reflect key radical technological changes on the supply side of the energy system. Ireland is used as a case study, but in reality this reflects many typical energy systems today which use power plants for electricity, individual boilers for heat, and oil for transport. The seven stages analysed are 1) reference, 2) introduction of district heating, 3) installation of small and large-scale heat pumps, 4) reducing grid regulation requirements, 5) adding flexible electricity demands and electric vehicles, 6) producing synthetic methanol/DME for transport, and finally 7) using synthetic gas to replace the remaining fossil fuels. For each stage, the technical and economic performance of the energy system is calculated. The results indicate that a 100% renewable energy system can provide the same end-user energy demands as today's energy system and at the same price. Electricity will be the backbone of the energy system, but the flexibility in today's electricity sector will be transferred from the supply side of the demand side in the future. Similarly, due to changes in the type of spending required in a 100% renewable energy system, this scenario will result in the creation of 100,000 additional jobs in Ireland compared to an energy system like today's. These results are significant since they indicate that the transition to a 100% renewable energy system can begin today, without increasing the cost of energy in the short- or long-term, if the costs currently forecasted for 2050 become a reality.

***Keywords:***

100% renewable energy;
smart energy system;
Ireland;
technical analyses;
economic analyses;
wind power;
job creation;

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## 1. Introduction

The energy sector is in a state of change and uncertainty. A change is necessary due to the environmental damage and risks associated with the existing energy system such as climate change, pollution, security of supply concerns, and unpredictable future energy prices. Numerous studies, debates, and public figures have highlighted the need for a radical change in the very near future, including the International Energy Agency who have recently stated that a radical change is necessary by 2017 [1].

Unfortunately, the pace of change is relatively slow today, even with all of these concerns and the large body of research to prove that a change is necessary. This could be attributed to numerous factors such as the strength of existing institutions in the energy sector and the lack of suitable policy and markets. In the authors' opinion, one of the key issues obstructing change in the energy sector is uncertainty.

A lot of this uncertainty is created by the variety of alternatives being proposed and debated for the energy sector. Typically, every country will have a few very powerful institutions in each of the electricity, gas, oil, and renewable energy sectors. Each of these institutions would like to remain powerful in the future and so, when debating the design of the future energy system,

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it is often very difficult to separate the optimum outcome from the vested interests. This is particularly true when debating renewable energy in the future [2, 3]. Renewable energy is still at the development stage and it requires a radical change in the way the energy system is operated. Therefore, its reliability, costs, and potential are often more difficult to illustrate and communicate. In line with this, the aim in this paper is to remove some of this uncertainty relating to the future design of the energy system, with a specific focus on renewable energy.

To do so, the technical and economic impact of redesigning a national energy system to incorporate high shares of renewable energy in the future is quantified. Ireland is used as a case study, but the methodology can be used for any other country and the results are applicable to other countries with similar climates and renewable energy potentials. The methodology utilised in this paper has been applied in numerous other studies by the authors such as a previous 100% renewable energy strategies [4–7]. In this paper, more details relating to the transport sector and the different stages of the transition to a 100% renewable energy system are presented.

The results indicate that a 100% renewable energy system is technical feasible, but the structure will be very different in the future. In general, combustion will be replaced by electricity in almost all sectors. This is already evident in the electricity sector where primarily wind turbines are replaced power plants. In the heat sector individual boilers will be replaced by heat pumps, while in the transport sector oil will be replaced by electric vehicles and synthetic fuels.

In terms of costs, based on 2020 price assumptions a 100% renewable energy scenario will be approximately 20% more expensive than a business-as-usual scenario, but under 2050 price assumptions they will be the same price. However, the key difference from a society perspective is not the total costs, but the method type of costs in these two energy systems. A business-as-usual scenario will result in a fuel-based system which is dependent on imports, while a renewable energy scenario will result in an investment-based system. This has a very positive impact on Ireland's balance of payment, since Ireland currently imports 90% of its fossil fuels. In total, there is approximately €2 billion/year more spent within Ireland when the investment-based renewable energy system is in place. This enables the creation of approximately 40,000–50,000 more direct jobs if all of the investments are spread out between 2020 and 2050.

The economic analysis suggests that 100% renewable energy systems will most likely result in the same socio-economic costs as a business as usual scenario. However, due to the type of costs in the investment-based renewable energy system, the local benefits for countries that currently import fossil fuels mean that a 100% renewable energy system is more cost effective for society.

## 2. Methodology

Any methodology used to develop future energy scenarios is open to deliberation, since the future is always uncertain. This section presents the key principles used to define the methodology in this paper followed by a brief overview of how these key principles were considered. It is supplemented by a range of data in the Appendix.

### 2.1. Key principles

The key principles that define how the analysis is completed are that:

- The analysis considers all sectors of the energy system, which are electricity, heat, and transport.
- It is possible to analyse a radical change in technology
- The analysis is completed over a long-term time horizon
- Renewable energy and demand fluctuations are accounted for hour-by-hour
- The analysis is completed from a socio-economic perspective

Firstly, the analysis will need to consider the whole energy system (i.e. not just one specific sector) along with a radical change in technology [8]. Not only does this mean that electricity, heat, and transport need to considered from both a consumption and production perspective, but it should also be possible to assess radical technological changes in each of this sectors. The significance of this is evident when considering the transition necessary from the existing fuel-based energy system (Figure 1) to a future renewable-energy based system (Figure 2). Unlike the existing energy system which consists of only a few linear relations between the resources and demand (Figure 1), a future energy system will include numerous interactions between the resources, conversion processes, and demands (Figure 2).

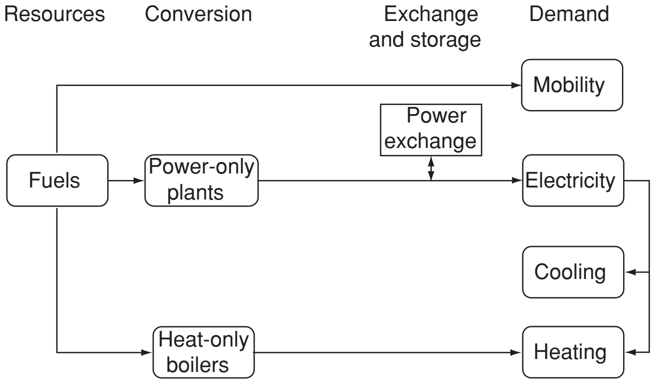

Figure 1: Interaction between sectors and technologies in today's typical energy system.

Therefore, when evaluating a future energy system, it is important to consider the impact that a technology can have across the entire energy system along with the consequences of a radical technological change in any one of these sectors.

Secondly, the timelines considered in this study will need to consider both the short-term fluctuations of intermittent renewable energy sources (IRES) over a long-term time horizon. It is important to consider the short-term fluctuations of IRES to account for intermittency and to ensure that the demand for electricity, heat, and transport is always met. The long-term time horizon is important from a technical perspective due to the lifetime of the technologies being considered. As outlined by the International Energy Agency (IEA) [1], energy production units typically have a lifetime of more than 20 years, energy networks have a lifetime of approximately 40 years, and some energy-related infrastructure can have a lifetime of 100 years or more. Consequently, the actions taken today will need to aid the operation of the future energy system displayed in Figure 2 and not the existing energy system displayed in Figure 1. This means that it is essential to plan for a long-term vision when evaluating energy systems for the future. Without this long-term perspective, a lot of money and resources could be spent today on actions that do not fit with the future sustainable energy system.

Thirdly, the future energy system should be evaluated from a socio-economic perspective [9], since today's energy markets often do not reflect benefits

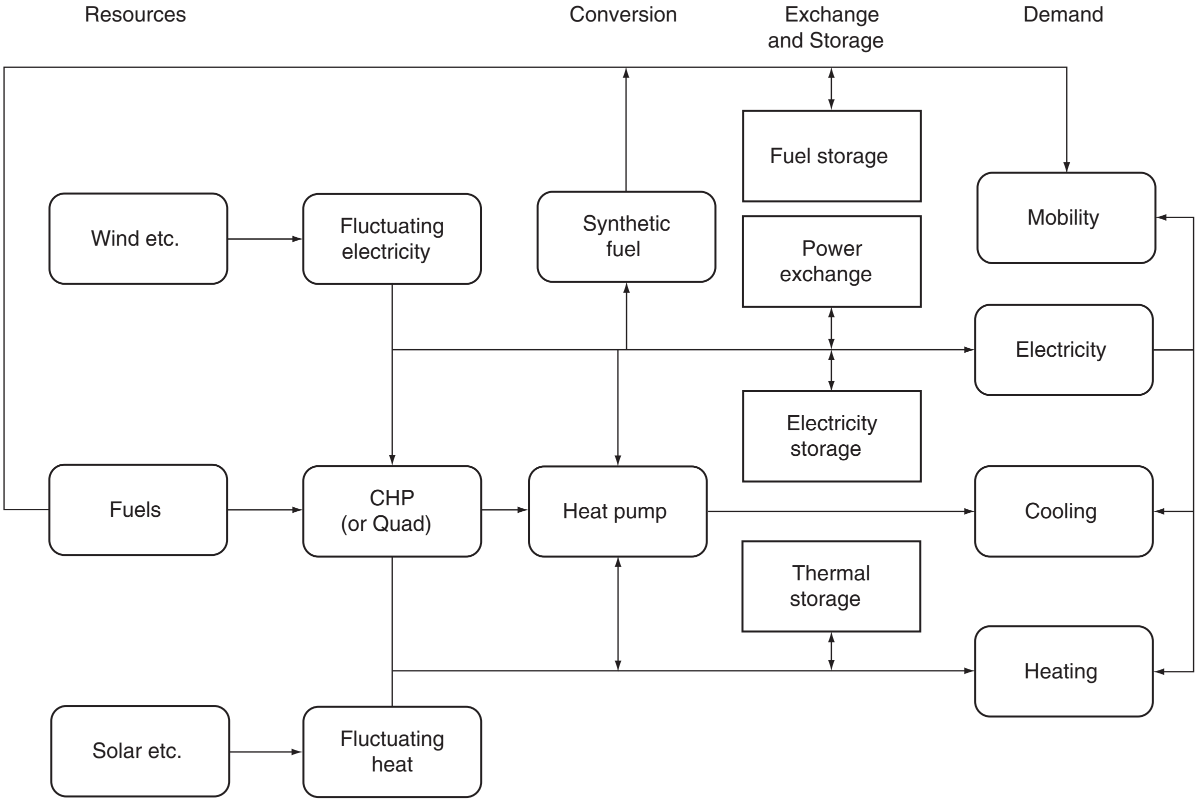

Figure 2: Interaction between sectors and technologies in a future smart energy system.

such as less pollution, lower GHG emissions, resource depletion, land-use change, waste, and security of supply. As outlined previously, a renewable energy system will be based on investments and not fuels. Naturally this transition will require many organisations to change. However, designing the energy system for the profits of one individual organisation is not the key concern for the citizens in society. Instead, it is the overall cost of energy, the type of resources used (i.e. environment), the number of jobs created, and the balance of payment for the nation that are examples of the key metrics which define a good or bad energy system from a society's perspective. Thus, future energy systems should be considered without imposing the limitations of existing institutions or regulations. For example, the existing electricity market is not designed for the future energy system in Figure 2 and so the future energy system should not be designed within its framework [10]. Therefore, when assessing the future energy system, it needs to be optimised from a societal perspective, and not from an individual organisation perspective.

In summary, the methodology used in this study will try to include all sectors of the energy system, consider radical technological change, account for the hourly fluctuations of IRES and demands, use a long-term time-horizon, evaluate the results from a socio-economic perspective, and exclude the limitations associated with existing institutional designs. To complete the analysis under these principles requires a number of complex technical and economic relationships and so the EnergyPLAN tool will be used to aid the analysis in this study.

### 2.2. How EnergyPLAN is used to account for the key principles

EnergyPLAN is an energy system analysis tool specifically designed to assist the design of national or regional energy planning strategies under the "Choice Awareness" theory [8]. It has been developed and expanded on a continuous basis since 1999 at Aalborg University, Denmark. As a result, it is now a very complex tool which considers a wide variety of technologies, costs, and regulations strategies for an energy system. The model can be downloaded for free [11] and the algorithms used to create the tool are described in detail in the user manual, hence these are not discussed here. Instead, the key features available in the tool and how they are used to account for the key principals of the methodology are presented.

#### 2.2.1. Considering the whole energy system

In line with selected methodology, EnergyPLAN considers all sectors in the energy system: electricity, heat, and transport, as outlined in Figure 3. Also, since the tool has been developed on a research basis, it includes a number of new technologies which incorporate radical technological change. This is demonstrated by the many analyses that EnergyPLAN has been used for to date. These include an analysis of the large-scale integration of wind [12] as well as optimal combinations of renewable energy sources [13], management of surplus electricity [14], the integration of wind power using Vehicle-to-Grid electric-vehicles [15], the implementation of small-scale CHP [16], integrated systems and local energy markets [17], renewable energy strategies for sustainable development [5], the use of waste for energy purposes [18], evaluating marginal energy technologies in life-cycle assessments [19], the potential of fuel cells and electrolysers in future energy-systems [20, 21], the potential of thermoelectric generation in thermal energy systems [22], various renewable fuels for transport [23], and the effect of energy storage [24], with specific work on compressed-air energy storage [25, 26], pumped-hydroelectric energy storage [27, 28], and thermal energy storage [12, 29, 30]. In addition, EnergyPLAN was used to analyse the potential of CHP and renewable energy in Estonia, Germany, Poland, Spain, and the UK [31]. EnergyPLAN has been used to simulate a 100% renewable energy system for the island of Mljet in Croatia [32], the local authorities of Frederikshavn [33, 34] and Aalborg [35, 36], as well as the countries of Ireland [37], Croatia [38], and Denmark [6, 7, 23]. Other publications can be seen on the EnergyPLAN website [11] and a comparison with other energy tools is available in [39]. Based on this research, EnergyPLAN is clearly capable of analysing all sectors in the energy system along with new technologies.

#### 2.2.2. Accounting for intermittency and a long-term time horizon

Secondly, EnergyPLAN simulates the energy system on an hourly basis over one year. The hourly time-step is essential to ensure that intermittent renewable energy is

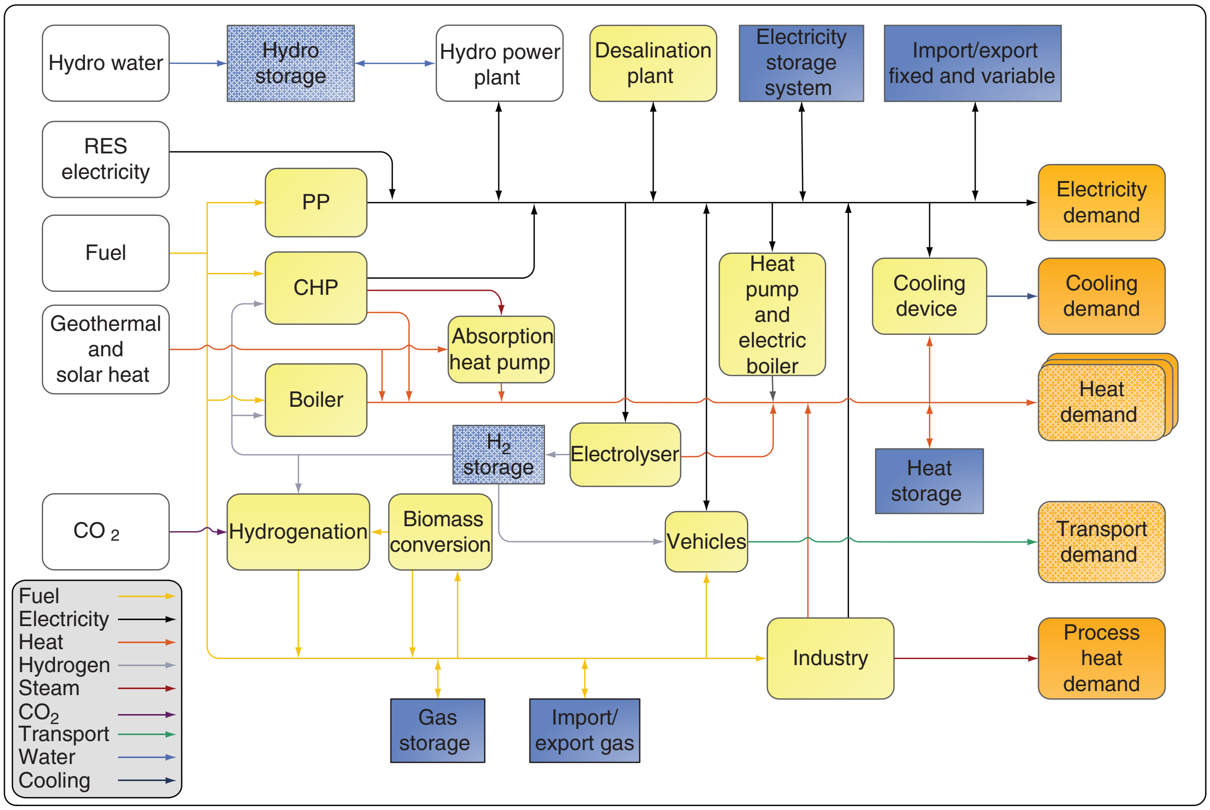

Figure 3: Flow chart of resources, conversion technologies, and demands considered in EnergyPLAN [11].

capable of reliably meeting the demands for electricity, heat, and transport. To ensure a long-term time horizon is considered, the analysis will focus on the steps towards a 100% renewable energy system by 2050. A 2050 scenario will ensure that any short-term actions will be in line with the long-term objectives of a low-carbon energy system for Ireland.

### 2.2.3. Using a socio-economic perspective

In relation to the socio-economic perspective, EnergyPLAN optimises the technical operation of a given system as opposed to tools which identify an optimum within the regulations of an individual sector. As a result, the tool focuses on how the overall system operates instead of maximising investments within a specified market framework or from one specific technology viewpoint. This is significant, as the structure of today's energy system will not be the same in the future, and the merging of energy sectors will increase significantly, hence markets will become intertwined.

The results quantify the primary energy supply (PES), renewable energy penetration, GHG emissions, and energy system costs. All costs are annualised according to Equation 1, which consists of the total investment costs I, the installed capacities C, lifetimes n, an interest rate i (which is assumed to be 3% in this study), and the annual fixed O&M costs as a percentage of the total investment.

$$I_{Annual} = (IC)\left\{\left[\frac{i}{1-(1+i)^{-n}}\right] + O\,\&\,M_{Fixed}\right\} \qquad (1)$$

In this way, various scenarios consisting of different technology mixes can be compared with one another. The fuel costs, investment costs, and operation and maintenance (O&M) costs used in this study are presented in the Appendix. EnergyPLAN does not calculate the job creation and balance of payment for the region, so this was completed outside the tool: the methodology used is described in detail in Lund and Hvelplund [40].

## 3. Case study and the stages analysed

These key principals have been used here to investigate the pathway towards a 100% renewable energy system for the Republic of Ireland. This is only used as a case study, since the energy system in Ireland is very similar to many other countries around the world.

Recent years have highlighted that energy demand can change dramatically in a relatively short period of time. To put this in context, Ireland's largest power station, which is called Moneypoint, was completed in 1987 and is still in operation today. Since Moneypoint came into operation, the demand for electricity in Ireland has more than doubled. This means that the electricity system expected at the time of Moneypoint's construction was completely different to the electricity system which actually evolved over the 26 years since it came into operation. Therefore, predicting the future energy system is a very uncertain practice and it is not the purpose in this paper. Instead, the purpose here is to present scenarios of how the Irish energy system could transition to a 100% renewable energy system by 2050, if alternative technologies were utilised for its energy production. The focus is thus on the design of the energy system and not on the expected evolution of the energy demands in Ireland. It will become apparent during the results that the radical technological changes required for a 100% renewable energy system mean that the exact energy consumption at a certain point in time is not as important. The reason for choosing a specific country as a case study is so that realistic values can be obtained for the relationships between different pieces of data in the analysis.

In brief, Ireland has a population of approximately 4.5 million people in an area of around 70,000 km$^2$. It is located in the north-west corner of Europe so it has excellent wind and wave resources. In total, the energy available from wind power is approximately 600 TWh/year based on technological constraints [41], of which approximately 55 TWh/year will be economically viable in 2020 [42, 43]. Based on a Pelamis wave energy device [44], previous research estimated Ireland's theoretically available wave energy to be 28 TWh/year [45]. In addition, Ireland has a very large agricultural sector which means that there is a significant biomass potential. For example, Corcoran *et al.* [46] calculated that if all suitable land was used for growing miscanthus energy crops in Ireland, then there would be approximately 200 TWh of biomass available each year.

On the demand side, the forecasted 2020 energy demands for Ireland will be used as a starting point in this analysis. These have been estimated by the Irish Energy Authority [47], who are formally known as the Sustainable Energy Authority of Ireland. Once again, just to emphasise that the specific demand is not essential for the analysis being carried out in this paper, due to the scale of the changes being proposed and due to uncertainties relating to future energy demands. However, a starting point is necessary, so these relatively short-term future projections have been chosen. In 2020 the electricity demand in Ireland is expected to be approximately 30 TWh, which will be supplied by approximately 6000 MW of condensing power plants. The heat demand is expected to be approximately 27 TWh, which will almost entirely be supplied by individual boilers. There are currently 2 million dwellings in Ireland [48], so it is assumed here that there are also 2 million individual boilers. The demand for industry is forecast to be around 25 TWh, while the transport sector will require 70 TWh of energy, including 1 TWh of electricity to meet the demands for 10% of the private cars. Ireland currently has 1.9 million private cars, 0.25 million vehicles below 2 t, and 0.08 million vehicles above 2 t [49]. Therefore, it is assumed here that there are 2.15 million cars/vans and 80,000 trucks/busses. A detailed breakdown of the reference scenario is provided later when discussing the scenarios in section 4.

Using the 2020 Irish energy system as a starting point, this analysis in this paper investigates the technical design and economic consequences of transitioning to a 100% renewable energy system. The transition proposed here is only one potential pathway to a renewable energy system: many others exist and even this particular pathway will change as more knowledge becomes available. However, the aim here is outline the key steps necessary towards 100% renewable energy, along with the technical and economic consequences of these steps. In total 7 different stages in the transition to a 100% renewable energy system are analysed here. Below is an explanation of each stage, outlining the initial motivation for analysing these technologies.

### 3.1. Reference

As already discussed, the 2020 Irish energy system is used as a starting point. This starting point defines the electricity, heat, and transport demands that will need to be satisfied in each of the other scenarios. In reality these demands will change over time: increasing due to society's desire to grow and consume more, but decreasing due to better efficiency. In this paper, changes in conventional demand have not been included in the analysis. This does not suggest that energy efficiency is not important. In fact, energy efficiency is often the most cost effective first step towards a more sustainable energy system [50]. However, this has not been included in this study since the focus here is to highlight how the supply side of the energy system will evolve, so future research could incorporate both the supply and demand.

Choosing a reference is also necessary to define the mix of power plants, the type of boilers, and the number of vehicles in the system being analysed. This forms the basis for other assumptions applied in the research. For example, during the next 6 stages of pathway proposed here, there are a number of assumptions from the reference which do not change in any of the scenarios, which are displayed in Table 1.

There is also a common procedure used to define the final amount of intermittent renewable energy sources (IRES) which can be used in the reference and the other scenarios. In all steps, the cost of the energy system is calculated for a wind power penetration of 0-100% of the electricity demand, in steps of approximately 10%. The cheapest scenario is then defined as defined as the 'optimal' for that particular scenario. IRES come in many forms, particularly from wind and solar. Due to Ireland's climate conditions, wind power is the primary form of IRES in this study (as mentioned earlier the technical potential is approximately 600 TWh/year [41], of which approximately 55 TWh/year will be economically viable in 2020 [42, 43].). In all scenarios, it is assumed that onshore wind power is the only source of intermittent renewable energy until it reaches a capacity of 10,875 MW: this corresponds to an annual electricity production of 30 TWh/year. After this it is assumed that offshore wind is used for any additional IRES that can be added to the system. In reality, there are other IRES that could be used such as PV, tidal, and wave power, but here wind is used on its own to simply the analysis. By combing wind with these other IRES, it would be possible to reduce the fluctuations from wind power [13]. Finally, in all scenarios it is possible to trade electricity with Britain over 1000 MW of interconnection, which is the expected capacity in 2020. However, this trading is seen as a last resort. The aim in these simulations is to design a flexible energy system in Ireland which can manage its own intermittency. The indirect assumption here is that Britain is also utilising a lot of wind power at the same time, which will make it difficult to balance wind with interconnection due to the high correlation between Irish and British wind speeds [51].

**Table 1: Common assumptions in all scenarios proposed in this paper.**

| | |
|---|---|
| Conventional Electricity Demand (TWh) | 30 |
| End-User Heat Demand (TWh) | 27.6 |
| Transport Demand (Billion km) | 103 |
| Average Power Plant Efficiency (%) | 48% |
| CHP Electricity Efficiency (%) | 40% |
| CHP Heat Efficiency (%) | 50% |
| Hydro Capacity (MW) | 250 |
| Hydro Production (TWh) | 1 |
| PHES Pump (MW) | 300 |
| PHES Turbine (MW) | 300 |
| PHES Storage (GWh) | 2 |
| PHES Pump & Turbine Efficiencies (%) | 85% |
| Industrial Electricity Production (TWh) | 1.5 |
| Interconnection Capacity to Britain (MW) | 1000 |
| Number of Buildings | 2,000,000 |
| Number of Cars | 2,150,000 |
| Number of Busses/Trucks | 80,000 |

### 3.2. District heating

The first key change in the system is the widespread implementation of district heating. There are three key objectives here: a) to save fuel by utilising waste heat in the energy system from power plants and industry b) to utilise more renewable energy by using heat from solar thermal and geothermal energy and c) to save money by using less fuel and by reducing the thermal capacity necessary in the heat sector i.e. by sharing the capacity in a common boiler instead of installing an individual unit in each building.

District heating is installed in cities and towns, where homes are located close together so the development of district heating is economically viable. There is currently no heat atlas available for Ireland, so the EU heat atlas developed in the Heat Roadmap Europe project [52] is used to estimate the potential for district heating. This heat atlas suggests that approximately 33% of the heat demand in buildings in Ireland is in areas with a heat density above 50 TJ/km$^2$, while 50% is in areas above 15 TJ/km$^2$. Therefore, it is assumed here that 10 TWh (37%) of the heat demand for buildings can be converted to district heating: 4 TWh (15%) is assumed to be in small towns while 6 TWh (22%) is in the large cities. Natural gas and oil boilers are replaced by these new district heating installations.

The heat for these new district heating networks is primarily supplied by combined heat and power (CHP) plants, which are supplemented by thermal storage and peak-load boilers. Losses in the district heating pipes are also accounted for by assuming that 17% of the heat produced does not reach the final consumer: thus 12 TWh of heat must be produced for the district heating systems to supply 10 TWh of delivered heat. The specific numbers altered for this transition are outlined in Table 2 and Table 3, which are based on the same methodologies described in Heat Roadmap Europe [52].

**Table 2: Changes to the Heat Supply for Stages 1–3. The assumptions in stage 3 are the same for all remaining scenarios.**

| Scenario | 1. Reference | 2. District Heating | 3. Heat Pumps |
|---|---|---|---|
| Individual Fuel Consumption (TWh) | 32 | 20 | 13 |
| Coal (TWh) | 3 | 3 | 0 |
| Oil (TWh) | 15 | 7.5 | 0 |
| Gas (TWh) | 9 | 4.5 | 4.5 |
| Biomass (TWh) | 1.5 | 1.5 | 1.5 |
| Heat Pump Electricity (TWh) | 0.33 | 0.33 | 3.6 |
| Direct Electricity (TWh) | 3.5 | 3.5 | 3.5 |
| Individual Heat Demand (TWh) | 28 | 18 | 18 |
| Coal (TWh) | 1.95 | 1.95 | 0 |
| Oil (TWh) | 12 | 6 | 0 |
| Gas (TWh) | 8.1 | 4.05 | 4.05 |
| Biomass (TWh) | 1.05 | 1.05 | 1.05 |
| Heat Pump Electricity (TWh) | 1 | 1 | 9 |
| Direct Electricity (TWh) | 3.5 | 3.5 | 3.5 |
| District Heating Supply (TWh) | 0 | 12 | 12 |
| With Decentralised CHP (TWh) | 0 | 5 | 5 |
| With Centralised CHP (TWh) | 0 | 7 | 7 |
| Includes Losses of (%) | n/a | 17% | 17% |
| Includes Losses of (TWh) | 0 | 2 | 2 |
| CHP2 (MW) | 0 | 750 | 750 |
| CHP3 (MW) | 0 | 1100 | 1100 |
| Thermal Storage (GWh) | 0 | 11.5 | 14 |
| Boilers (MWth) | 0 | 3500 | 3500 |
| Large Heat Pumps (MW) | 0 | 0 | 185 |
| Electric Boilers (MW) | 0 | 0 | 185 |

**Table 3: The number of heating units for steps 1–3 (rounded to the nearest 1000). The assumptions in stage 3 are the same for all remaining scenarios.**

| Scenario | 1. Reference | 2. District Heating | 3. Heat Pumps |
|---|---|---|---|
| Number of District Heating Substations | 0 | 726,000 | 725,000 |
| Number of Individual Boilers | 2,000,000 | 1,274,000 | 1,275,000 |
| Oil | 870,000 | 436,000 | 0 |
| Gas | 587,000 | 293,000 | 293,000 |
| Biomass | 217,000 | 218,000 | 76,000 |
| Air Heat Pumps | 0 | 0 | 0 |
| Ground Heat Pumps | 72,000 | 73,000 | 652,000 |
| Electric Heating | 254,000 | 254,000 | 254,000 |

**Table 4: Grid regulation requirements in all scenarios.**

| Scenario | 1–3 | 4. Grid Regulations | 5–7 |
|---|---|---|---|
| Min PP Production (MW) | 700 | 0 | 0 |
| Min CHP Production (MW) | 200 | 0 | 0 |
| Min Grid Stabilisation Share (%) | 30% | 0% | 0% |
| Stabilisation Share of Decentralised CHP Plants (%) | 100% | n/a | n/a |
| Maximum Heat Pump Load in DH Networks (%) | 50% | 50% | 50% |

### 3.3. Heat pumps

District heating is ideal for areas with a high heat density, but it is too expensive in rural areas where the heat density is too low. In these areas an individual heat pump is proposed in this pathway since they are very efficient, typically the coefficient of performance (COP) is 3-5, and they enable the integration of more wind power. Furthermore, it is also assumed in this step that large-scale heat pumps and electric boilers are added to the district heating network. This enables the wind power to access the flexibility in the large thermal storage capacities connected to the district heating network.

### 3.4. Grid regulation

Until now, it is assumed that 30% of the electricity being produced must come from power plants at all times. However, the electricity grid will become easier to operate as more flexibility is added to the energy system, while wind turbines will become better at providing ancillary services and responding to grid requirements. This will allow power plants to shut down completely for short periods so that wind power can provide all of the electricity required. It is difficult to identify an exact point when this will happen, but here it is assumed to occur at stage once the electricity and heat sectors have been fully integrated. This is based on Danish experiences, where wind power has already provided over 80% of all electricity production during some hours [53]. In practice this will not be a single step in the transition to a 100% renewable energy system, but instead it will occur in mini-phases across steps 1–5.

### 3.5. Demand side management (DSM) and electric vehicles & (EVs)

There are some electricity demands which can be used when it is suitable for the grid, since the end-user often doesn't need to turn them on straight away. For example, at a residential level this includes washing machines and dishwashers while at an industrial level this often includes refrigeration and processing plants. Similarly, when petrol/diesel cars are replaced by electric vehicles, this will also introduce a very flexible load into the home. In this step it is assumed that approximately 10% of the conventional electricity demand becomes flexible, while 80% of private cars are converted to electricity (see Table 5 and Table 6).

### 3.6. Syn-methanol/DME

Although a high proportion of the private car fleet is expected to convert to electricity, there is still a significant amount of energy-dense fuel required for other vehicles such as trucks, busses, ships, and aeroplanes. One of the main solutions proposed to solve this challenge is biofuels, but recent research indicates that this is not a sustainable way to use our limited biomass resource [54, 55]. To ensure that there is enough biomass for a 100% renewable energy system, synthetic fuels are utilised here. Hydrogen and carbon are combined at different ratios to make these synthetic fuels. In the pathway proposed here, it is assumed that the synthetic fuel produced is methanol or dimethyl either (DME), using the energy flows displayed in Figure 4 [23]. The hydrogen can be produced using electricity from wind power while the carbon can be captured from the atmosphere, industry, or power plants. This process requires a lot of electricity so the total electricity demand is increased by 125%. However, this is in return from two really important benefits: a) oil can be replaced in large vehicles which require energy-dense fuel with electricity from wind turbines (via a synthetic fuel) and b) the wind power now has access to gas and fuel storage. To put this in context, Ireland has approximately 33 TWh of oil storage today [56], which is 18 times more than the electricity storage feasible in Ireland's only pumped hydroelectric facility (Turlough Hill has a storage capacity of ~1.8 GWh [57]). It is important to emphasise that this transforms the energy system as we know it today. At this stage, the energy system now has an extremely intermittent supply which is possible thanks to an extremely flexible demand (today it is the opposite).

### 3.7. Syngas

The only fuels that are not renewable at this point are those required for industry (see Table 7) and for some of the power plants. The fuels in industry are necessary for various chemical and manufacturing processes as well as

Table 5: Transport fuel supply for all scenarios.

| Scenario | 1 - 4 | 5. DSM & EVs | 6. Syn-Methanol/DME | 7. Syngas |
|---|---|---|---|---|
| Oil | 69 | 33.9 | 0 | 0 |
| Jet Fuel (TWh) | 9 | 9 | 0 | 0 |
| Diesel (TWh) | 38 | 22.4 | 0 | 0 |
| Petrol (TWh) | 22 | 2.5 | 0 | 0 |
| Biofuels | 5.4 | 0 | 0 | 0 |
| Biodiesel (TWh) | 2.7 | 0 | 0 | 0 |
| Bioethanol (TWh) | 2.7 | 0 | 0 | 0 |
| Electricity | 1 | 13.2 | 13.2 | 13.2 |
| Power Capacity (MW) | Dump Charge | 9000 | 9000 | 9000 |
| Battery Capacity (GWh) | Dump Charge | 45 | 45 | 45 |
| | | | | |
| Synthetic Methanol/DME (TWh) | 0 | 0 | 35.7 | 35.7 |
| Fuel for Cars & Trucks (TWh) | 0 | 0 | 24.9 | 24.9 |
| Fuel for Jets (TWh) | 0 | 0 | 10.8 | 10.8 |
| Hydrogen Production (TWh) | 0 | 0 | 41.1 | 41.1 |
| Electrolyser Capacity (MW) | 0 | 0 | 16500 | 16500 |
| Electrolysis Electricity (TWh) | 0 | 0 | 56.2 | 56.2 |
| Electricity for $CO_2$ Capture (TWh) | 0 | 0 | 2.6 | 2.6 |
| $CO_2$ Captured (Mt) | 0 | 0 | 9.0 | 9.0 |

Table 6: The number of vehicles in all scenarios.

| Scenario | 1–4 | 5. DSM & EVs | 6. Syn-Methanol/DME | 7. Syngas |
|---|---|---|---|---|
| Total Cars and Vans | 2,150,000 | 2,150,000 | 2,150,000 | 2,150,000 |
| Conventional | 1,935,000 | 430,000 | 0 | 0 |
| Electric | 215,000 | 1,720,000 | 1,720,000 | 1,720,000 |
| Syn-Methanol/DME | 0 | 0 | 430,000 | 430,000 |
| EV Charging Stations | 215,000 | 1,720,000 | 1,720,000 | 1,720,000 |
| Total Busses/Trucks | 80,000 | 80,000 | 80,000 | 80,000 |
| Conventional | 80,000 | 80,000 | 0 | 0 |
| Syn-Methanol/DME | 0 | 0 | 80,000 | 80,000 |

for high-temperature heat. The power plants need some fuels, primarily gas, so that there is some form of fuel available when there is not enough wind power. Gas is the chosen fuel since these power plants are the most flexible so they are able to respond to changes in the wind power production. In this final step, all of the fossil fuels used in industry are replaced by syn-methane or biomass. Using syn-methane means that the existing natural gas gird and storage facilities can also be used to aid the integration of wind power. The syn-methane is produced using almost the same process as for syn-methanol/DME, with the only difference being the chemical synthesis of the final fuel. However, it is important to mention that multiple sources of $CO_2$ can be used for both the production of syn-methanol/DME and syn-methane. To account for this uncertainty, different sources of $CO_2$ are used for the production of syn-methane here. In total, two sources are utilised: biogas as outlined in Figure 5 and gasified biomass as outlined in Figure 6. It is important to highlight that the uncertainty levels increases as the transition progresses by each stage. Stage 7 is therefore the most uncertain at present, so it is also the most likely one that will change in the transition proposed here. There may also be numerous niche technologies that contribute to the final stages such as electricity storage.

## 4. Results and discussion

The transition from the initial reference system to a 100% renewable energy system transforms how energy is provided. The most visible change is that the electricity sector becomes the backbone of the energy

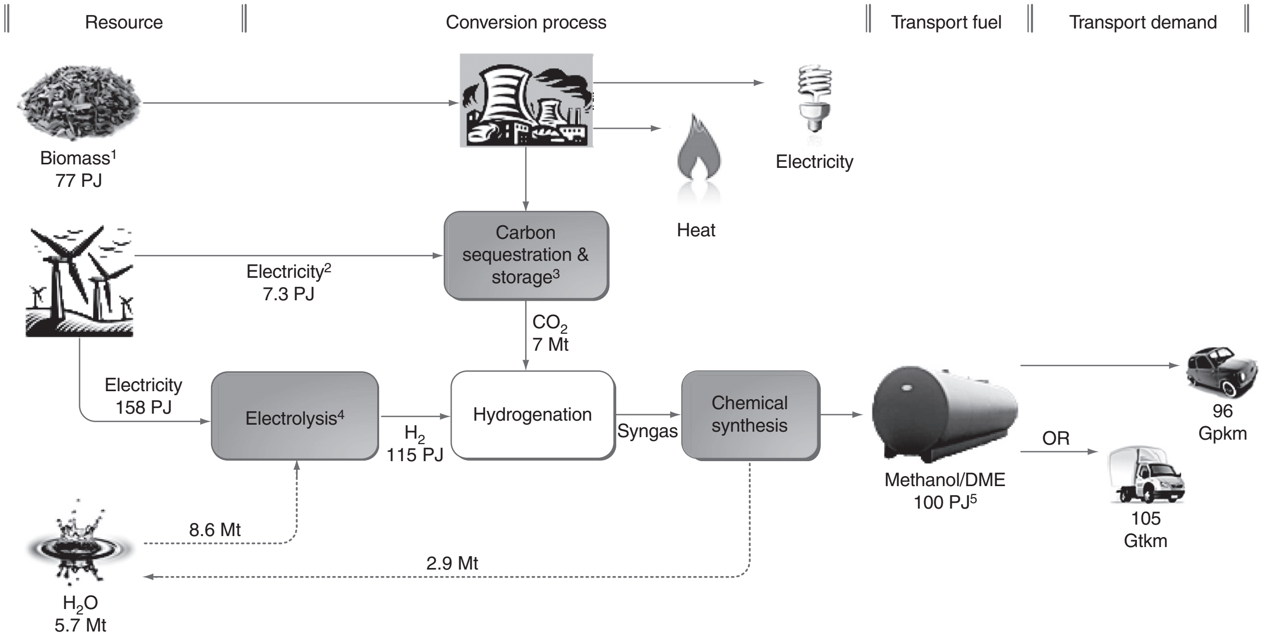

Figure 4: Hydrogenation of carbon dioxide sequestered using CCR to methanol/DME. [1]Based on dry willow biomass. [2]Based on an additional electricity demand of 0.29 MWh/t$CO_2$ for capturing carbon dioxide from coal power plants [58]. [3]If carbon trees were used here, they would require approximately 5% more electricity [59]. [4]Assuming an electrolyser efficiency of 73% for the steam electrolysis [60, 61]. [5]A loss of 5% was applied to the fuel produced to account for losses in the chemical synthesis and fuel storage.

**Table 7: Industrial fuel demands for all scenarios.**

| Scenario | 1–6 | 7. Syngas |
|---|---|---|
| Coal | 1 | 0 |
| Oil | 10 | 0 |
| Gas | 10.5 | 0 |
| Biomass | 4 | 9.5 |
| Syngas | 0 | 16 |
| Total | 25.5 | 25.5 |

**Table 8: Syngas production for all scenarios.**

| Scenario | 1–6 | 7. Syngas |
|---|---|---|
| Syngas Production | 0 | 57.5 |
| Biogas | 0 | 10.0 |
| Biomass which is Gasified | 0 | 34.6 |
| Syngas from Gasified Biomass | 0 | 27.9 |
| Hydrogen for Syngas Production | 0 | 25.7 |
| Electricity for Electrolysis | 0 | 32.1 |
| Electrolyser Capacity (MW) | 0 | 5000 |

system, with the demand for electricity increasing by over 400%. As displayed in Figure 7, new electricity demands in heat pumps and electric vehicles increase the overall electricity demand by approximately 50%, but it is the introduction of synthetic fuels that play the most significant role.

As mentioned earlier, the purpose of synthetic fuels is to put electricity from IRES into energy-dense fuels which can be used for long-distance or heavy-duty transport. The transport sector today is approximately the same size, in energy terms, as the electricity sector, so transforming transport from oil to electricity has a major impact on the level of electricity consumed. It is important to recognise that this creates enormous levels of flexibility in the energy system because this connects the IRES to a very large fuel storage system: for example, Ireland currently has 33 TWh of oil storage [56].

This changes the dynamics of the energy system from today's 'smart supply' where production follows demand, to the future's 'smart demand' where demand accommodates supply. In other words, the role of supply and demand is reversed in the smart energy system. This is evident from the scale of IRES on the supply side of the electricity sector. Figure 8 outlines how the role of wind power increases as the energy system progresses through each stage of the transition. The most economic wind penetration in the reference scenario is approximately 35%, which increases to approximately 85% in the 100% renewable energy system.

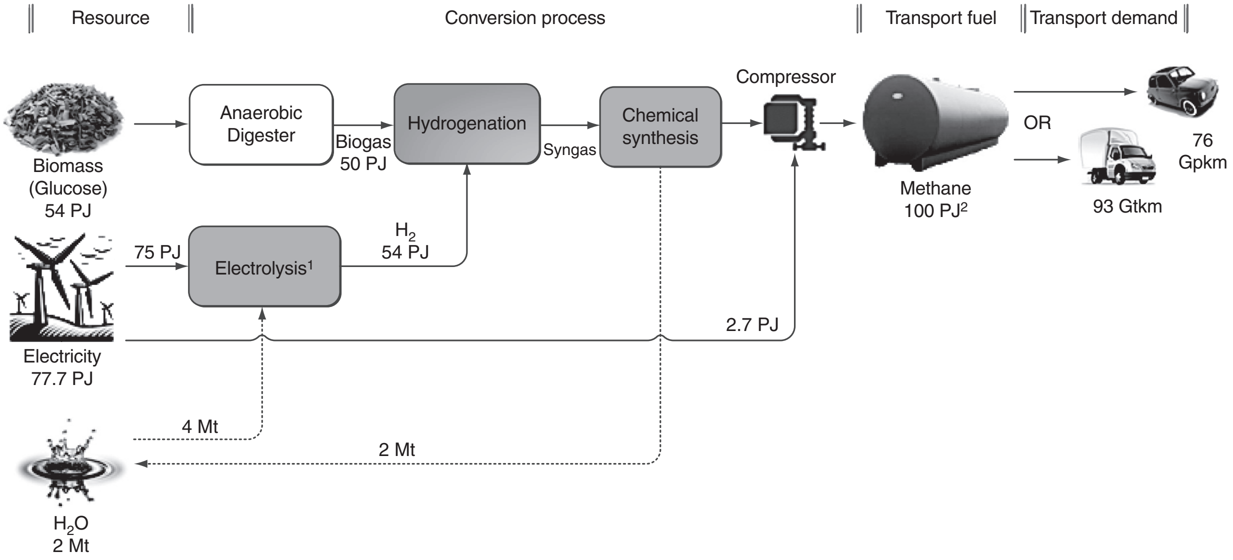

Figure 5: Production of biogas from biomass which is subsequently hydrogenated to produce methane. [1]Assumed an electrolyser efficiency of 73% for the steam electrolysis [60, 61]. [2]A loss of 5% was applied to the fuel produced to account for losses in the chemical synthesis and fuel storage.

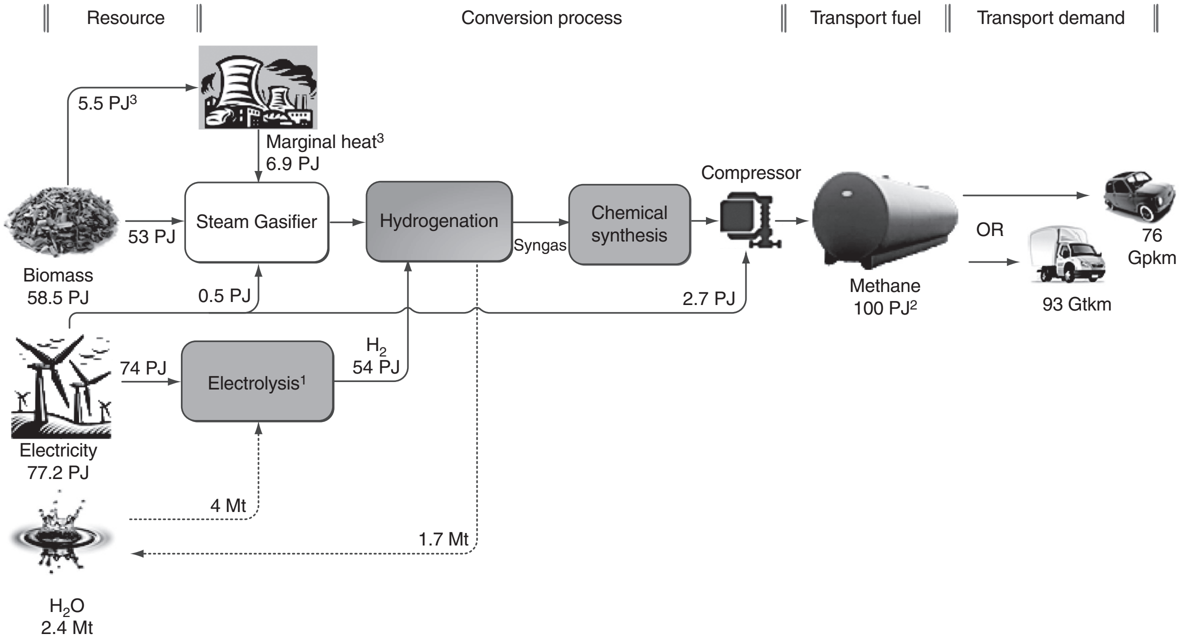

Figure 6: Steam gasification of biomass which is subsequently hydrogenated to methane. [1]Assumed an electrolyser efficiency of 73% for the steam electrolysis [61]. [2]A loss of 5% was applied to the fuel produced to account for losses in the chemical synthesis and fuel storage. [3]Assuming a marginal efficiency of 125% and a steam share of 13% relative to the biomass input.

When accounting for the complete energy system, Figure 9 indicates that the primary energy supply in the 100% renewable scenario is the same as the reference scenario (the difference is <2%). Although it appears that the 100% renewable energy scenario is less complicated since it only contains IRES and biomass, there are many more conversion technologies within this scenario than in the reference (see Figure 2). For

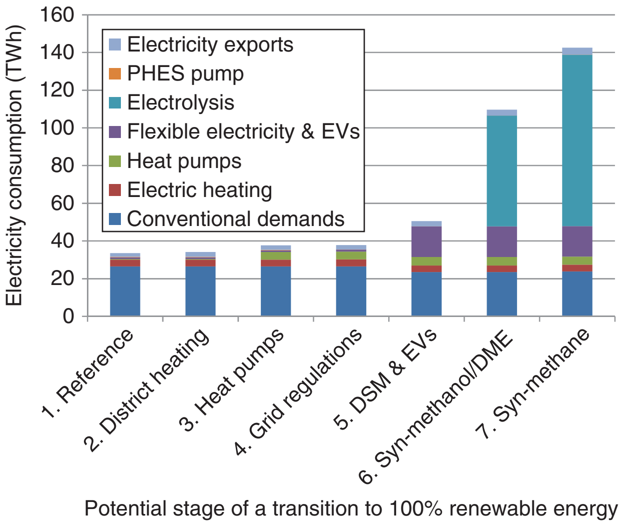

Figure 7: Electricity consumption for each potential stage of the transition to 100% renewable energy.

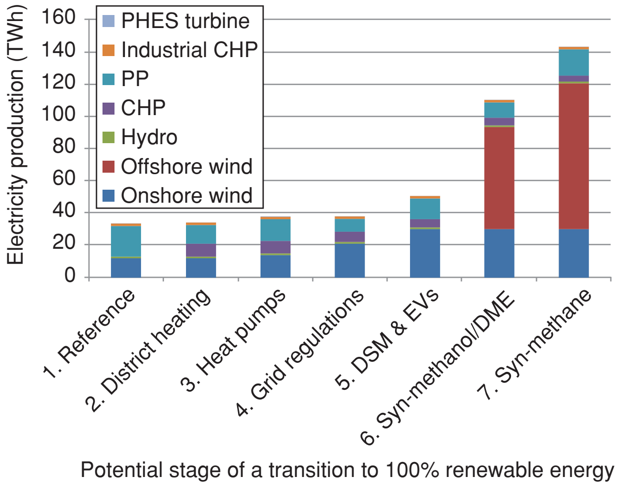

Figure 8: Electricity production for each potential stage of the transition to 100% renewable energy.

example, it includes biomass conversion plants such as gasification and biogas, as well electricity conversion plants such as the electrolysers, $CO_2$ hydrogenation plants, syngas plants, electric vehicles, and heat pumps.

The introduction of district heating, the electrification of heat using heat pumps, and the electrification of private cars all reduce the primary energy supply (see Figure 9). For district heating this is primarily because surplus heat from power plants replaces fuels in individual boilers. For the electrification of heat and transport, the primary energy supply is reduced since these technologies are more efficient than their combustion alternatives. A heat pump has a COP of 3 and an individual boiler has an efficiency of 80–95%, while an electric vehicle can travel 1 km using 25% of the energy that a conventional petrol or diesel car would use. As a result of these measures, the primary energy supply is reduced by 25% between the reference and stage 5 of the transition to 100% renewable energy. The subsequent increase is due to the multiple conversion processes necessary to create synthetic fuel (see Figure 4, Figure 5, and Figure 6).

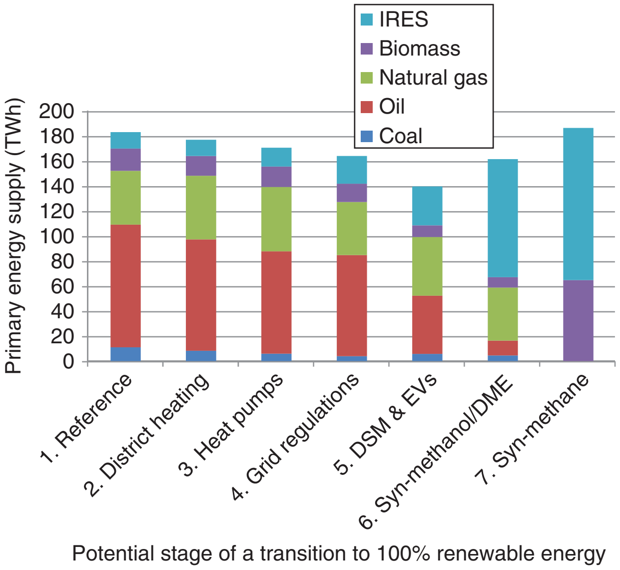

Figure 9: Primary energy supply for each potential stage of the transition to 100% renewable energy.

The cost of this transition is naturally another critical metric that needs to be considered. Therefore, the costs of each stage have also been estimated based on 2020 costs for fuels, $CO_2$, energy plants, vehicles, boilers, and district heating, which are available in the Appendix. The results are displayed in Figure 10, which indicate that the cost of the energy system will be the same for the first 4 stages. When the private car fleet is electrified the cost of the energy system is reduced by 5%, but the cost begins to increase again once syn-methanol/DME and syn-methane production is introduced. As a result, the final 100% renewable energy system scenario is approximately 30% (€5 billion/year) more expensive than the original reference scenario. However, this is based on 2020 prices whereas the transition to 100% renewable energy will occur over a much longer time scale. For example, Denmark is a front-runner in renewable energy and is aiming to be 100% renewable by 2050. Therefore, the results have been repeated based on 2050 price forecasts.

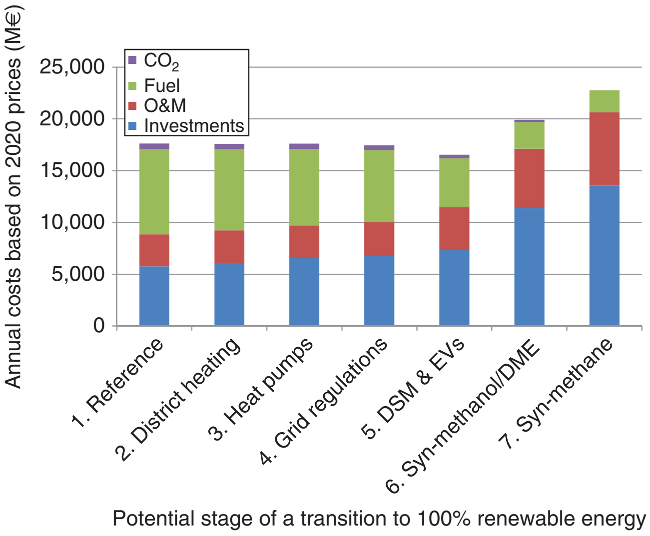

Figure 10: Annual costs of each stage in the transition based on 2020 prices.

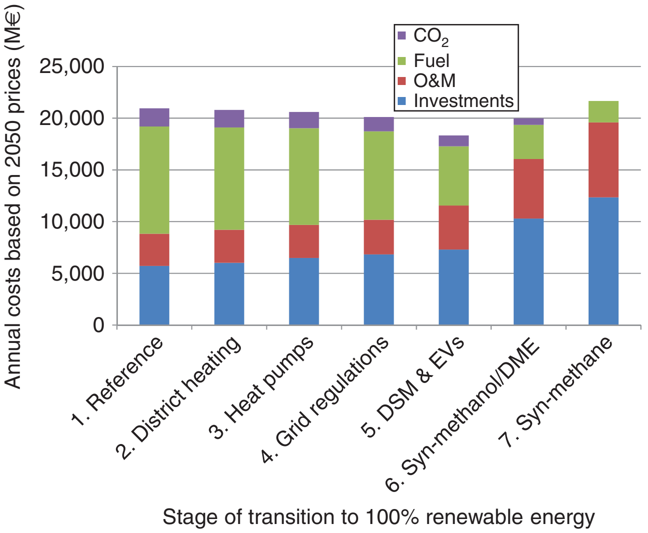

Figure 11: Annual costs of each stage in the transition based on 2050 prices.

Not all of the costs have been updated to 2050 prices, but instead only the fuel, $CO_2$, and wind power costs were adjusted (see Appendix and Table 9). Using these assumptions, the 100% renewable energy scenario costs approximately the same as the original reference scenario (see Figure 11): the exact difference is 3%, but considering the uncertainties associated with many of the forecasted costs, this is deemed the same. This is a very significant result because although the total costs are the same, the structure of the costs is altered dramatically.

The dominant cost in the reference scenario is 'fuel', accounting for approximately half of the total costs. In the 100% renewable energy system, fuel is a relatively small part of the total costs. Instead it is 'investments' and 'operation and maintenance (O&M)' costs which are the major forms of expenditure. This has a major impact on the balance of payment for Ireland, since Ireland currently imports around 90% of its fuel. If Ireland transitions to an investment/O&M-based energy system, more money will be spent within Ireland instead of being spent abroad by importing fuels. It is very difficult to be exact when calculating the impact of this change, but an estimate has been made here. It is assumed that the average Irish employee earns _45,000/year and that the transition to 100% renewable energy occurs over a 30 year period, from 2020 to 2050. It is also assumed that the import share for investments, O&M, fossil fuels, biomass, and vehicles is 60%, 20%, 90%, 10%, and 10% respectively.

Based on these assumptions, over the whole period from 2020 to 2050, there would be 100,000 more direct jobs in the energy sector in the renewable energy scenario compared to the reference scenario. This is not the same 100,000 jobs over the whole period, since different sectors would create jobs at different times. For example, there would be a lot of jobs installing district heating pipes in the early stages of the

**Table 9: Investment costs assumed for onshore and offshore wind power in 2020 and 2050.**

| Technology | Unit | Investment (M€/Unit) 2020 | Lifetime (Years) | Fixed O&M (% of Investment) |
|---|---|---|---|---|
| Onshore Wind | $MW_e$ | 1.25 | 20 | 3.0% |
| Offshore Wind | $MW_e$ | 2.30 | 20 | 2.9% |
| | | 2050 | | |
| Onshore Wind | $MW_e$ | 1.22 | 30 | 3.2% |
| Offshore Wind | $MW_e$ | 2.10 | 30 | 3.2% |

transition, but this would move to wind power and electrolysers towards the latter stages. Also, these 100,000 additional direct jobs are created if the investments are spread evenly over the whole period. In reality, this would not be the case since there would be years with high investments and years with low investment. The 100,000 additional jobs over the whole period is an average.

This means that the 100% renewable energy scenario can provide energy at a similar price to the reference, while at the same time producing no $CO_2$ emissions and creating approximately 100,000 more jobs. This is in line with similar conclusions from other studies for Denmark [6, 7].

### 4.1. Limitations

Creating scenarios for the future is also subject to many uncertainties and limitations. To reduce this, the assumptions and methodologies used to create the scenarios in this study have been clearly presented.

From a technical perspective, the most uncertain aspect of the pathway presented here is the production of synthetic fuels. Although many of the individual components for the production of synthetic fuels are already in use today, there are only a few pilot studies that have combined them all together. This means that the efficiencies assumed here may not fully reflect what will be possible in reality, although it is currently unclear whether they will be better or worse.

The analysis here has also been limited to the supply side of the energy system, so reductions in the energy demand have not been accounted for. This is not a reflection on the importance of reductions in the energy demand, since this is likely to play a key role in a sustainable energy system. Instead it is has been omitted so the focus could be on the supply side. Similarly, only wind power was considered here whereas in reality this electricity will come from a mix of wind, solar, wave, and tidal power.

The other significant uncertainties are primarily related to costs. The costs of expanding the electric grid are very uncertain, firstly due to the fact that the demand for electricity is increased by over 400%, but also because the design of the electricity system with these new synthetic fuel plants is still very unclear. For example, a lot of this electricity may not be transported over long distances and therefore the grid itself might not be expanded proportionally to the increase in electricity demand. Similarly, the cost for eliminating the need to provide grid regulations is not included here. In other words, it is assumed that this is included in the cost of ‘smarter’ technologies which are used in the energy system. For example, it is assumed that an electric car will include the cost of knowing when to charge at a time which is beneficial for the rest of the electric grid. The costs of the synthetic fuel plants are also very uncertain since there is currently no large-scale demonstration plant in operation, but since these are the final steps in this transition, there is still a lot of time for more knowledge to be developed in relation to these final two steps.

Finally, it is important to remember that the pathway proposed here is only one proposed pathway to 100% renewable energy. Many others could also be pursued so future work could analyse variations of this pathway. For example, some of the steps could be removed and different IRESs could be utilised depending on the local context.

## 5. Conclusions

This paper has outlined how an existing energy system can be transformed into a 100% renewable energy system. Technically the same end-user demands are met at all stages of this transition, but due to some radical changes in the conversion technologies utilised, the final demand for electricity is over 4 times higher in the renewable energy system. Seven different stages are defined here, and in general there are more uncertainties as the transition progress by each stage. However, for the first 5 stages, all of the technologies required are in existence today, although they require some development to achieve the final targets suggested here. In conclusion, the technology currently exists to begin the transition to a 100% renewable energy and it is very likely that technology will be developed sufficiently to provide all end-user demands solely based on renewable energy, especially when intermittent renewable energy is connected to the flexibility of liquid or gaseous fuels.

In terms of costs, based on 2020 and 2050 fuels, the first five stages of the transition to 100% renewable energy are either socio-economically the same or cheaper than the reference. The final two stages are more expensive based on 2020 prices, but approximately the same cost based on 2050 prices (note that for the investment costs, only wind power was updated to 2050). This only reflects part of the story, since the structure of the costs in each alternative is as important as the costs themselves. The reference scenario is primarily a fuel based system so most of the energy system costs are based on importing fuel into the energy system, since Ireland currently imports 90% of its fuel. In contrast the renewable energy system is primarily based on investments and O&M costs, so more money is spent in the local economy. Here the impact of this has been estimated, with the results indicating that approximately 100,000 additional jobs can be created in the energy sector in the 100% renewable energy scenario. These are only direct jobs, so this can be seen as a conservative estimate since it does not include indirect jobs, for example in shops and cafes, or jobs created due to the development of technologies for export. In conclusion, based on forecasted prices for fuel, $CO_2$, and wind power for the year 2050, a 100% renewable scenario is approximately the same cost as an energy system like today's, but it will result in the creation of approximately 100,000 additional direct jobs.

The results in this paper are significant since they demonstrate the technical and economic potential of renewable energy in a country that has sufficient renewable resources and currently imports fuel. The first steps in the transition proposed here have already been completed in Denmark and Sweden, where district heating, CHP, thermal storage, and large-scale heat pumps are well-known technologies. Similarly, stage 4 (relaxing grid regulations) has also been demonstrated in Denmark where wind power has successfully supplied over 80% of the electricity demand in the past [53]. Electric vehicles are developing rapidly, so if these technologies fulfil their potential, the most economic scenario for Ireland will occur at a wind penetration of 60–70% in the future. The production of synthetic fuel is still subject to many uncertainties and so there are likely to be some developments in the last few stages of the transition proposed here. In any case, the results suggest that the transition to a 100% renewable energy system can begin today without increasing the costs of the energy system and by creating more local jobs.

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## 7. Appendix A: Cost assumptions

**Table 10: Fuel and $CO_2$ prices assumed for 2020 and 2050.**

| €/GJ | Oil (US$/bbl) | Gas | Coal | Fuel Oil | Petrol/Diesel | Jet Fuel | Biomass | Nuclear | $CO_2$ (€/t) |
|---|---|---|---|---|---|---|---|---|---|
| 2020 | 107.4 | 9.1 | 3.1 | 11.9 | 15.0 | 16.1 | 7.3 | 1.5 | 15 |
| 2050 | 142.0 | 12.2 | 3.4 | 16.1 | 19.6 | 20.6 | 9.3 | 1.5 | 47 |

**Table 11: Individual heating unit cost assumptions [62].**

| Heating System: | New Building: One-family house (2020) | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | Heat pump | | | |
| **Heating Unit** | **Oil** | **Gas** | **Biomass** | **Air to water** | **Brine to water** | **Electric heating** | **District heating substation** |
| Average Heat Capacity (kW/unit) | 22.5 | 11.5 | 12.5 | 10 | 10 | 5 | 10 |
| Technical lifetime (years) | 20 | 22 | 20 | 20 | 20 | 30 | 20 |
| Average investment (1000€/unit) | 6.6 | 5 | 6.75 | 12 | 16 | 4 | 2.5 |
| Additional investment (1000€/unit) | 0 | 2 | 1.6 | 0 | 6 | 0 | 3 |
| Fixed O&M (€/unit/year) | 270 | 46 | 25 | 135 | 135 | 50 | 150 |
| Variable O&M (€/MWh) | 0 | 7.2 | 0 | 0 | 0 | 0 | 0 |

**Table 12: District heating cost assumptions. It is assumed here that all district heating is low-temperature district heating. This is suitable for the smart energy system since it is designed for low-energy buildings and low distribution temperatures, which enables more heat sources to be utilised.**

| Technology | Low-temperature district heating network |
|---|---|
| Heat density for consumer (TJ/km$^2$ land area) | 45–50 |
| Net loss (%) | 17 |
| Average Technical lifetime (years) | 40 |
| Investment costs (1000 €/TWh) | 522,000 |
| Fixed O&M (1000 €/TWh/year) | 3,960 |
| Variable O&M (€/MWh) | 0 |

**Table 13: Cost assumptions for vehicles [63]. It is assumed that all vehicles have a technical lifetime of 13 years.**

| Vehicle Costs from the Danish Energy Agency | | |
|---|---|---|
| **Year** | **2025** | |
| Vehicle | Investment (€/vehicle) | Annual O&M (% of Invest) |
| | **Cars** | |
| Diesel | 12,822 | 7.21% |
| Petrol | 11,480 | 8.19% |
| Electric Vehicles | 12,971 | 11.16%* |
| Methanol/DME | 14,104 | 6.55% |
| | **Busses** | |
| Diesel | 161,074 | 1.23% |
| Methanol/DME | 163,960 | 1.20% |
| | **Trucks** | |
| Diesel | 161,074 | 1.23% |
| Methanol/DME | 163,960 | 1.20% |

*The battery costs are included in the O&M costs.

**Table 14: Investment costs assumed for the year 2020 and 2050, which are primarily based on the forecasted prices for the year 2020 [23, 50, 64–70]. For the 2050 analysis, the wind power investment costs were updated as outlined in Table 9.**

| Production Type | Unit | Investment (M€/unit) | Lifetime (Years) | Fixed O&M (% of Investment) |
|---|---|---|---|---|
| Solar Thermal | TWh/year | 440 | 20 | 0.001% |
| CHP | MWe | 0.84 | 25 | 2.30% |
| Large-Scale Heat Pumps | MWe | 2.7 | 20 | 0.20% |
| Thermal Storage | GWh | 3 | 20 | 0.70% |
| Centralised Thermal Boilers | MWth | 0.15 | 20 | 3.00% |
| Centralised Electric Boilers | MWe | 0.15 | 28 | 1.00% |
| Average Power Plant* | MWe | 0.89 | 26.0 | 1.82% |
| Coal Power Plant | MWe | 1.98 | 30 | 1.77% |
| Peat Power Plant | MWe | 1.69 | 30 | 3.25% |
| OCGT | MWe | 0.40 | 25 | 2.00% |
| CCGT | MWe | 0.68 | 25 | 1.51% |
| Wind Onshore | MWe | 1.25 | 20 | 3.00% |
| Wind Offshore | MWe | 2.3 | 20 | 2.90% |
| Hydro Power | MWe | 1.9 | 50 | 2.70% |
| Hydro Storage | GWh | 7.5 | 50 | 1.50% |
| SOEC Electrolyser | MWe | 0.57 | 20 | 2.46% |
| Hydrogen Storage | GWh | 10 | 30 | 0.50% |
| Pump | MWe | 0.6 | 50 | 1.50% |
| Turbine | MWe | 0.6 | 50 | 1.50% |
| Pump Storage | GWh | 7.5 | 50 | 1.50% |
| Waste CHP | TWh/year | 250 | 20 | 1.82% |
| Biogas Plant | TWh/year | 376.5 | 20 | 11.25% |
| Gasification Plant | MWgas | 0.649 | 20 | 9.77% |
| Biodiesel Plant | MW-Bio | 0.272 | 20 | 1.00% |
| Bioethanol Plant | MW-Bio | 1.92 | 20 | 3.32% |
| $CO_2$ Hydrogenation | MW-Fuel | 0.90 | 20 | 2.46% |
| Carbon Capture | Mt | 30 | 25 | 0.00%^ |
| Chemical Synthesis | MW-Fuel | 0.49 | 20 | 3.96% |
| Smart Meter | Device | 0.0002 | 30 | 2.00% |
| Electric Grid | MWe | 0.165 | 45 | 1.00% |

*Based on the current mix of power plants in Ireland.

^Included in the investment cost.