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Modelling the Irish Energy System to Evaluate Potential Energy System Pathways

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Summary

The aim of this thesis is to provide technical energy system options to Irish policymakers that could be implemented to meet the applicable EU-target of a 32% share of energy from renewable sources by 2030 [1]. As has been widely publicised, Ireland's compliance record to date has been well behind what is necessary despite the efforts of the two main actors in energy in Ireland; semistate bodies, the ESB and Eirgrid. Although they have successfully developed and incorporated high levels of wind in an island electricity grid system, which is a considerable achievement, Irish progress is hampered by lack of substantial inroads in applying renewables to the heat and transport sectors.

An energy system is made up of three components; electricity, heat and transport. To quantify both the inter-connectivity and changes needed, a reference model of the 2017 Irish energy system was developed and used to test potential changes as applied to the system using EnergyPLAN software. This modelling software was created and used in Denmark, a country which stands as an inspirational precedent for Ireland in terms of how it tackled and transformed its own energy system in recent decades. It models electricity, heat and transport, takes in hourly electricity demand and intermittent renewable supply distributions and matches dispatchable supply to meet any gaps between supply and demand. It, therefore, can model the impact of renewables hour-by-hour on the different components of the energy system.

The construction of the reference model was a long, iterative process which consisted of comparing the model's energy system outputs to the recorded 2017 energy system outputs. Where data was unavailable it was necessary to make assumptions, a detailed discussion of which can be found in Section 3.5. Once the reference model was built and tested, proposed system changes by the Government's Joint Committee on Climate Action, the ESB and Eirgrid were then incorporated into the model. These proposed, anticipated or interpreted changes were:

1. 1.3 GW loss of electricity production [2].
2. 60% increase in electricity demand [2].
3. 8000 MW of renewable electricity capacity made up of 6704 MW actual capacityThis is equal to 7327 MW of installed onshore capacity due to the 8.5% curtailment factor, 435 MW of offshore[i] and 238 MW of hydro [3].
4. 2326 MW of new CCGT power plants.
5. 700 MW of added interconnection [4, 5].
6. Coal generation repowered to gas and peat generation to biomass [4, 6].
7. 136 MW of battery power with 0.2 TWh of electricity storage [7].
8. 1000 MW total flexible demand.
9. 1.5 million homes deep retrofitted with corresponding 75% decrease in demand per home and the installation of a heat pump in each home for heating [6].
10. District heating networks installed to distribute heat at Poolbeg [8].
11. 12% of diesel and petrol by volume to consist of biofuels [6].
12. 300,000 electric cars on the road, with 50% of cars are allowed charge during peak demand and 75% of parked electric vehicles are grid connected (assumptions) [4].

[i]This is equivalent to a 1 billion euro investment in offshore wind

It was found that the newly modelled system would cost roughly 8.7 billion euros with the majority of these costs (5.17 billion) coming from further investment in onshore wind. 61.6% of electricity and 23.4% of primary energy would be provided in this scenario by renewable energy, which is less than the target of 32%. Due to the intermittent nature of wind energy the useful energy return from installed wind capacity rapidly diminishes with increased capacity. By adopting a smart energy systems approach it may be possible to reduce this effect by putting intermittent energy to use in the heat and transport sector and benefit from synergies between technologies. The following synergies were identified from literature:

- Increased electrification of transport provides a potential source of electricity storage. Eirgrid's recommendation of 300,000 electric vehicles was adopted in an EnergyPLAN model[4]. They added a significant load but also a source of storage for the grid. In order to harness the storage potential of electric vehicles drivers will need to be incentivised to keep them connected to the grid as much as possible. Although increasing the number of vehicles will mean that additional electricity generation is required this type of load is well suited to harnessing renewable electricity.
- Large scale implementation of district heating in cities. Although there are already plans to implement district heating for waste heat from incinerators and data centres this does not take full advantage of district heating's potential. It is possible to either retrofit existing Combined Cycle Gas Turbine (CCGT) power plants[i] or build future CCGT plants with the ability to produce process heat for district heating. District heating is more beneficial from an energy system perspective than heat pumps for individual households as it can easily be supplied by thermal storage. This thermal storage can in turn be supplied by intermittent renewables during periods of excess production. Heat pumps cannot be as easily synchronised with storage and so cannot take advantage of excess renewables to the same extent.
- Using Power to Gas (P2G) to fuel heavy vehicles, freight and aircraft which are not currently considered suitable for electrification. It will be necessary to develop either P2G or hydrogen production to meet the fuel demands of these vehicles [10, 11]. P2G holds advantages over hydrogen as the fuel produced is compatible with existing gas infrastructure and can be stored cheaply and efficiently. Regardless of whether P2G or hydrogen is chosen the electrolysis infrastructure will need to be developed. Both technologies can be used as a form of electricity storage if operated during periods of excess production. This need for production of synthetic gas (syngas) from P2G (or hydrogen from hydrogen production) for transportation will, in turn, incentivise the use of this technology to meet long-term electricity storage demands [11].

The real advantage of smart energy systems is not for a short-term 2030 system but for a longer term 2050 system. The associated synergy advantages will become more useful as renewable energy contributions to electricity reach the 100% level rather than the 60-70% level.

[i] Halligan's paper puts the cost of this retrofit at roughly 9.5 million euros [9]

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First of all, I would like to thank thank my supervisor, Professor Breiffni Fitzgerald, for his continuous guidance and patience throughout the year. Our weekly meetings were both a strong motivator and an extremely useful source of thesis-related and personal advice. Secondly, I would like to thank Professor Darina Murray for her expert advice and for kindly lending me her books on renewable energy technologies and energy systems transitions.

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Glossary of Non-Obvious Terms

APC	Active Power Control; allows wind turbines to participate in stablising the grid in the event of power loss
DO	Distillate Oil
Capacity	The power delivered by a certain source of energy
CCGT	Combined Cycle Gas Turbine
CHP	Combined Heat and Power; a power plant that can produce both heat and electricity
Curtailment	The dumping of renewable energy when in excess
COP	Coefficient of Performance
EV	Electric Vehicles
Feed-in Tariff	The payment made for contributing electricity to the grid
HFO	Heavy Fuel Oil
Iterative	The repetition of a process to generate a sequence of outcomes
OCGT	Open cycle Gas turbine; a type of gas power plant process
OM	Operation and Maintenance
P2G	Power to gas; the name of the process whereby electricity and biomass are combined to produce synthetic gas
RESS	Renewable Energy Support Scheme; the support program put in place by the Irish Government
Syngas	Synthetic gas; produced by the P2G process
REFIT	Renewable Energy Feed-in Tariff scheme;
TSO	Transmission System Operator; the organisation in charge of balancing the electricity grid.
V2G	Vehicle to grid; the name of the process whereby electric vehicles feed back electricity

1 Introduction & Background

Note: In the following sections footnotes will be used to explain the various terminologies used (such as primary electricity consumption, radiative forcing etc.).

Current trends indicate that Ireland will not meet its EU-imposed 2020 target of a 16% share of energy from renewable sources in gross[i] final energy consumption [20], and thus may face fines of up to 200 million euro per year [21, 22]. With a 2030 target currently set at 32% rapid change is needed [1].

As shown in Table 1.1, Ireland has made the most progress in electricity (27.2%) with comparatively slower progress in renewable heat (6.8%) and transport (5%) [23]. However, as it has a higher 2020 target of 40%, it's relative progress towards its target is comparable to the other sectors at 68%. The terms 'Actual Renewables' and 'Notional Renewables' have been used in the table below to illustrate the difference between actual progress and adjusted progress. In order to incentivise the uptake of new technologies in transport, the EU 2009 directive applies a multiplier to the consumption of energy by certain sources [20]. Therefore, some sources of energy contribute more towards the EU target and so progress towards targets is not fully representative of actual progress. This is true for biofuels from waste which count for twice as much non-waste sourced biofuels, so their actual contribution in terms of progress towards the EU-imposed target. Similarly, as progress in electricity and heat is measured in terms of gross, not primary[ii], final energy consumption, 'notional' renewables count for higher than actual renewables. In 2017 44% of total electricity generation was lost in combustible electricity generation processes, and so if these losses are ignored the contribution of renewable energy increases significantly [iii].

Table 1.1: Breakdown of Energy Consumption in Ireland (2017) [12]

	Electricity	Heat	Transport	Total Renewable Contribution	Total Progress To Target
Share of Total Energy (primary)	32.4%	33%	34.6%	-	-
Share of Fossil Fuels (primary)	84.2%	92%	96.8%	-	-
Share of Actual Renewables (primary)	14.8%	6.2%	2.4%	5.9%	-
Notional Renewables (gross)	30.1%	6.9%	7.4%	10.6%	-
2020 Target	40%	12%	10%	16%	-
Progress To 2020 Target	75.3%	57.5%	74%	-	66.3%

[i] Gross final energy consumption means that generation conversion losses are neglected

[ii] Primary energy includes conversion and transmission losses. Gross energy is the actual delivered energy after these losses.

[iii] Although generators of renewable energy do also suffer from losses these losses are typically not included in primary energy as most renewable processes do not involve a conversion of fuel into energy

Figure 1.1 below provides a more detailed breakdown of the primary energy use:

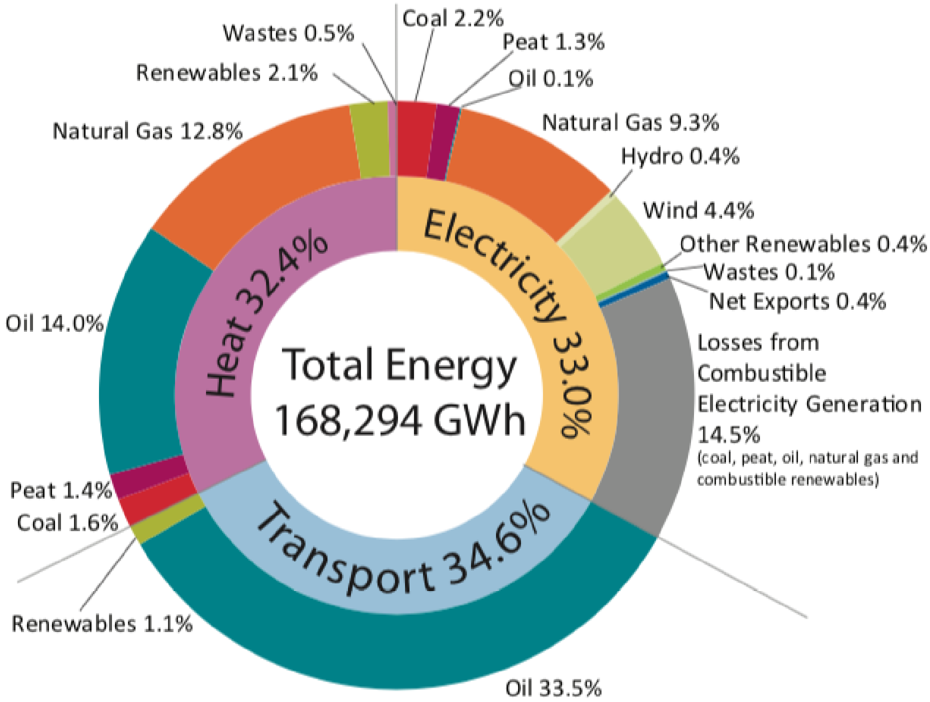

Figure 1.1: Total Primary Energy Use in Ireland (2017) by mode and fuel [12]

Ireland's renewable progress in electricity has been mainly due to further development of onshore wind, in heat mostly due to solid biomass[i], and in transport mainly due to rising 'Biofuel Obligation Scheme' targets (from 4% biofuel penetration by volume in diesel and petrol in 2010 to 6% in 2013) [24]. Globally progress has been similarly slow in heat and transport [25], with the exception of some countries such as Denmark which has made great progress in renewable heat [26]. Denmark currently supply 51% of their district heating from renewable sources, and district heating covers around 50% of heat production which means that around 25% of their heat comes from renewable sources compared to Ireland's 6.9% [26].

1.1 Consequences of business as usual

A recent report released by the Intergovernmental Panel on Climate Change (IPCC), a United Nations body, provides further incentive for energy system change in comprehensively outlining the potential impacts of global temperatures rising 1.5 °C above pre-industrial times as a result of greenhouse gas emissions (GHG) [27]. Some of these risks include droughts, floods, extreme heat and poverty for hundreds of millions of people [28]. Significantly, Irish cities are predicted to be among the worst affected in Europe by flooding [29, 30]. How likely are we to avoid this 1.5 °C limit? In 2011, van Vuuren et al. outlined four pathways (RCP2.6, RCP4.5, RCP6, RCP8.5) as a basis for short-term and long-term experiments which have been adopted by the IPCC [31, 32].

[i]Used as an energy source in the wood products and food sub-sectors of industry [24]

Each of these pathways is based on the peak radiative forcing[i] level that will occur between now and 2100 (e.g. RPC2.6 = 2.6W/m^2 of peak radiative forcing). The higher the greenhouse gas emissions the higher the radiative forcing [33]. Alarmingly, the RCP8.5 scenario (in which current levels of emissions continue until 2100) predicts a global average temperature rise of between 3 and 6.5 degrees by 2100 [34]. Only the RCP2.6 and the RCP4.5 scenarios are predicted to have a chance of avoiding the 1.5 degree limit, and these pathways require a radiative forcing stabilization which requires net zero or lower emissions [35]. This may prove difficult to achieve given that even if all emissions ceased today, committed warming[ii] could result in global temperatures continuing to rise from the current 0.9 °C [36] to above the 1.5 °C limit (the estimate is a 13% chance) [37].

As approximately 75% of emissions in Ireland are energy related (Electricity, Heat & Transport) [38] - with the remainder coming from agriculture - it is in these sectors that change is needed most. The bulk of Ireland's energy demand is currently met with fossil fuels (coal, peat, oil, gas etc.) [24] which are poor in terms of both human health (GHG emissions and pollution) and energy security[iii] [40]. Fossil fuel contribution to air pollution can be linked directly to premature deaths[iv]. Coal, oil, gasoline, peat and diesel are all sources of fine particulate matter pollution [42, 43], which in 2012 was responsible for 403,000 premature deaths in the the European Union's 28 member states [44]. The bulk of these fossil fuels are imported, which means that Ireland is dependent on continued supply from foreign countries (such as Russia) and so is vulnerable to price rises and global security issues. Native renewables (such as wind), gas and peat resources reduce this dependency. However, as both peat and gas are finite resources, renewables are widely seen as the long term solution [13, 45, 46].

This poses the following research question:
How might Ireland's energy system transition from fossil fuels to renewables?

This transition must be discussed in the context of both the current energy system and the problems associated with using renewables as a replacement. These issues will be examined in detail in the following sections.

[i]Radiative forcing is the imbalance resulting from more heat being radiated into the earth than reflected back [33].

[ii]Committed warming is a global temperature rise even after net zero emissions are achieved

[iii]According to the International Energy Agency (IEA) Energy Security is the uninterrupted physical availability of energy sources at an affordable price' [39]

[iv]Death that occurs before the average age of death in a certain population [41]

1.2 Why an energy system model is useful

The current Irish energy system functions similarly to the diagram illustrated in Figure 1.2 below with transport, heat and electricity all mostly functioning as separate stand-alone systems.

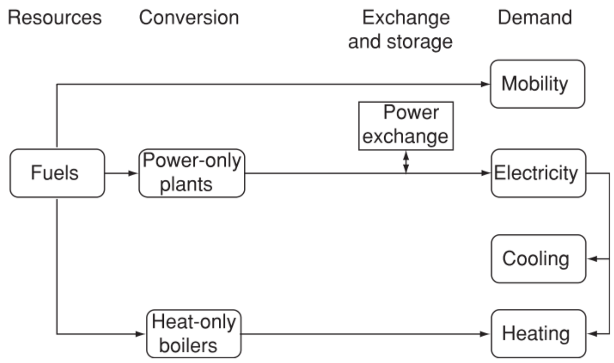

Figure 1.2: Interaction between sectors and technologies in a conventional fossil fuel based energy system [13]

For an energy system to function supply and demand must always match. For both heat and transport matching supply and demand is a straightforward process as demand can be met by easily-stored fossil fuels. If demand rises more fossil fuels can be stockpiled to ensure this rising demand can be met. Meeting electricity demand, on the other hand, is a more complex process as it cannot be stored easily. This means that supply and demand must be continuously matched. In Ireland this balance is maintained via two mechanisms: an Integrated Single Electricity Market (ISEM) (launched in Ireland in October 2018 [47]) and Transmission System Operators (TSOs)[i]. The ISEM consists of two markets: a capacity market and a balancing market. The capacity market ensures that there is enough generation capacity available to meet demand by enabling generators to sell their electricity to suppliers (who sell it on further to end-users) [48][ii] up to a half-hour before the capacity is needed. To ensure that supply and demand match at the time of generation the TSOs pick generators (or demand-side units[iii]) from the balancing market which then sets the price for suppliers.

Electrification of both heat and transport (through heat pumps and electric vehicles) enables the use of renewable sources of energy in these traditionally fossil-fuel dependent sectors. As this electrification develops further the Irish energy system will likely develop in a manner similar to Figure 1.3 [13].

[i] Eirgrid is the TSO in the Republic of Ireland and SONI is the TSO in the North of Ireland

[ii] On the capacity market the suppliers set limits on what they are willing to pay and, where this crosses what generators are willing to accept, this sets the market price [48].

[iii] Demand-side units are demand sites with a reduction capacity of at least 4MW [49]

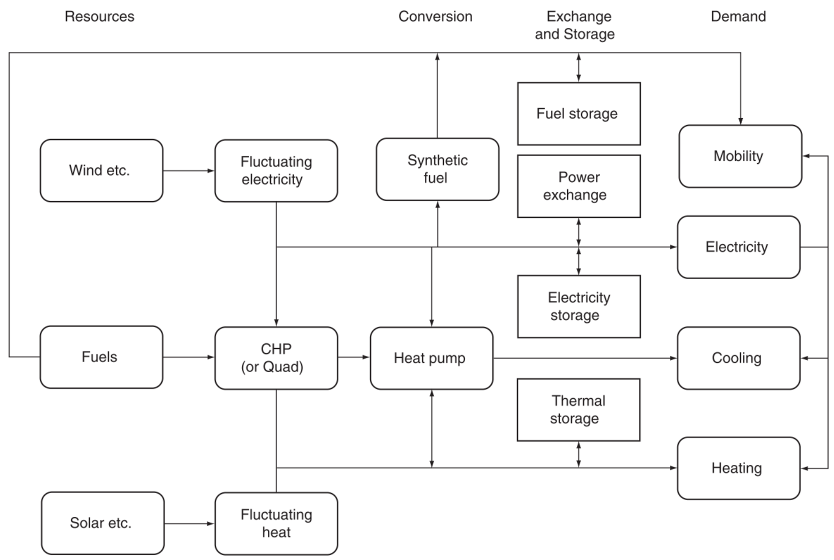

Figure 1.3: Interaction between sectors and technologies in a future smart energy system [13]

As this inter-connectivity between heat, electricity and transport grows the consequences of system failure due to an excess or deficit of electricity will become more serious. This is where a system model is a useful tool. EnergyPLAN, the modelling software tool in use in this thesis, allows for the modelling of hourly supply and demand. By modelling the hourly wind supply distribution and electricity demand for a previous year, it is possible to map this distribution to any wind capacity and quantify the maximum electricity excess and deficit for that capacity. This information can be used to inform the power plant capacity or electricity storage needed to backup this wind in order to guarantee that the installed capacity will meet future demand. In other words, the impact or knock-on effect of a change in one technology can be quantified so that the system changes needed to accommodate it can be found.

Potential system changes and issues associated with these changes will be discussed in the next section.

2 Literature Review

The transition away from a fossil-fuel based energy system requires more than just a simple swap out of generation sources, it requires major technological changes. As this literature review progresses a list of possible changes and requirements will be built and displayed at the end of this chapter.

2.1 How to transition

In order to consider all possible system changes in heat, electricity and transport the 'Danish Society of Engineers' organised 40 seminars with over 1600 participants (in 2006) in which a model of the future energy system of Denmark was discussed and designed [46]. Lund, Mathieson and their team then tested each proposal against the current (at the time) overall system - using what now is known as 'EnergyPLAN' modelling software - to determine how well each proposal fitted into the overall system, both technically and economically [46][ii,iii]. They used this data to recommend a single energy system for 2030 and multiple systems for 2050. They did not, however, recommend a transition pathway towards achieving these systems.

In Connolly and Mathiesen's 2014 paper they also used 'EnergyPLAN' to model the current system (in this case Ireland) and suggest an alternative system, however, they went one step further. They divided the transition towards a 100% sustainable energy system into seven key stages, and assessed each of these stages individually in terms of technical and economic performance [13]. Each new stage was assessed with respect to a system containing all of the additional infrastructure required to complete the previous stages. They recognised that any energy system change must make sense with respect to the system at hand. Their results indicate that Ireland can transition to a 100% sustainable energy system by 2050, and moreover, that this transition will not increase the price of energy in the short- or long-term [13]. However, they acknowledge that these suggestions were made amid much uncertainty. The validity of both their cost and technical estimates hinge upon the following assumptions:

1. Ireland can supply 100% of its electricity with a wind energy and syngas system even if electricity demand increases by over 400%
2. Syngas is a viable and cost-effective solution for renewable intermittency.
3. District heating is the best heating solution for cities and towns, and heat pumps for rural areas.

The focus of the papers by Lund et al. and Connolly et al. is predominantly on the technical challenges

[ii] If the proposal created an imbalance, Lund et al recommended a suitable investment in system flexibility. The more flexible an energy system is the better it can respond to changes. For example: one method of meeting wind intermittency is to have a gas power plant backup generator which can be quickly turned on to correct his imbalance [13]

[iii] Lund et al point out that the feasibility of a system change depends on the system; insulation of houses may not be suitable if solar thermal is applied to the same house [46].

and costs of potential energy systems [13, 46]. In other words, their main goal is to find out if a 100% sustainable energy system is possible, and if so, if it makes sense from a cost perspective. In their 2013 paper Deane et al. go into more depth on the implications of a change to a lower carbon energy system on the economy as a whole [19] in considering the resulting import dependency, the carbon tax needed, the impact of this tax on each sector[i] and on the competitiveness of Irish exports[ii] for both of their proposed energy roadmaps (CO2-80[iii], CO2-95[iv]) [19]. It is especially important to examine the underlying assumptions of the roadmaps in this paper as these roadmaps inform the Irish Government's current known strategy outlined in the 2015 white paper: 'Ireland's Transition to a Low Carbon Future 2015-2030' [50]. Both roadmaps assume the following for 2050:

1. Continued usage of natural gas (and to a lesser extent coal) is necessary to balance the intermittency of renewable sources.
2. Oil will continue to be used in the transport sector - particularly in aviation.
3. Biomass will be the most dominant source of renewable energy.
4. Bioliquids and biogas will be equally as important a source of renewable energy as wind.
5. Solar PV will provide an insignificant contribution (<2.1%)

Table 2.1: Deane et al's Roadmap Primary Energy Supply in 2050 [19]

Type	2017 [51]	CO2-80	CO2-95
Fossil Fuels	**90.4%**	**50.6%**	**26.1%**
Coal & Peat	12.2%	2.9%	2.5%
Oil (incl. Int Aviation)	48.9%	20.9%	15.7%
[Oil (excl. Int Aviation)]	[40%]	[10.7%]	[6.2%]
Natural Gas	29.3%	26.7%	7.9%
Renewables (incl. waste)	**10%**	**48.3%**	**72.8%**
Hydro	0.4%	0.7%	0.6%
Wind	4.4%	10.5%	12.5%
Biomass	2.6%	18.4%	40.4%
Bioliquids	1.1%	10.5%	9.7%
Biogas	0.1%	8%	7.4%
Other (incl. waste)	1.5%	0.2%	2.1%
Electricity Imports	**-0.4%**	**1.1%**	**1.1%**

Deane et al's roadmap is far from the only roadmap created for Ireland. Table 2.2 on the following page summarises key system aspects of other previously proposed roadmaps for Ireland.
In the following sections the technologies needed to meet these assumptions will be analysed first from an individual point of view and finally from a synergistic point of view in a smart energy system.

[i] Some sectors will be more affected by rising fuel prices than others [19]

[ii] If Ireland has a higher carbon tax than other EU countries or non-EU countries this may damage exports [19]

[iii] Emissions are reduced by 80% between 2010 and 2050

[iv] Emissions are reduced by 95% between 2010 and 2050

Table 2.2: Primary energy supply breakdowns of various pathways

Authors	Description	Primary Energy Breakdown			Wind/year	Total/year	Large-scale Storage?[I]
		Fossil Fuels [II]	Wind	Ren-Fuel [III]			
SEAI [12]	2018 System	90.2%	4.4%	4.4%B	7.44 TWh	168.32 TWh	No
Deane et al. [19] [IV]	80% reduction by 2050	50.6%	10.5%	36.9%B	18.25 TWh	173.83 TWh	No
Deane et al. [19] [IV]	95% CO_2 reduction by 2050	26.1%	12.5%	57.5%B	23.36 TWh	186.90 TWh	No
ESB [52][V]	80% CO_2 reduction by 2050 [VI]	31%	60%	5 %B	-	-	No
Connolly et al. [13]	100% sustainable energy by 2050	0%	$\approx$ 66.66%	$\approx$ 33.33%S	120 TWh	180 TWh	Yes

[I] Is energy storage used to solve the renewable intermittency problem

[II] All fossil fuel generation uses Carbon Capture & Storage (CCS) except the 2018 system

[III] 'Ren-fuel' = Renewable Fuel, includes biogas and syngas (using CCS where possible), 'B' = biofuel and 'S' = synfuel

[IV] Pathway for the 2015 Irish White Paper [50]

[V] ESB's roadmap recommendations were made in the context of a study and review of 25 previous roadmaps including Deane et al's study

[VI] Electricity generation only

2.1.1 Intermittency

With normalised[i] wind accounting for 25.2% of gross electricity consumption in 2017 it was the second-largest source of electricity generation after natural gas [12]. It massively outproduced the second-best renewable hydro which contributed to a mere 2.4% [12]. However, as wind is a highly intermittent source of energy this growth is not without its problems. The extent of this intermittency is evident from Figure 2.1.

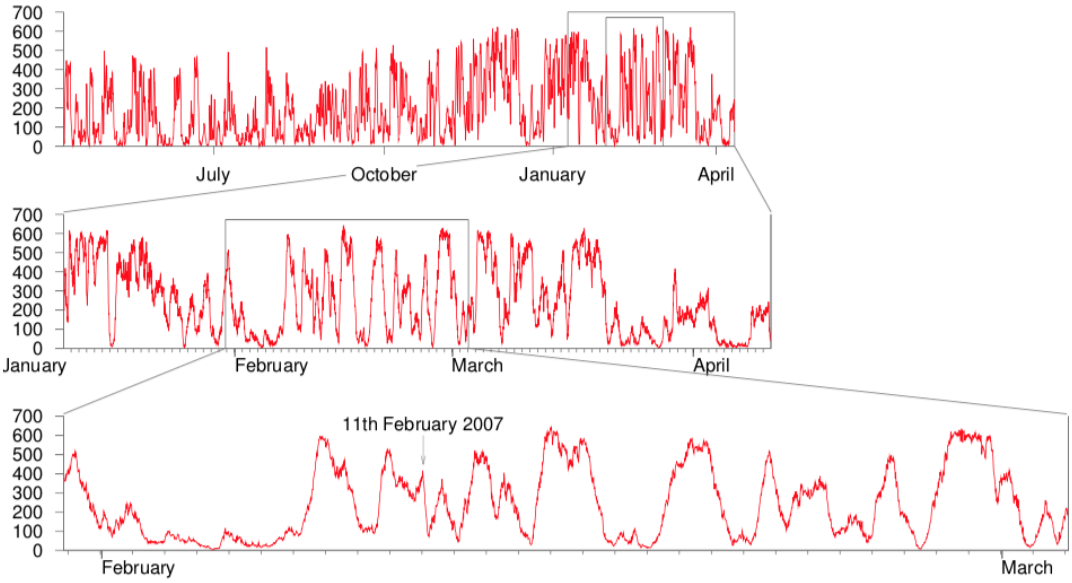

Figure 2.1: Total output, in MW, of all wind farms (745MW of capacity, dispersed in about 60 wind farms) of the Republic of Ireland 2006-2007 (data provided every 15 minutes by Eirgrid) [14]

This figure illustrates the fact that wind varies massively on a seasonal, daily and hourly basis:

- There was higher wind production in winter.
- There was almost no wind produced during the first several in February.
- Within a single day wind can go from almost 0 to maximum production.

Rapid Fluctuations

As supply must always match demand rapid fluctuations in wind energy supply can result in grid instability. Short-term fluctuations (up or down) can be met by either curtailment or by more flexible resources on the ISEM balancing market: Demand-side units, electricity storage (a Pumped Hydro facility at Turlough Hill), interconnection (to the UK) and open cycle gas turbines (OCGT)[ii]. If this fluctuation barrier is overcome, there is still the issue of frequency response.

[i]Normalised wind means that the capacity factor has been accounted for. A capacity factor is the ratio of actual electrical energy output over the maximum possible electric output over a given period of time. For a wind turbine rated at 2MW with a capacity factor of 0.3 has a normalised output of 0.6MW.

[ii]A minimum of 325MW (out of 708MW) of OCGT capacity is kept in replacement reserve [53]

Grid stability

Wind is a a non-synchronous source of electricity generation operating in a synchronous electricity system[i]. Traditional, large synchronous generators can react to a sudden loss in total generation connected to the grid and restore grid stability in a mostly automatic process [15]. They first react with an initial inertial response and decelerate due to the increased electrical load on the grid [15]. Automatically controlled generators then respond directly to changes in grid frequency [15]. Finally, the frequency is restored to nominal (AGC) by adjusting power levels in response to requests from the systems operator [15]. An illustration of this process is given in Figure 2.2 below.

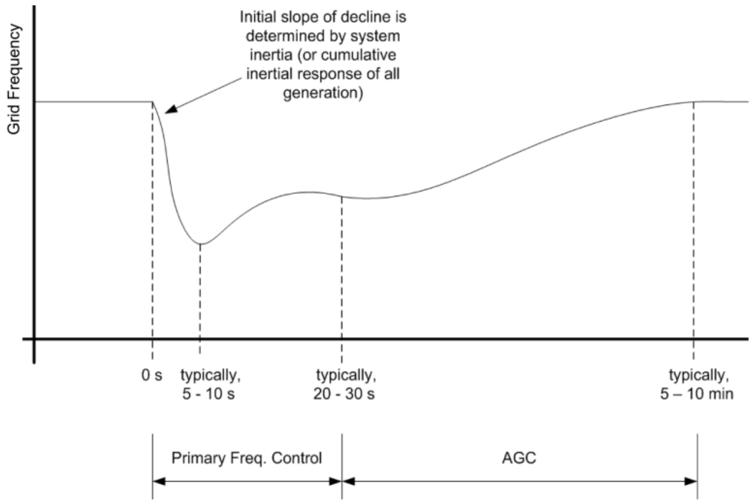

Figure 2.2: Inertial, primary frequency controls and AGC (secondary) response [15]

Most modern turbine generators output voltage synchronous with the utility grid by using power electronics which decouples them from the utility grid [15]. As result of this decoupling the inertia of the turbine generator and rotor do not automatically participate in the grid inertial response in the same way as traditional synchronous generators, and so they cannot provide the same service of grid stability [15]. By implementing active power control (APC) it is possible to control the real power output of a wind turbine or collection of wind turbine in order to assist in balancing supply and demand [15], however, there is no evidence that APC has been implemented by any Irish wind farms so it is likely that this potential capability has yet to be exploited.

Multiple-hour, multiple-day and seasonal fluctuations

Keeping supply balancing with demand in a wind-reliant electricity system through multiple days of low wind is perhaps the biggest challenge facing wind and other intermittent renewables. Interconnection to other countries and large-scale storage are both good solutions [14]. However, interconnection is an issue if neighbouring countries are reliant upon the same renewable sources of energy and storage needs to be on a massive country-wide scale to have a significant impact [14]. An energy system model can be used to compare these options technically and economically. Connolly et al. propose

[i] A synchronous system is a power grid where electricity is generated at a single synchronised AC frequency [53]

syncing power-to-gas storage with Open Cycle Gas Turbines (OCGT) to power the grid during these lull periods [13]. The viability of this energy storage technique will be discussed in the following section

Significance of wind intermittency

Although Eirgrid does require wind farms to implement active power control and frequency response, the grid penetration of intermittent sources of energy (or system non-synchronous penetration) is still limited to a maximum of 65% [53, 54]. Consequently, Deane et al's study (which informs the 2015 Irish White paper [50]) assumes a maximum instantaneous penetration of 70% which is moderately less than in Eirgrid & SEMO's 2017 DS3 programme aim of 75% [55].

If improvements in APC and frequency response barriers are overcome there is still the issue of long lull periods as demonstrated in Figure 2.1 which means that either large-scale back-up storage or dispatchable generators are needed to balance the grid.

Solar Photovoltaics (PV)

Solar PV panels allow for the generation of electricity from direct sunlight. Although solar PV is intermittent, like wind, it does provide a more predictable energy output than wind. However, as Ireland receives low solar irradiation compared to southern European countries [56] and is prone to cloudy conditions installed solar PV in Ireland typically has a lower capacity factor than wind, and so has not been viewed as a major component of a future Irish energy system [3]. Consequently policy supporting solar PV uptake has not been strong with no feed in tariff[i] or net metering[ii] currently in place [57].

Solar PV has fallen from $2 million per MW in 2013 (when Deane et al's paper[iii] was released) to $1.2 million per MW in 2018 - a decrease of 40% [19, 58]. As the cost of solar PV has fallen so significantly in recent years, perhaps a change in policy should be considerered. In a departure from previous studies, La Monaca et al. [59] found that as of 2017 solar PV in households is financially viable under several scenarios. However, without a further policy incentive their calculated payback period is likely to still be too long for all but high energy demand households [59]. Similarly, grid-connected solar PV arrays are also in need of policy support to improve their payback times and incentivise investment [60]. In Murphy et al's 2017 feasibility assessment of solar PV in Dublin they strongly recommend solar PV to be included in the Government's REFIT[iv] scheme so that similar economic payback times can be achieved as those in other European countries [60].

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[i] A feed in tariff means that when a households generates more electricity than they use they can sell this electricity back to the grid.

[ii] PV customers are paid the retail rate for the total amount of electricity they generate

[iii] Recall that Deane et al's paper informs the Government's current whitepaper

[iv] Renewable Energy Feed-In Tariff

2.1.2 Power-to-Gas (P2G): Syngas & Syn-methanol/DME

The Irish Academy of Engineering believes that natural gas is essential to the future of Irish energy security as there is an indigenous supply (the Corrib gas field), it has the lowest emissions of any fuel, and it is an effective complement to renewables as a dispatchable back-up [61]. Recent plans by ESB to construct 450 MW of gas-fired power by 2023 [7] posit that ESB is of the same viewpoint. Power-to-Gas (P2G) offers a potential net-zero emissions alternative.

The P2G storage method can be used to synthesise a grid-compatible gas using electrical power and a carbon source as inputs [16]. If renewable power (such as wind) and a renewable source of carbon (such as biomass[i]) are used as inputs in this process then P2G is a renewable process. This synthetic gas (or syngas) can be stored, transported and burnt using existing infrastructure, and so can function as a backup generator if intermittent renewable supply cannot meet demand. The P2G process has an advantage over other renewable energy storage options (such as pumped hydro, hydrogen and battery) in that it can be stored, transported and burnt using existing infrastructure but it does face a number of challenges:

The Irish Context

P2G is often reliant on a renewable technology such as wind or PV as its power source in order to reduce its own carbon footprint. It is typically pitched as a good option for the storage of excess renewable electricity. However, as the current Irish rewewable penetration is only around 27%, it is probably rare for renewable electricity generation to exceed demand. Therefore the incentive to build a P2G plant beside a wind farm is reduced as there is not a significant amount of electricity being wasted. Furthermore, with demand set to rise rapidly in the coming years owing to the construction of several data centres overcapacity of renewables is unlikely to be a problem in the short-term [62]. However, in the long-term when intermittent renewables have become a dominant energy source, energy storage options such as P2G may be a necessity in guaranteeing a secure supply of electricity (and heat[ii]).

- Compete with fossil fuel imports
  - If P2G is to be built to complement renewable electricity instead of natural gas or instead of LPG in heavy vehicles then syngas generated by P2G must compete with natural gas imports. Therefore, a P2G generation facility needs to be built with a Levelised Cost of Electricity or Energy (LCOE)[iii] similar to or less than current gas fuel costs for it to be used in either a gas power plant or in gas-powered vehicles.

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[i] Biomass such as wood is commonly described as 'carbon-neutral' as it takes in carbon during its lifetime and emits this stored carbon when burnt. Fossil fuels are not 'carbon-neutral' as they are counted as net contributors of carbon to the atmosphere when burnt.

[ii] Waste heat is released during methanation [63]

[iii] LCOE is useful in comparing renewable electricity generation with non-renewable as we cannot compare like-with-like in this scenario. Non-renewable electricity costs are typically dominated by fuel costs and renewable by infrastructural. LCOE measures the lifetime costs of energy production and so accounts for both fuel and infrastructure [64]

- Renewable Intermittency
  - If P2G is to be used as an energy storage method to be implemented during periods of renewable intermittency only it needs to be more cost effective than other forms of dealing with intermittency.
- 'Peaker'
  - Currently, the energy system can turn on gas turbines when required to meet periods of high energy demand. A system without this flexibility requires 'peakers' that can be quickly turned on to meet added demand. If P2G is to be built for use as a 'peaker' to be used by Ireland's energy operator it needs to be cost competitive with other renewable 'peaker' options.
- Wind Curtailment
  - If it is to be used to store energy lost during 'wind curtailment' - when the output of a wind farm is curtailed for reasons of grid stability [65] - it needs to be profitable enough to pay back its infrastructural costs in a short enough time frame to satisfy investors.

P2G vs Natural Gas in Generation

Götz et al's 2016 paper[i] indicates that syngas from P2G processes ($\approx$ 16.5 - 90 ct/kWh) is not competitive with either natural gas ($\approx$ 2 - 3 ct/kWh) or even biomethane ($\approx$ 7 ct/kWh) in terms of generation costs, not including added infrastructural costs [16].

P2G vs Biomass in Generation

Biomass is typically gasified into syngas as it makes it a more versatile and efficient fuel; it can be used for transport or as a direct replacement for gas heating, and it tends to burn more efficiently than biomass as it burns at higher temperatures [66]. In other words, it is a more useful form of biomass.

P2G vs Other Renewable Energy Sources in Electricity

In the long term electric vehicle battery storage makes sense as a demand response measure for grid stability as electric vehicles (EV) will likely become widespread in the coming years. However, as EVs will not be always ready-to-use it is rather battery storage that must be considered instead as a means of meeting lull periods or dispatchable grid generation. Some of the other major storage methods include: hydrogen storage, compressed air storage and pumped hydroelectric storage. P2G has a major advantage in that it is compatible with existing natural gas infrastructure.

The biggest barrier facing all of these methods of storage is the low price of fossil fuels. So long as fossil fuels are the more economic method of meeting electricity demand these technologies will likely not be developed.

[i] Costs are calculated in euros.

P2G vs Other Renewable Energy Sources in Transport

Figure 2.3 below displays the relative energy efficiencies of different renewable fuel sources for transport [10]. Synthetic natural gas (SNG) from P2G is not viable compared to direct electrification in terms of the resources consumed [10]. However, this direct electrification is not suited in scenarios where high energy-dense fuels are needed such as freight and aircraft [10]. Hydrogen fuel appears to be the most efficient high-density energy carrier. However, were infrastructural and vehicle costs added to the production costs, as shown in Figure 2.3, Methanol/DME (a similar process to syngas but with an added chemical synthesis step [13]) would likely be the more efficient high-density energy carrier [10]. Although the cost of P2G when compared to natural gas is currently a barrier to adoption, some form of power to fuel process using electrolysis (hydrogen, P2G or Power-to-DME) will be necessary in the future to meet the energy needs of freight and aircraft and so future investment in this technology is needed.

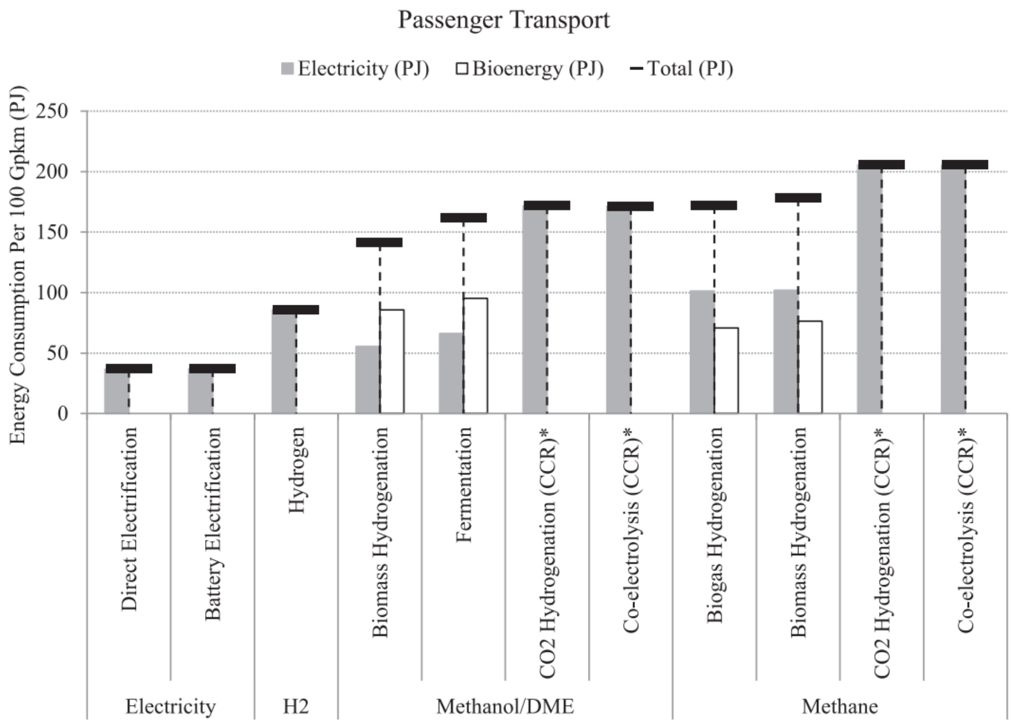

Figure 2.3: Comparison of Renewable Energy Sources for Transport, where CO_2 Hydrogenation and Co-electrolysis = different P2G processes and Gkpm = passenger transport demand in PJ (pkm) [10]

Peaker

Using P2G as a 'peaker' is likely not cheapest option in the short-term as implementation of demand-side energy management involves less infrastructural costs. When implemented, the TSO can pay demand-side units[i] to reduce their electricity usage during periods of peak demand.

[i]Demand-side units are big users of electricity who can be called upon by the TSO to reduce their electricity usage.

P2G for Wind Curtailment

As wind energy is a non-synchronous[i] energy source operating in a synchronous system, it is sometimes necessary to curtail it in order to limit non-synchronous system penetration [65]. If this penetration is too high it can result in grid instability [65]. Energy storage methods or grid interconnection provide a means to dump this curtailed energy. This resource is not insignificant with Garrigle et al. estimating that wind curtailment in Ireland could be between 7 and 14 % in 2020 [65].

Qadrdan et al. found that implementation of hydrogen storage (i.e. the H_2 component of P2G only) significantly reduces wind power curtailment and operating costs of the integrated system, with a payback period of 10-14 years from these savings [67]. The bonus of using some energy storage method for wind curtailment is that the energy would otherwise be wasted. Although Qadrdan et al's paper refers to hydrogen production and storage only, this small scale investor-driven approach could also work well for P2G development, with P2G having the added benefit of gas-grid compatibility.

P2G Infrastructure and Fuel

The cost breakdown in Figure 2.4 shows that the highest investment costs for a P2G plant are for the electrolysis process and hydrogen storage [16], therefore the most improvement is needed in these areas in order to lower the processes LCOE.

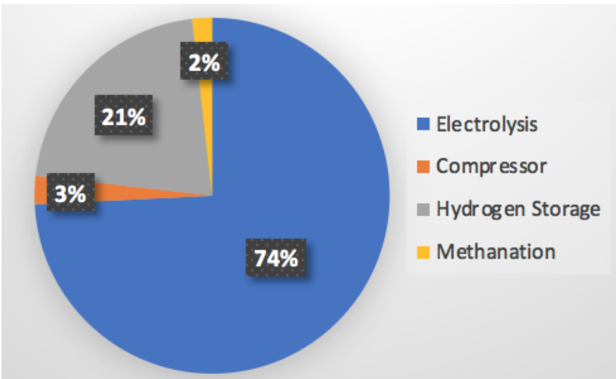

Figure 2.4: Investment for different parts of a 38.8 million euro Power-to-Gas plant (36 MW electrolysis, pressure in H_2 storage: 30-200 bar, methanation pressure: 20 bar) [16]

Unlike many other renewable energy technologies P2G requires a continuous fuel input in the form of a carbon source[ii]. Fossil fuel sources are extracted from a single source (i.e. an oil rig, a coal mine etc.) whereas P2G fuel output must be both extracted (i.e. farmed biomass) and generated. This added step will likely continue to keep P2G fuels higher than fossil fuels without the introduction of a significant carbon tax on fossil fuels.

[i] A synchronous system is a power grid where electricity is generated at a single synchronised AC frequency [?].

[ii] Were Direct Air Capture (DAC) to be used as process' carbon source it would not require this fuel input, so P2G would operate in a similar manner to wind turbines as it would only require an initial infrastructural cost. However, as previously stated this process has yet to be proven.

Summary of challenges

- There is currently a low demand for P2G due to a relatively low renewable grid and a consequently a low demand for storage of excess electricity.
- The electrolysis process and hydrogen storage are components of P2G are very costly.
- P2G is more expensive than hydrogen production and storage only.
- P2G requires a fuel input in the form of a carbon source. For P2G to be reneable this carbon source must be biofuel which is a limited resource. Biofuel production for P2G must compete with both food and other biofuel demands for space.
- P2G is reliant upon a cheap source of carbon and electricity to be cost competitive.

The adoption of large scale P2G by Public Transmission System Operators, such as Eirgrid, will not take place until it is a proven technology. Although methanation and hydrolysis processes such as fixed-bed and AEL are well-developed technologies, the combination of these processes is not. For this development to occur one or more of P2G's associated cost challenges must be overcome. Deployment of this technology in one of these sectors could lead to cost reductions ensuing from economies of scale[i] which in turn will push costs down further. For P2G to become viable as a replacement for fossil fuels in power generation a strong carbon tax or other policy incentive is needed as the capital and fuel costs required for P2G are far too high to incentise investment for this application.

The most promising application of P2G appears to be in wind curtailment as this energy would otherwise be wasted, and so it simply must be profitable enough to earn back its initial infrastructural costs in a short enough time to satisfy investors. The necessity of energy-dense fuels for freight and aircraft is another incentive to invest and develop electrolysis at a minimum to ensure that in the future the needs of these sectors can be met in a zero-carbon manner.

2.1.3 Nuclear

In 1999 the construction of nuclear power plants in Ireland was prohibited, and this ruling has continued to the present day [68]. This decision was likely made in response to a public view of nuclear power and nuclear waste as too dangerous. According to MIT's interdisciplinary study 'The Future of Nuclear Energy in a Carbon-Constrained world' advanced reactors (such as advanced Light Water Reactors) include engineered safety systems that require no emergency AC power and minimal external interventions thereby reducing the probability that severe accidents occur and drastically reducing the consequences in the event that they do [69]. There also exist robust technical solutions for waste management such as permanent disposal in geological repositories [69]. Another argument against nuclear power is that it is not sustainable as it is powered by finite uranium ore - this may not remain the case. It is estimated that there are around 4.5 billion tonnes of uranium in seawater, which is sufficient to power the world energy fleet for 13,000 years [70]. 2015 estimates put the cost

[i]Increased production often leads to decreased costs. This is commonly referred to as 'economies of scale'

of recovery from seawater at $400-1000 per kg versus the 2015 market price of $100 [70]. According to the World Nuclear Association uranium fuel acquisition costs are only around 14% of total costs [71] and so the effect of this price discrepancy on overall costs is relatively minor.

The main barrier facing nuclear globally is not safety but the high capital cost of installing new nuclear capacity [69]. With no carbon constraint fossil fuels are a lower cost alternative to nuclear (particularly since the discovery of shale oil/gas pushed prices down) and under a modest carbon constraint renewable generation offers a lower cost alternative [69]. However, this same study also found that at levels of 'deep decarbonisation' (such as zero net emissions for 2050) including nuclear in the mix of capacity options helps to minimise or constrain rising system costs, which makes achieving these goals more realistic [69].

2.1.4 District heating

Denmark has made much progress in renewable heat by utilising district heating fueled by Combined Heat and Power (CHP) (using municipal waste biomass) and industrial waste heat [72]. Perhaps Ireland should follow suit? In considering whether or not to implement district heating powered by combined heat and power (CHP) power plants as in Denmark the following question must be answered:

Is it the most energy efficient means of generating heat?

Business as Usual (BaU)

Currently in Ireland around 70% of gross electricity consumption electricity[i] is produced by fossil fuels [12] and around 70% of homes use gas, oil or solid fuel boilers for heating [18]). Therefore figure 2.5 below, from David McKay's book 'Sustainable Energy: Without the Hot Air', which illustrates the combined efficiency of using a boiler for heat and a thermal power plant for electricity is roughly representative of business as usual in Ireland [14]. The line between the boiler heat efficiency on the y-axis and the power plant electrical efficiency (using coal or gas) on the x-axis represents the combined efficiency of this system. The 'new standard solution' is more reflective of the current Irish setup than the 'old standard solution' as the majority of power plants in Ireland are gas and boiler efficiencies are clser to 90% since part L regulations began enforcing a minimal seasonal efficiency of 86% in 2007 and 90% in 2011 for oil and gas boilers in dwellings [73, 74].

[i] Gross electricity consumption includes own use electricity in generation plants

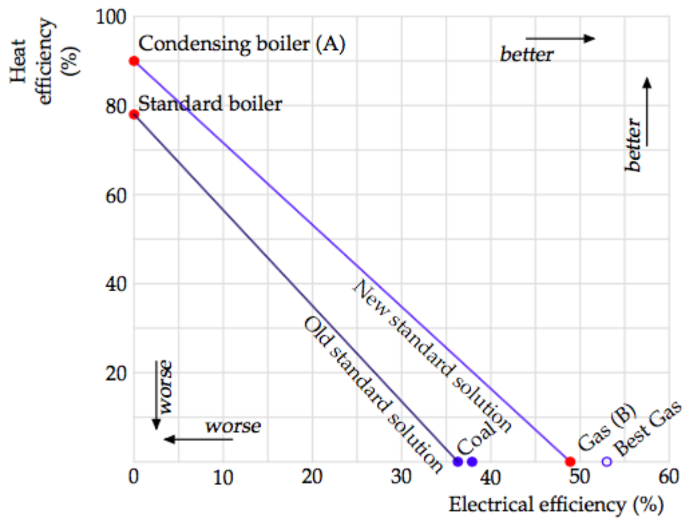

Figure 2.5: Combined efficiency of BaU electric and heating systems [14]

District heating and CHP

McKay's next diagram in figure 2.6 below uses filled dots to represent actual average performances of CHP plants and hollow dots to represent the performances of ideal CHP systems [14]. Only the two orange filled 'ct' dots (representing Freeman Hospital and Elizabeth House) are of a higher efficiency than the BaU condensing boiler and gas turbine system [14].

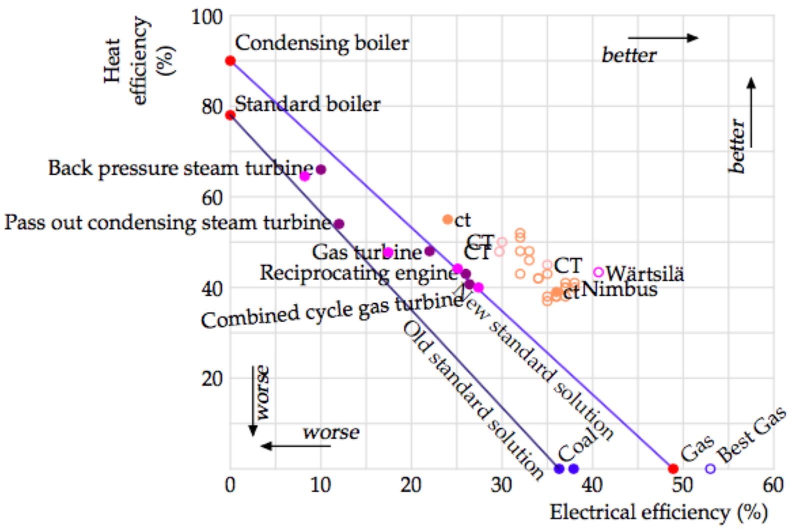

Figure 2.6: Efficiency of district heating systems [14]

On the surface CHP power plants seems like an obvious choice to provide both heating and electricity as they use waste heat for a purpose rather than discarding it in a cooling tower. However, this heat doesn't come for free. The ideal CHP cycle, shown on the left hand side of Figure 2.7 below, that uses 100% of its waste heat is not useful in practice as this cycle cannot adjust to variations in power and process heat loads [17].

Therefore in reality CHP cycles more closely resemble the more complex cycle on the right hand side of Figure 2.7. To improve thermal efficiency in this cycle electrical efficiency must decrease. This is the reason why the efficiency of the CHP plants is not significantly better than BaU in figure 2.6.

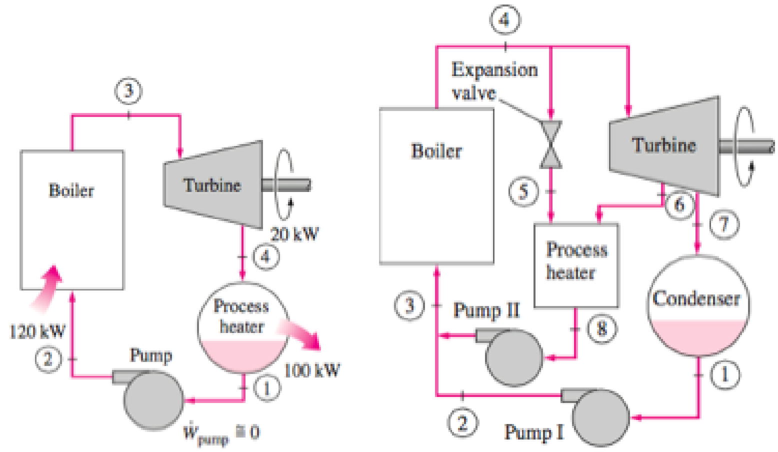

Figure 2.7: The ideal (left) and actual (right) combined heat and power cycle [17]

A Heat pump and gas system

Unlike boilers heat pumps do not create heat, instead they operate like a reverse fridge to move heat from one location to another. As a result a heat pump can operate at efficiencies of over 100%. In other words one unit of electricity input can generate more than one unit of heat output so heat is not worth as much as electricity. In McKay's diagram in Figure 2.8 below a heat pump with a Coefficient of Performance (COP) of 4 (i.e. 400% efficient heat output) used in conjunction with a gas turbine has an efficiency of over 50% which outperforms all of the CHP solutions. Therefore using a heat pump for heat and a gas power plant for electricity is significantly more energy efficient than using district heating, and this is before heat loss through pipes during transmission is accounted for. Moreover, as technology improves heat pump heat efficiency does not face the same 100% upper limit as CHP plants.

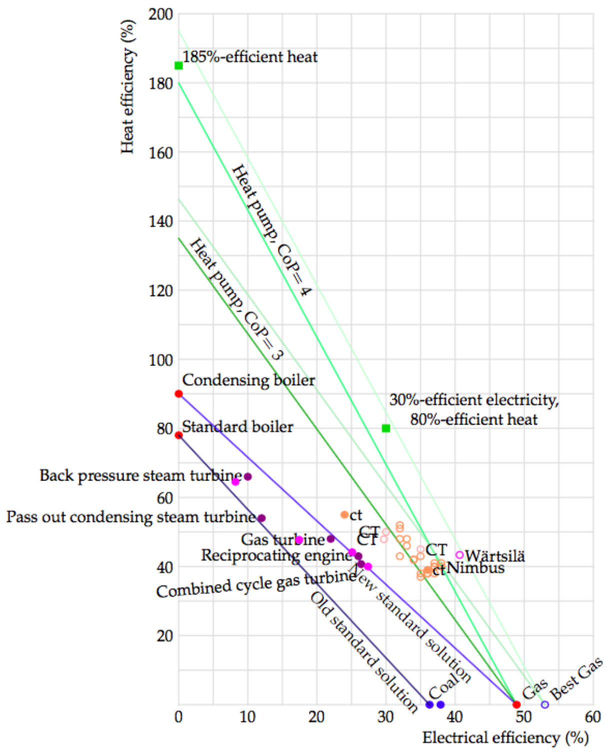

Figure 2.8: Efficiency of heat pump and gas systems [14]

On top of energy efficiency heat pumps are also future-proofed as they can be used with any source of electricity such as solar or wind.

Conclusions

- Heat pumps combined with a high efficiency power plant are a more energy efficient than district heating powered by combined heat and power plants as a means of producing heat.
- District heating is feasible as a means to distribute waste heat (as in a data centre or incinerator).

2.2 Smart Energy Systems

So far in this literature review wind, solar, P2G, nuclear, district heating and heat pumps have all been considered in isolation. In isolation, none of these solutions can solve the two major problems involved with high penetrations of intermittent renewables:

- Excess electricity production must be used, stored or exported. Compressed Air Energy Storage (CAES), pumped storage, battery or hydrogen/fuel cell storage are too expensive to be the sole replacement for conventional power generation [11].
- Supply must always meet demand so some form of dispatchable power is needed if intermittent renewables cannot meet demand.

In Henrik Lund's book 'Renewable Energy Systems A Smart Energy Systems Approach to the

Choice and Modeling of 100% Renewable Solutions' he posits that high penetrations of intermittent renewable energy systems such as wind will only become viable if synergies between the electricity, heat and transport are fully taken advantage of [11]. Lund believes that Renewable Energy Systems (RES) can't be regarded as the only measure when conducting analyses of large-scale integration - the long-term relevant system are those in which these measures are combined with energy conservation and system efficiency improvements [11]. He identified the following synergies as a means to improve the feasibility of intermittent renewables:

- District heating and CHP doesn't make sense in terms of energy efficiency when compared to heat pumps and CCGT, however, if CHP plants incorporate thermal storage and heat pumps they can be used to store excess electricity production in the form of heat [11]. Not only is thermal storage considerably cheaper than electricity storage but it also allows CHP plants to operate at full electrical efficiency if required to balance the grid as they do not need to produce process heat. Therefore a CHP and district heat solution improves the feasibility of high wind capacity. Nonetheless, district heating is only practical in built up areas such as cities, and so heat pumps are advisable elsewhere [11]. CCGT plants cannot benefit from this heat storage and so will incur damaging costs if electricity production is turned off for long periods.
- Certain modes of transport are not suited to electrification (aircraft and freight). Using power to gas to boost the conversion of biomass into gas from electrolysis was identified as the best solution to meet this need [10, 11]. This need for power to gas for transportation makes it possible to replace the potential long-term need for electricity storage with gas storage which is both more efficient and cheaper [11].
- Electric vehicles connected to the grid (V2G) can be used as a form of electricity storage for intermittent renewables to capture excess production [11].
- A smart energy system consists of a smart electricity, thermal and gas grid. These grids must be combined and coordinated so that synergies between them can be identified [11].

Lund also warns against overly relying on flexible consumer demand to increase system flexibility as it faces the same problem as electricity storage: "the nature of fluctuating RES calls for high energy amounts and long time spans that a realistics flexible consumer demand cannot really do the job [11]."

2.3 Literature Review Conclusions

In summary, the following conclusions can be drawn from the literature review:

1. **Technologies on an individual basis:**
   (a) Wind energy needs to be backed up by some dispatchable power source in the form of energy storage, grid interconnection or demand reduction to ensure grid stability is maintained. Alternatively or additionally wind turbines could incorporate active power control (APC) so that they can dynamically respond in the event of a grid power loss.
   (b) Solar PV still needs policy support to become cost effective.

(c) Nuclear power could be a reliable source of renewable power if uranium harvesting from seawater is commercialised.
(d) Syngas is not cost effective in the short-term as a replacement for natural gas in power generation, however, it may be cost effective as storage for wind curtailment.
(e) It is necessary to develop either hydrogen production or P2G to meet the fuel demands of the transport vehicles that cannot be electrified.
(f) District heating only makes sense when used to distribute waste heat (such as for data centres or incinerators). District heating provided by Combined Heat and Power plants is not as energy efficient as using heat pumps for heat.

2. **Technologies in a smart energy system:**
    (a) Integrating intermittent renewables (such as wind and solar) becomes more feasible once supported with parallel development of the heat (CHP, district heating and heat pumps) and transport (electric vehicles and power to gas for non-electric fuel).
    (b) Consumer demand flexibility and electricity storage are of limited feasibility in terms of costs and impact when compared to the use of conversion synergies between electricity, heat and transport and the development of energy efficiency measures.

An EnergyPLAN model was developed to test these insights from literature in practice. The development of a 2017 reference model will be discussed in the following section.

3 Development of Reference Model

EnergyPLAN was used to develop a reference model of the Republic of Ireland's 2017 energy system. This reference model will be used as the building block upon which to test potential system changes in later sections. To build a model EnergyPLAN requires numerous inputs. For the model to be accurate these inputs must be both representative of actual energy system inputs and in the correct form for use in EnergyPLAN. Where data was available it required manipulation, and where it was unavailable assumptions were made. In the following sections this process will be discussed input-by-input.

A more detailed discussion of the assumptions made in the following section can be found in the 'Summary of Assumptions' section

Note: An Excel spreadsheet was used to perform many of the relevant data manipulations and to track all of the model inputs.

3.1 Demand

This section discusses the data inputs for any component of the energy system (electricity, heat and transport) that demands/needs energy.

3.1.1 Electricity

1. **Total electricity demand (TWh/year):** This input was treated as total electricity production rather than electricity demand. EnergyPLAN has no explicit input for electricity losses, instead it requires that any losses be accounted for in the total electricity demand input. EnergyPLAN manipulates electricity production to meet this demand - it has no 'electricity loss' output. Therefore, if the actual electricity demand (with losses) is inputted to EnergyPLAN, the model will produce less electricity than actually required. Therefore it makes sense to treat this input as production because this enables easy comparison of actual production values and EnergyPLAN production values for each electricity production technology. This electricity production was found by summing the 'public thermal power plant', 'CHP - Electricity' and primary energy supply for wind and hydro in SEAI's energy balance [51]. Actual total electricity demand is equal to the total electricity production minus plant's own use and transmission and distribution losses.
2. **Hourly electricity demand distribution:** The 'Electricity demand' input and distribution are based on electricity demand data available online at Eirgrid's website [75]. 'EnergyPLAN' requires 8784 hour-by-hour data points to build a distribution. As the 'Eirgrid' data provides data for every 15 minutes (i.e 08:00, 08:15, 08:30, 08:45, 09:00) some excel data manipulation was required to convert it to hourly for use in an EnergyPLAN distribution (i.e. 08:00, 09:00)

(See Appendix 7.1).

The 'Electricity demand' found from the 'Eirgrid' data represents the total recorded demand for the year 2017, therefore it contains the electricity used for heat and heat pumps. However, as these specific demands are accounted for in the demand > heat tab in 'EnergyPLAN' and added to this total in EnergyPLAN they had to be subtracted from this total 'Electricity demand'. Initially, electricity for import/export was also removed from this total demand as it is accounted for in the 'Fixed import/export' input, however, this proved problematic. As 'EnergyPLAN' dynamically allocates imports or exports electricity - regardless of the fixed import/export input - to balance the grid, the monthly demand values varied from the actual demand values by around 2%. By including the fixed import/export value in the total demand this error was reduced to less than 1%.

3. **Fixed annual import/export (TWh/year):** Found from SEAI's 2017 energy balance [12].
4. **Electric heating:** Electric heating is accounted for in the demand > heat tab.
5. **Electric cooling:** As there was no data available on electric cooling demand in Ireland, it was assumed to be negligible.
6. **Flexible demand:** EnergyPLAN requires a fixed annual flexible demand and flexible capacity. This flexible capacity was found from the 2016 capacity data as the flexible capacity in the 2017 data was only added in the December 2017 capacity auction and so is not representative of the annual capacity [2, 76]. To find the annual flexible demand it was assumed that this flexible demand is only used during the four hours of maximum electricity demand from 16.00-21.00 as shown in Figure 3.1 below [2], and 100% of this capacity is in use during these hours. As this demand is only implemented during peak hours it falls under the 'daily flexible demand' category in EnergyPLAN only.

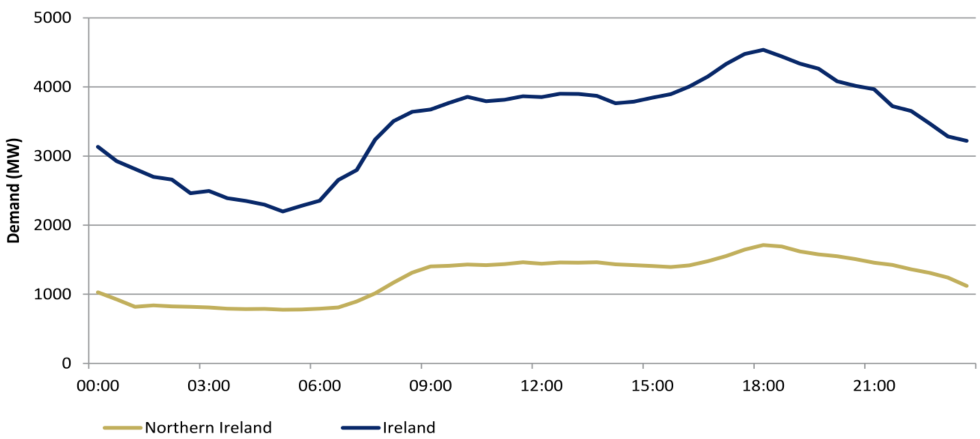

Figure 3.1: Typical winter day profile [2]

3.1.2 Heat

According the EnergyPLAN Finding and Inputting Data into EnergyPLAN (FIDE) guide all 'individual heating' inputs in EnergyPLAN are equal to the combined heating demand of the commercial and residential sectors [77]:

1. **Oil & natural gas annual fuel demands and thermal efficiencies:** The total annual

fuel consumption by the residential and commercial sectors was found in SEAI's 2017 energy balance excel spreadsheet [51]. This spreadsheet is a more detailed version of the energy balance presented at the end of SEAI's 'Energy in Ireland' report [12]. According to SEAI's 2018 report 'Energy in the Residential Sector' approximately 100% of fossil fuels used in the residential sector are used for heating purposes [18]. This data could not be found for the commercial sector and so the same trend was assumed to be true for this sector. To find the total 'individual heating' consumption; each fuel used for heating in the residential and commercial sectors was summed.

To find the thermal efficiencies for each boiler type it was neccessary to make some assumptions. The SEAI 'Energy in the Residential Sector' 2018 report provides the following Building Energy Rating (BER) breakdown of the 2016 housing stock:

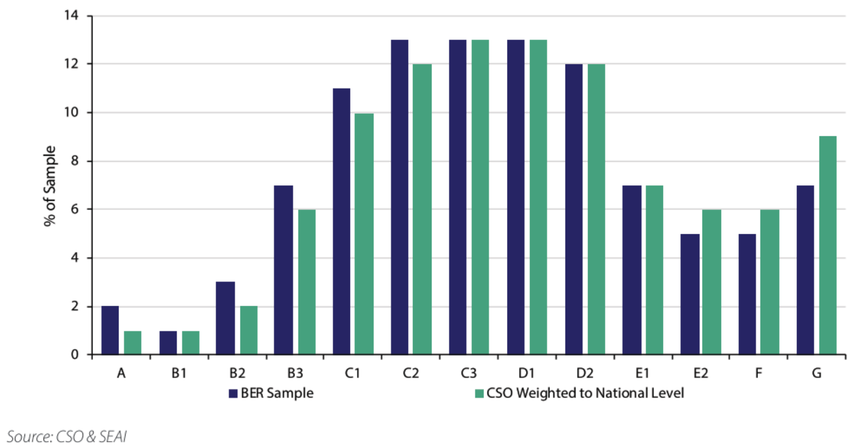

Figure 3.2: 2016 Housing stock BER [18]

SEAI's HARP database allows for gas and oil boilers to be sorted into A,B,C,D,E,F energy ratings in the same manner as the BER distribution with efficiencies listed for individual boilders of each energy rating [78]. The following assumptions were made to combine both of these data sets:

- The efficiency of any 'A' rated boiler is representative of all 'A' rated boilers (etc.).
- An 'A' rated home has an 'A' rated boiler (etc.).

By weighting the boiler efficiency for each energy rating by its proportion relative to the overall population it possible to find the overall average efficiency for gas and oil boilers

2. **Coal and biomass annual fuel demands and thermal efficiencies:** Coal and peat fuel inputs were combined as EnergyPLAN has no option for a peat fuel input. The difference in emissions between the two fuels will be accounted for in the fuel emissions tab of EnergyPLAN. Biomass & coal (Solid fuel) boilers can't be sorted by energy rating on the HARP database, they can only be sorted by manufacturer. Therefore rather than manually recording the boiler efficiencies one-by-one (as the HARP database requires) and averaging values these out, it was assumed that the efficiency of a single boiler for each manufacturer is representative of that manufacturer. To find the overall boiler efficiency for coal and biomass these manufacturer efficiencies were averaged to find an overall efficiency.

3. **Annual electric heating demand:** SEAI provide estimates on the breakdown of residential electricity used for hot water and space heat in their 2018 'Energy in the Residential Sector' report [18]. As there was no data available on the commercial electricity used for heating and cooling an estimate of 12 % of electricity will be used as in the 2006 report; Bioenergy action plan for Ireland [79].
4. **Annual Heat pump demand and thermal efficiency:** It was assumed that the 2017 Energy Balance 'geothermal' input represents the entirety of Ireland's ground-source 'heat pump' energy demand. The average heat pump COP was assumed to be 3.
5. **Solar thermal annual demands and thermal efficiencies:** It was also assumed that the solar thermal heat supply was negligible as there was no specific data available on the number of solar thermal heaters in Ireland - it is included under 'solar' in the 2017 energy balance along with solar PV [51].
6. **Heat demand per building:** To find the heat demand per residential building (this input doesn't include commercial heat) the total residential heat demand was divided by the total number of buildings. Unlike the previous 'individual heat' inputs 'building' represents residential buildings only[i].
   - SEAI's 2018 'Energy in the Residential Sector' report provides data on the total energy demand for space heat and water heating (for 2016) and thus the total heat demand [18].
   - SEAI's 2018 'Energy in the Residential Sector' report provides an estimate of the total number of occupied residential dwellings in 2016 [18] (their source is the Central Statistics Office's (CSO) 2016 census).
7. **Hourly heat demand distribution:** To create a representative hourly distribution Irish Heating Degree day (HDD) data from 2017 [80] was mapped onto an existing EnergyPLAN heat demand distribution for Denmark using a MATLAB script (all relevant code is included in Section 7.2). The HDD data represents the daily Irish heat demand while the Denmark distribution represents the hourly demand for each day. The mapping involved adding/subtracting a correction to each data point in the danish distribution so that the average of each day is the same as the HDD daily distribution as shown in Figure 3.3 below.

[i]The 'notes' feature associated with this input in the EnergyPLAN software indicates this

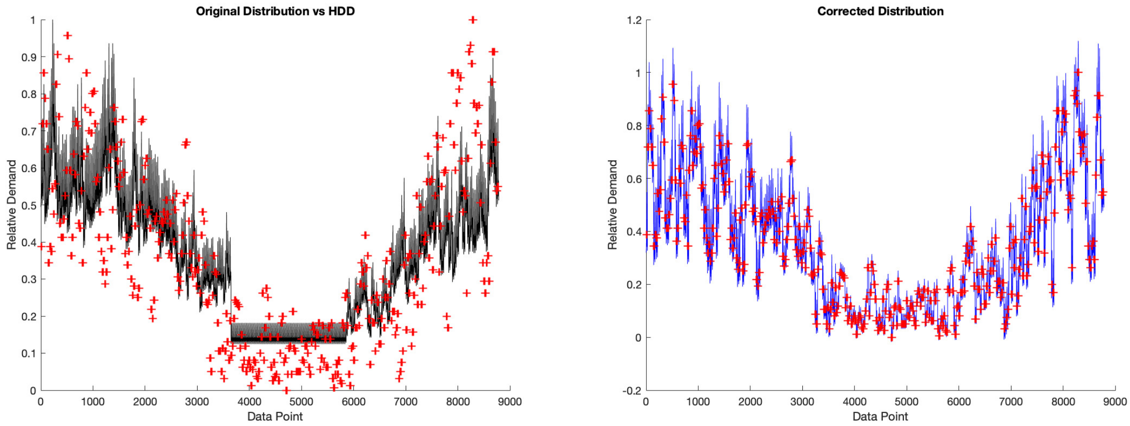

Figure 3.3: Original and corrected demand distribution (lines) vs heating degree days (+)

8. **Hourly solar thermal heat production distribution:** Solar thermal energy was not included in this model and so this distribution was not developed.
9. **District Heating:** There was no district heating in Ireland in 2017 [12].

3.1.3 Cooling

It is assumed that there was no cooling demand in Ireland in 2017 (see 'Summary of Assumptions').

3.1.4 Industry & Other Fuel Consumption

1. **Coal, Oil, Natural Gas, Biomass industrial fuel inputs:** The total industrial fuel input for each fuel can be found on the 2017 Irish Energy Balance [51].
2. **Industrial fuel demand distributions:** These distributions were assumed to be constant as data reflecting the actual distributions could not be found.
3. **Other inputs:** The following energy uses are inputted in the 'various' input because they are not accounted for elsewhere in the model:
    - Waste input to industry
    - Oil refinery energy usage
    - Briquetting plants energy usage

3.1.5 Transport

1. **Jet Fuel, Diesel, Petrol, Natural Gas, LPG and Biofuel inputs :** These values are available on the 2017 Irish Energy Balance [51].
2. **Electric Vehicle Specifications:** As the share of electric vehicles is almost negligible in terms of transport demand (around 0.08%) these inputs were excluded from the reference model.

3.2 Supply

This section discusses the data inputs for any component of the energy system which supply energy.

3.2.1 Heat & Electricity

1. **CHP Capacity and efficiency:** As CHP plants in Ireland are only used to produce electricity it is not necessary to split up electricity from CHP plants and public thermal power plants into separate inputs, so data from SEAI's 2017 energy balance was combined for these power plants to create a single dispatchable power plant input in EnergyPLAN. Therefore, this input was set to 0.
2. **Industrial CHP:** Industrial power production is assumed to be 0 as there is no data available on total industrial production.

3.2.2 Central Power Production

1. **Total Dispatchable Fossil Fuel Thermal Power Capacity (Condensing PP2):** A breakdown of dispatchable capacity was found in the appendices of Eirgrid's 'All-Ireland Generation Capacity Statement' [2]. By summing the thermal generation plants (Gas, Distillate oil (DO), Peat, Heavy Fuel Oil (HFO)) it was possible to find the total dispatchable power. Dispatchable waste and biomass generators are not included in this total, and instead are inputted in the 'waste' tab. Recall industrial electricity supply is also included in this total.
2. **Total Dispatchable Fossil Fuel Thermal Power Efficiency (Condensing PP2):** The overall efficiency was found by dividing the total power plant electricity output by the fuel input (all found in SEAI's energy balance [51]).
3. **Transmission Line Capacity:** Available in the appendices of Eirgrid's 2018 'All-Ireland Generation Capacity Statement' [2].

3.2.3 Variable Renewable Electricity

EnergyPLAN calculates the total annual electricity generation for each of the following technologies by multiplying the input capacity by the input hourly distribution [81].

1. **Wind Capacity:** The overall wind capacity for 2017 was found in Eirgrid's 2018 'All-Ireland Generation Capacity Statement' [2]. This wind capacity doesn't account for wind curtailment so in reality wind generation is lower than would be predicted by it, therefore, a curtailment factor of 8.5% (found in literature) was applied as a correction to this capacity [82]. It was assumed that the entirety of Ireland's wind supply comes from onshore wind as offshore contribution was comparatively minor.
2. **Wind Distribution:** The total annual wind production and distribution in 2017 was found by manipulating Eirgrid's excel data using the same method as the demand calculation (See Appendix 7.1). The annual production was also calculated in excel using this data, and was used as a reference for the EnergyPLAN predicted value.

3. **Solar Photovoltaic:** It was assumed that in 2017 solar PV contribution to the grid was negligible.
4. **River Hydro:** Available in Eirgrid's 2018 'All-Ireland Generation Capacity Statement' [2]. It was assumed - for the reference model only - that all of Ireland's 2017 river hydro was non-dispatchable and that the river hydro distribution was identical to the 2009 demand curve so that this historical river hydro could be accurately modelled in EnergyPLAN. This assumption was made due to a lack of data on the hourly river hydro distribution for 2017.

3.2.4 Fuel Distribution

1. **Dispatchable Fossil Fuel Thermal Power Capacity (Condensing PP2):** The fuel balance was found by summing the fuel usage in the 'public thermal power plants' and 'combined heat and power - electricity' outlined in SEAI's 2017 Energy Balance [51].

3.2.5 Waste

1. **Total Waste Input:** The total waste input was found using values from SEAI's 2017 energy balance [51]. To find the total waste electricity output it was necessary to make an assumption; the efficiency of electricity production for waste and biomass is roughly the same as that of fossil fuels. As 'waste' is included in the 'public thermal power plant' and 'CHP - electricity' production this assumption is neccessary in order to pull the waste electricity production out of this total. The waste electricity output was found by multiplying the total power plant electricity output by the % fuel input for waste (i.e. waste fuel/overall fuel input),
2. **Waste Electricity Production Efficiency:** This was assumed to be the same as the efficiency found for the total dispatchable power plant production (PP2)

3.2.6 CO2

EnergyPLAN requires that the CO2 emissions (kgCO2/GJ) of coal, natural gas, oil and LPG be quantified:

1. **Natural Gas & LPG emissions factors:** These can be found in the appendix of SEAI's 2018 report 'Energy in Ireland' [12].
2. **Coal, Oil & Waste emissions factors:** As there is no 'peat' or no 'biofuel' emission factor input the EnergyPLAN inputs 'coal' and 'waste' were weighted to represent these factors as well as coal and waste. Emission factors for each fuel were weighted according to their relative share of overall primary energy[i]. The emissions factors for most fuel types were found in SEAI's 'Energy In Ireland' 2018 report with the remainder sourced from the Netherlands Enterprise Agency's 2018 report [12, 83].

[i]Ex: 'coal' factor = (sod peat PER)/(coal + peat overall PER) + (coal PER)/(coal + peat overall PER) + ...

3.3 Balancing & Storage

This section discusses the inputs required to balance supply and demand.

3.3.1 Electricity

1. **Minimum Stabilisation Share:** The minimum stabalisation share is the max share of electricity production that has to come from a grid stabilising unit. Eirgrid's maximum non-synchronous grid penetration (SNSP) is equivalent to this as it represents the maximum penetration allowed for non-synchronous energy sources (i.e. wind). The maximum allowable SNSP for 2017 was found using the MAX function on the excel spreadsheet data provided by Eirgrid to find the max for 2017.
2. **Electricity Storage:** David Connolly's 2009 article 'developing a model of the Irish energy-system' contains all relevant information on the Irish pumped hydro electricity facility at Turlough Hill [84]. No additional electricity storage has been installed since this article.

3.4 Cost

This section discusses all cost related inputs for the system (Investment, Operation & Maintenance, Fuel etc.).

3.4.1 Investment & Fixed OM (Operation & Maintenance):

1. **Waste CHP Costs:** Found in EnergyPLAN's database [85]. The database specifies that the fixed OM cost of waste CHP is 0 which in reality is unlikely to be the case (see discussion).
2. **Large Power Plants Costs:** It was assumed that all power plants can be subdivided into the four categories and weighted according to their percentage of the total capacity to find an overall cost. The categories were:
   (a) CCGT: 100-500 MW
   (b) CCGT: 10-100 MW
   (c) Biomass: 250-450 MW
   (d) Coal: 400-700 MW

   It is assumed that CCGT costs capture both the costs of gas turbines and steam turbines using Gas, Gas/DO (distillate oil) and DO inputs, the Biomass captures steam turbines using Peat and Peat/Biomass, and the coal captures steam turbines using Coal and Coal/HFO (Heavy Fuel Oil). The existing biomass and coal power plants are all at a lower capacity than the specified range, and so they are likely to be more costly in reality than is captured by this cost data.

   It was necessary to make this assumption as these are the only power plants in the EnergyPLAN cost database that can be related to the actual power plants in Eirgrid's capacity statement [2, 85].
3. **DC Interconnector Costs:** The total investment cost of the East-West interconnector is discussed in an FTI Treasury case study of this interconnector [86] and the number of

operational years in an Eirgrid document on the interconnector [87]. As no data could be found on the operational costs these were assumed to be 0.

4. **Pumped Hydro Costs:** The pumped hydro pump and storage costs were found in EnergyPLAN's cost database [85]. It assumes that the turbine costs are the same as the pump costs as this cost is not included in the database.
5. **Biopetrol Plant Costs:** Found in EnergyPLAN's database [85].

3.4.2 Renewable Energy

1. **Onshore Wind Costs:** The latest EnergyPLAN cost value was for 2016 so the installation costs from IRENA for 2017 was used instead as the cost of wind has been rapidly decreasing in recent years [88, 89]. The non-installation cost information was taken from the EnergyPLAN database [85]
2. **River Hydro Costs:** Found in EnergyPLAN's database [85].

3.4.3 Liquid & Gas Fuel:

1. **Biopetrol Plant:** Found in EnergyPLAN's database [85].

3.4.4 Heat Infrastructure:

1. **Individual Boilers:** The cost values for oil, biomass, natural gas, and solid fuel for Ireland are all listed in the EnergyPLAN FIDE guide [77]. A weighted total was found by weighting each of these values according to their relative share of non-electric heat boilers calculated using residential heating data from SEAI's 2018 'Energy in the Residential Sector' [18].
2. **Individual Heat Pumps:** Found in EnergyPLAN's database [85].
3. **Individual Electric Heat cost:** The total individual electric heat cost was found by weighting the costs of electric boilers and heaters (found in EnergyPLAN's cost database) according to their relative share of heat usage [85]. The data in SEAI's 2018 'Energy in the Residential Sector' indicates a share of approximately 80:20 for space heating to water heating.

3.4.5 Road Vehicles:

The transport data provided in the EnergyPLAN cost database was used in conjunction with information provided by the Central Statistics Office (CSO) to find the number of vehicles, the cost of these vehicles, their lifetime and the percentage OM cost [85, 90]. Where data was not present in the cost database the most popular vehicle of that mode was taken to be representative of the mode as a whole. It was also assumed that the 'Exempt' and 'Other' category of vehicles in the CSO's statistics represent conventional cars [90].

3.4.6 Fuel Costs:

The fuel price and handling cost data was taken from the EnergyPLAN cost database [85].

3.4.7 Variable OM Costs:

The variable OM cost data was taken from the EnergyPLAN cost database [85].

3.4.8 External Electricity Market

It was assumed that the Nordic system price in 2017 is representative of the Irish system price [91]. Data on the 2017 and 2018 hourly spot prices were pulled from the 'historical market price' database. As EnergyPLAN requires that input distributions to consist of exactly 8784 data points in '.txt' file format some excel manipulation was required. 32 data points were taken from the beginning of the 2018 data set and added to the end of the 8752 data points of 2017 hourly data. This data had to be converted from a comma decimal point system to a dot decimal point system before finally outputting it as a .txt file.

3.5 Summary of Assumptions

A significant number of assumptions were made in the development of this model. The accuracy of this model is only as good as the assumptions upon which it is built so the following sub-section was created to both summarise and explain each of these assumptions.

1. **Demand**
   (a) **Cooling demand was 0 TWh in 2017.** In 2016 cooling demand accounted for 10% of total electricity demand in the UK [92]. Although Ireland and the UK have similar climates Ireland is not as heavily populated and industrialised as the UK and so it was decided that a 0% demand would be more reflective. This assumption was also made in a previous model of Ireland in EnergyPLAN [77]. The only effect of cooling demand would be on the electricity demand distribution and not on the overall demand as the energy balance demand for 2017 is a fixed value.
   (b) **Flexible demand was only used between the four peak hours of 16.00 and 21.00,, and 100% of this capacity is in use during these hours.** Feedback from an interview with a member of the strategy department of the ESB indicated that demand side units are only used during peak demand. However, the peak demand hours chosen here could be longer or shorter than assumed here as there was no indication in literature as to the actual duration of peak time. As 260MW is very small compared to overall capacity the impact of this discrepancy is likely minimal.
   (c) **100% of fossil fuels used in the commercial/services sector were used for heating.** While there is no explicit breakdown by category in SEAI's 2018 'Energy in Ireland' report it does specify "oil & gas are predominantly used for space heating, but also for water heating, cooking and, in some sub-sectors, laundry" therefore this assumption is likely to hold true. This is also the case for all fossil fuels used in the residential sector except for natural gas of which 2% is used for cooking.
   (d) **The efficiency of one boiler of a certain energy rating (A,B,C,D,E,F) is representative of the efficiency of all boilers of that rating - all 'A' rated natural**

gas boilers have the same efficiency. This is a reasonable guess for high rated homes ('A' and 'B') - as Part L enforces a minimum efficiency for new build of which these homes likely are [74] - but not as good for lower rated homes.

(e) **The efficiency of a single manufacturer's solid fuel boiler is representative of the efficiencies of all of their boilers - all 'Ecotec' boilers have the same efficiency - as solid fuel boilers can only be sorted by manufacturer in the HARP database [78].** Efficiencies likely vary across products for each manufacturer, however, for the purposes of saving time manually collecting this data one-by-one this assumption was necessary.

(f) **12 % of commercial electricity is used for heating and cooling as in the 2006 report; Bioenergy action plan for Ireland [79].** This is a relatively old estimate so this figure has likely since increased as building regulations have become more strict. Building energy policy in recent years has likely increased the uptake of electric heating and heat pumps with NZEB (near zero energy buildings) standards now a requirement for new build [93]. As a result the commercial sector's electricity usage for heat is likely an underestimate so the commercial sectors 'direct' fossil fuel usage was lower.

(g) **In SEAI's 2017 energy balance 'Geothermal' represents all of the energy demanded by ground-source heat pumps in Ireland.** No documentation could be found describing this energy balance term and so this assumption was made based on an interpretation of the 2018 'Energy in Ireland' report [12].

(h) **The average COP of heat pumps in Ireland was 3 in 2017**. The 2011 Kingspan guide claims in the technical specifications section of their guide that all of their heat pumps operate between a COP of 3-3.2 [?]. Heat pump technology has likely improved since 2011 and so a COP of 3 may underestimate heat pump contribution.

(i) **The heating contribution of Solar Thermal and the grid-contribution of Solar PV was 0 in 2017.** It was not possible to differentiate solar thermal from solar PV as SEAI provide only a single 'solar' term with no documentation. At 12 ktoe this term is extremely small compared to overall heating demand. Solar PV capacity is also less than 1% of that of wind and less than 0.1% of overall (5MW) the effect of solar on the grid was insignificant [2].

(j) **Heating Degree Day (HDD) data is fully representative of actual daily space heating demand**. A heating degree day is a measure of how cold it is outside relative to a day on which no heating would be required - this is represented by a cumulative temperature deficit of the outdoor temperature relative to a base temperature representing a no heating scenario. It is therefore commonly used as a guide for space heating demand [12], and so this is a fair assumption for this model.

(k) **Hourly fluctuations (within day) in heating demand in the Danish EnergyPLAN heating demand distribution fully capture the hourly fluctuations in Irish heating demand**. Inter-day fluctuations are captured by HDD data and so capture seasonal demand while within day fluctuations capture daily demand. Within day heating demand is mainly due to water demand. Danish daily hot water demands are likely similar to Irish hot water demands as both countries have comparable climates. The differences between

Irish and Danish within day demand are likely small enough as to have no impact on this model.

(l) **Energy demand distributions, where unavailable, were assumed to be of a constant distribution.** This is the case for industrial fuel demand.

(m) **The impact of electric vehicles on the grid was negligible in 2017.** As the share of electric vehicles is almost negligible in terms of transport demand (around 0.08%) this energy requirement was excluded from the reference model.

2. **Supply**

(a) **Industrial power production is assumed to be 0.** With only 5MW of capacity - or <1% of total power plant production - of industrial capacity specified in Eirgrid's capacity statement this assumption will only result in a minor reduction of overall power production in the model.

(b) **8.5% of overall wind capacity was lost to curtailment in 2017.** The paper from which this factor was found specifies a curtailment range of 5.6-8.5% so this assumption is at the higher end of the estimated range [82] - a lower curtailment factor would mean the model would have a higher wind output.

(c) **All of Ireland's 2017 wind supply comes from onshore wind.** Ireland only had 25MW of offshore wind operational (in Arklow Bank) in 2017 which is less than 1% of overall capacity. Therefore its impact on overall supply was insignificant.

(d) **Solar PV contribution to the grid was negligible in 2017.** See discussion of solar in the 'demand' section above.

(e) **The river hydro distribution in 2017 was the same as for 2009.** With no data available on the hourly river hydro distribution it was necessary to use a hydro distribution previously calculated for the Irish energy system in 2009. The hydro capacity has not changed since, however, the hydro contribution to the grid most definitely has, so this distribution may produce an overestimate or underestimate of hydro contribution.

(f) **All river hydro production in 2017 was assumed to be non-dispatchable for the reference model only (to prevent EnergyPLAN from manipulating hydro production) which results in more reflective hydro values.** EnergyPLAN adjusts dispatchable energy sources to fill in gaps in the energy system of high demand (increase supply) or high supply (lower demand).

(g) **The waste electricity power production is assumed to have the same efficiency as conventional fossil fuel power production.** Efficiency was calculated based on SEAI's energy balance so it was not possible to separate out this efficiency by fuel input. Electricity by waste is produced at an efficiency similar to coal and biomass (30-40%) but than natural gas (45-55%) [94, 95, 96, 97]. With natural gas accounting for about 60% of electricity production this assumption overestimates waste electricity production efficiency. The higher the gas contribution the more inaccurate this assumption becomes. However, the contribution of waste is small so this discrepancy of little importance.

3. **Balancing & Storage**

(a) **All of David Connolly's information on Ireland's pumped hydro facility at Turlough**

Hill is still accurate [84]. No additional capacity has been added so this is likely the case.

4. **Cost**

   (a) **Waste CHP power production had 0 OM costs in 2017.** This assumption was made by EnergyPLAN. Waste CHP likely does have OM costs, however, it could be the case that the profit made from power production more than covers these OM costs. Waste CHP plays a minor role in overall production (<10%) and OM costs a minor role in waste CHP costs and so the impact of this assumption is small.

   (b) **Combined Cycle Gas Turbine (CCGT) power plants costs are representative of the costs of all Gas, DO (distillate oil) and Gas/DO fueled power plants in Eirgrid's capacity statement [2].** Eirgrid identify power plants in their capacity statement as either gas or steam power plants and CCGT makes use of both. Of the 4266MW these power plants represent 2726MW or 64% was confirmed in the 'Energy In Ireland' 2018 report as CCGT [2, 12]. There was no information available on the remaining power plants other than they use gas turbine technology.

   (c) **The cost data for 250-450MW peat/biomass power plants is the same as 50-150MW plants (actual capacity). Similarly, the cost data for 400-700MW coal power plants is the same as for 200-300MW HFO[i]/coal plants (actual capacity).** This assumption likely underestimates the cost of power from both of these fuel sources as bigger power plants typically push down production costs.

   (d) **Interconnector OM costs were 0 in 2017.** No data could be found on the OM of the east-west interconnector and so it is assumed that it requires no OM costs. Compared to the capital costs the actual OM costs are likely insignificant.

   (e) **The pumped hydro turbine costs were the same as the pump costs.** Accurate data could not be found on pumped hydro turbine costs and so it was assumed that these costs are approximately the same as the pump costs. Pumped hydro infrastructure costs are a small once-off cost with respect to overall system and ongoing costs and so this discrepancy is of small importance.

   (f) **The overall individual electric heating cost (space and water heat) was proportional to the relative share of space heating to water heating.** The more energy used for heating the higher the corresponding cost of infrastructure. As space heating requires more heat it will have a higher contribution to electric heating costs.

   (g) **The 'Exempt' and 'Other' category of vehicles in the CSO's statistics represent conventional cars.** Three out of the four categories of which 'Exempt' ('disabled drivers', 'diplomatic', 'state owned') and three out of five categories of 'Other' ('Public Service Vehicles', 'Vintage Vehicles', 'Island Vehicles') are likely composed of are likely conventional cars [98].

   (h) **The Nordic (Norway, Denmark, Sweden and Finland) system price for 2017 is representative of the Irish system price [91].** As there was no data available on

[i] Heavy Fuel Oil

the hourly marginal cost of electricity for 2017 this assumption a necessity. In reality, the interconnection between countries in the Nordic region likely lowered the price of electricity for the consumer and so the electricity system cost estimate by this model will be lower than was the case for 2017.

4 Benchmarking of Model

To ensure that the outputs of the model were accurate they were benchmarked (or compared) against real data wherever possible. If the model outputs are not demonstrated to be accurate/representative the model cannot be trusted, and so this is a crucial step. The 2017 energy system was used as this benchmark as this was the most recent year for which data was available at the time this data was being gathered [12, 51]. In the following subsections the accuracy of the model will be discussed criteria-by-criteria.

Note: In order to speed up the process of getting and analysing EnergyPLAN results an Excel template was created. This template can be used easily by selecting 'Run (Clipboard)' in EnergyPLAN and pasting this model output into the green cell in the template

4.1 Electricity

Monthly electricity production, monthly wind supply and total electricity production were used as measures to test both the accuracy of both the total production and the model's temporal distribution of electricity demand and supply. If the model doesn't reflect real demand and supply values hour-by-hour it cannot be trusted to reflect the capacity needed to match supply and demand on an hourly basis.

4.1.1 Comparison of Monthly Demand Values

The model's monthly electricity production outputs were compared to real monthly data to test its validity. As the data provided by Eirgrid is 'demand' data and not 'production' data it was necessary to apply a correction factor to the monthly values calculated from this data[ii]. This correction factor is equal to the difference between the total electricity demand calculated from the Eirgrid data and the total electricity production found from SEAI's energy balance [51, 75]. There is no heading for electricity production in this energy balance and so it was interpreted as the sum of the electricity power plant output and the primary energy supply of wind and hydro. The real monthly data used here was found by manipulating the raw Eirgrid data in Excel to reflect monthly values [75].

EnergyPLAN uses a different distribution for both heat and electricity demand. EnergyPLAN categorises electric heating demand under the heat demand category and not electricity demand, therefore the choice of heat demand distribution affects the electricity demand output. Consequently the accuracy of the model's monthly electricity production output can be improved if the electricity

[ii]Recall from the previous section that the model's electricity 'demand' input is being interpreted as electricity 'production' as inputting demand results in the model underestimating electricity production. Electricity production includes plant's own use and distribution losses whereas demand does not.

demand distribution is used for both heating and electricity. This difference is illustrated in Table 4.1 and Figure 4.1 below.

Table 4.1: Average Monthly Electricity Production Comparison

	Corrected 2017 Eirgrid Data [75]	EPLAN Both		EPLAN Elec. Only	
	MW	**MW**	**% Diff.**	**MW**	**% Diff.**
January	3696	3835	3.77	3659	1.00
February	3744	3865	3.23	3721	0.62
March	3610	3651	1.14	3573	1.02
April	3395	3443	1.41	3367	0.83
May	3246	3153	2.86	3230	0.49
June	3217	3036	5.64	3199	0.57
July	3168	2962	6.50	3150	0.56
August	3210	3009	6.27	3189	0.66
September	3350	3215	4.03	3326	0.72
October	3454	3363	2.64	3448	0.18
November	3748	3857	2.91	3722	0.70
December	3794	3946	4.00	3758	0.95

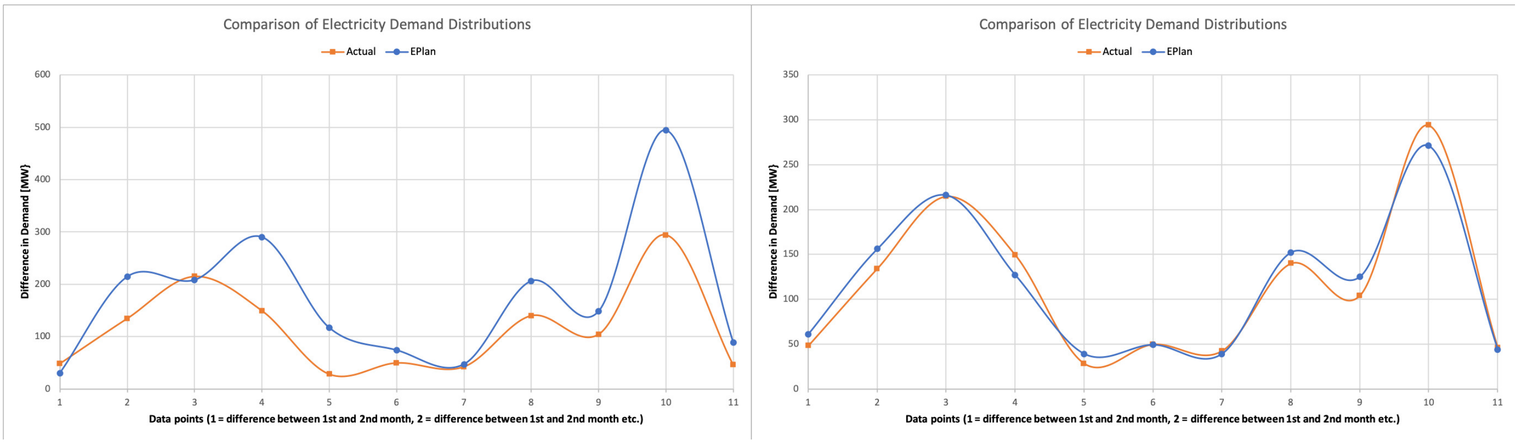

Figure 4.1: Monthly electricity demand output using different heat and electricity demand distribution inputs (left) and only an electricity demand distribution (right)

Evidently from plot on the left hand side of Figure 4.1 using a different demand distribution for heat and electricity distorts the accuracy of EnergyPLAN's monthly demand values. Nonetheless this heat distribution should be used, regardless of its impact upon EneryPLAN's monthly demand distribution, as it is more reflective of actual heating demand. It is also still reasonably reflective with the highest monthly difference at less than 7%. The significance of using different distributions for heat and electricity demand will become more significant as heat becomes more electrified. As this electrification increases electricity demand will come to resemble resemble heating demand more closely than is the case for 2017.

4.1.2 Comparison of Electricity Production by Source

The model's energy outputs for each energy source were compared to the energy system outputs according to SEAI's 2017 energy balance [12]. According to this energy balance there was only

7.44 TWh/year of wind production in 2017, however, calculations performed on Eirgrid's data in Excel indicate that actual wind generation in the Republic of Ireland was 7.78 TWh/year and so this value was used instead [51, 75]. As can be seen in Figure 4.2 the model calculated wind, hydro, pumped hydro and power plant production within a reasonable degree of accuracy given only capacity, demand/generation distributions and efficiency (in the case of the power plants). In the case of 'waste' the model used the input directly which produces what appears to be 100% accuracy.

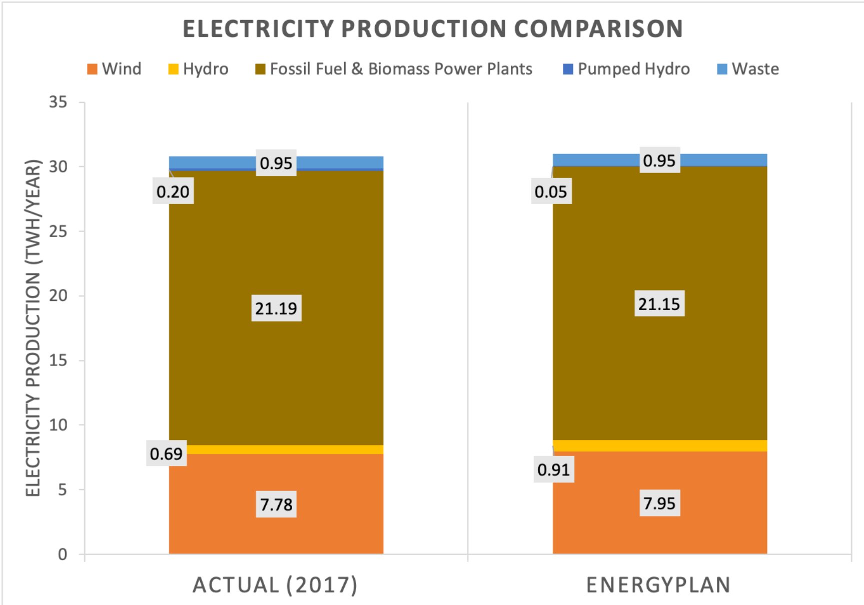

Figure 4.2: Comparison of Electricity Production by Source

4.1.3 Comparison of Monthly Wind Production

The model's monthly wind production outputs match up well with Eirgrid's data as illustrated in Table 4.2 and Figure 4.3 [75]. Similarly to the monthly demand data, the real data used here is based on data manipulation performed in Excel on Eirgrid's spreadsheet of raw data [75].

Table 4.2: Average Monthly Wind Generation Comparison

	Actual 2017 [MW][75]	EnergyPLAN [MW]	% Diff.
January	918	944	2.85%
February	1274	1265	0.70%
March	1063	1092	2.77%
April	644	647	0.41%
May	649	678	4.40%
June	861	866	0.59%
July	590	600	1.65%
August	639	651	1.91%
September	906	945	4.30%
October	1093	1089	0.33%
November	895	919	2.67%
December	1160	1196	3.09%

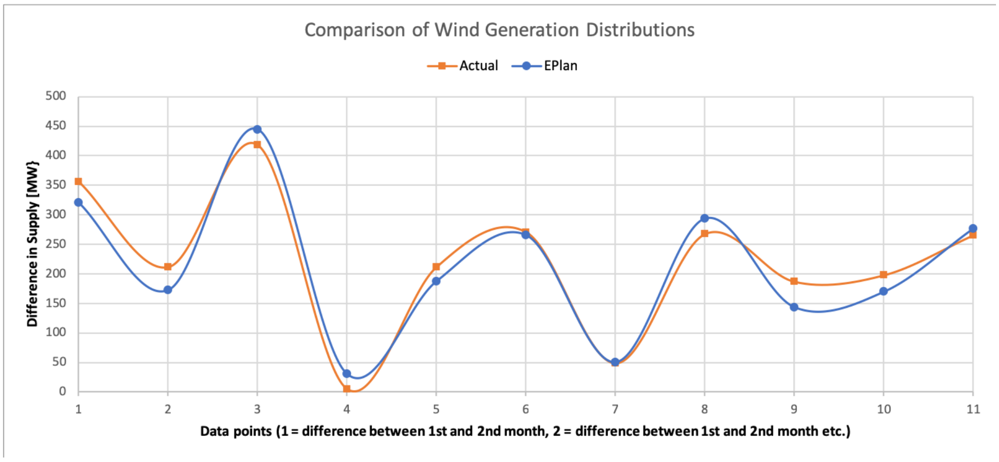

Figure 4.3: Wind Production Distribution Comparison

4.2 Fuel Consumption

This model's fuel consumption output captures all fuel used by the model for electricity, heat and transport. EnergyPLAN calculates the fuel consumption (or primary energy requirement) for all fuels except waste. It was found that EnergyPLAN moderately underestimated the fuel requirement for power plant electricity production and so power plant efficiency was decreased from 48% to 46% as recommended in the FIDE guide [77]. The resulting model outputs match up well with real values (from SEAI's energy balance [51]) as shown in Figure 4.4 below.

Note: The fuel consumption data in SEAI's energy balance includes the energy lost through a power plant's own usage and distribution losses while the model does not. Therefore, this was subtracted from the primary energy requirement for each fuel to allow for comparison of like with like.

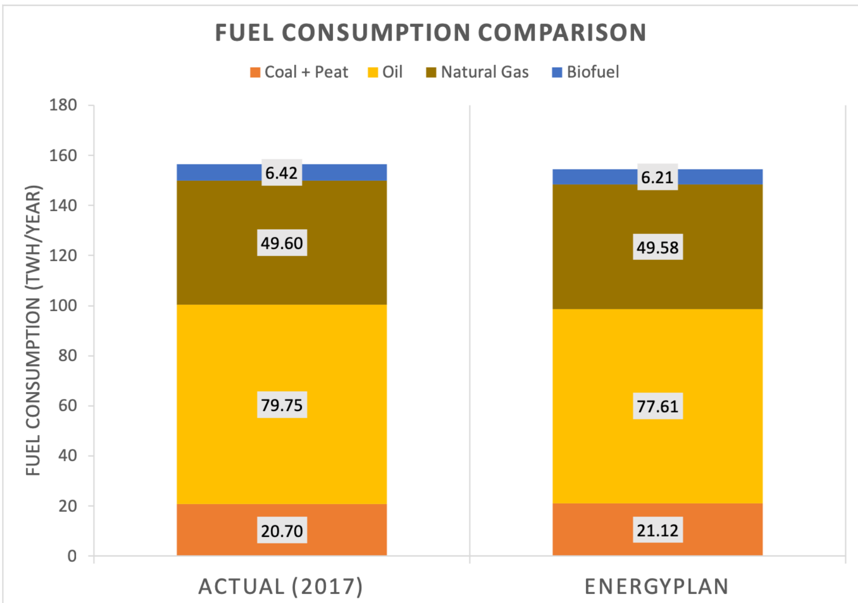

Figure 4.4: Fuel Consumption Comparison

4.3 Emissions

EnergyPLAN slightly overestimates overall emissions by 0.9 MtCO2 or 2.29%, however, this a small enough difference as to accept the model's emissions as representative of the real 2017 system emissions.

Note: EnergyPLAN does not display a breakdown of emissions by fuel if the spreadsheet (or 'Run (Clipboard)') output results option is chosen. It only does so for the 'Run (Print)' option. Secondly, EnergyPLAN only calculates biomass emissions based on the 'waste' input of the model. It also ignores biomass emissions from power production, industry and heating. Therefore, to calculate biomass emissions it is necessary to temporarily move all of these energy inputs into the 'waste' input in the supply tab.

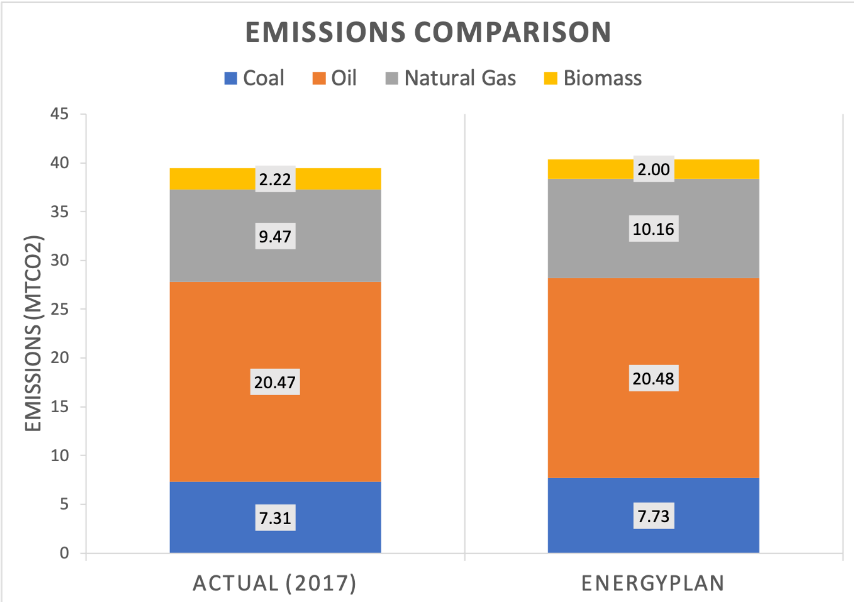

Figure 4.5: Emissions Comparison

4.4 Heat Production

EnergyPLAN does not manipulate heat inputs. It multiplies the heat inputs provided to the model by the corresponding efficiency of the technology providing heat to calculate the model's heat production output. The resulting model efficiencies are 100% accurate as there was no heat balancing required as is the case for electricity production. Were district heating added to the system the model would then be required to perform a heat balance.

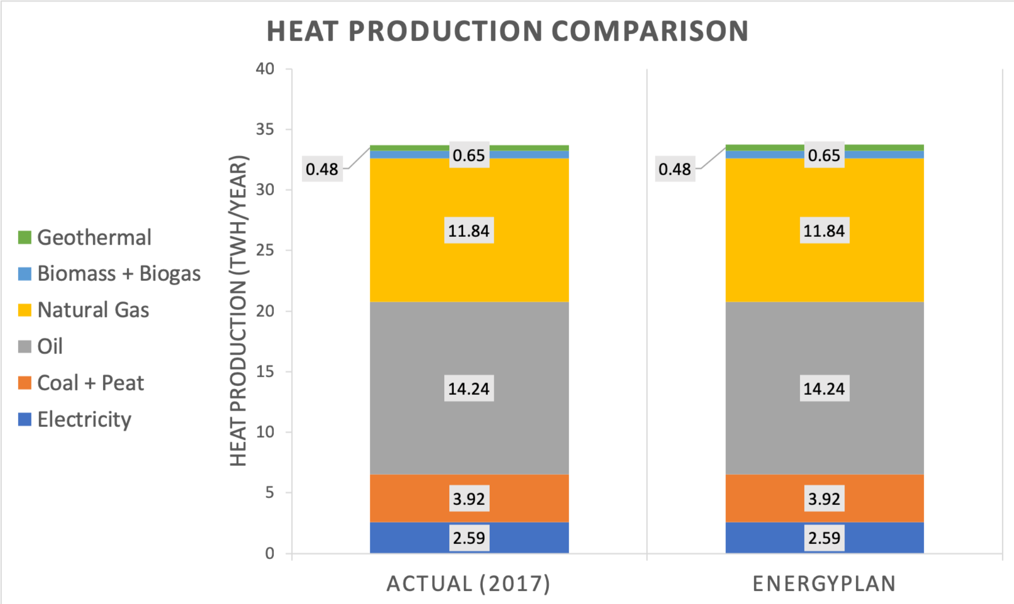

Figure 4.6: Heat Production Comparison

4.5 Conclusion

The reference model outputs, in terms of electricity production, fuel consumption, emissions and heat production, are sufficiently close to the real 2017 energy system outputs that the model can be used as a representation of the 2017 energy system. In the following section this reference model will be used as a benchmark to test proposed system changes.

5 Current plans implemented

In the previous sections the discussion has centered around the creation and verification of the 2017 reference model. In this section this reference model will be put to use as the building block upon which to test energy system changes currently being proposed by the main actors in the Irish energy system: the Government, the ESB and Eirgrid. All three have published documents outlining their views on both the challenges facing the energy system and the changes needed to overcome them. To better understand the consequences of these views in practice an EnergyPLAN model was built that incorporates the following views from these three actors:

Explicit Targets:

1. 70% of electricity generated by renewable sources (RES-E) [6].
2. A cap set on biofuels of 10% of total energy use by 2030 [52].

Challenges facing the energy system:

1. 348 MW of gas power is shut down at Agadha, 85 MW of gas power at Marina CC, 104 MW of gas power at North Wall CT, 560 MW of heavy fuel oil power at Marina CC [2]. Including generators that will be unavailable at the latter end of next decade Eirgrid believe that 1.3 GW of production will be lost by 2027 [2].
2. Overall electricity demand increases by 30-60%. Increased electricity demand from data centres from around 1 to 20 TWh/year or an increase from less than 5% of demand to 31% of all demand on top of existing demand [2, 4, 76]. The worst case scenario of 60% by 2030 will be assumed here.

How targets will be met:

1. Minimum of 5200 MW of onshore wind to be installed by 2030 [4]. According to the 2018 RESS a 55% RES-E scenario requires 8000 MW of renewable electricity generation to be installed by 2030 [3], the Committee on Climate change has set their sights higher but have not agreed on a capacity [6].
2. The Celtic interconnector adding 700MW of interconnection capacity to the grid is in planning for 2025/26 [4, 5].
3. Coal generation is repowered to gas and peat generation to biomass by 2025 [4, 6].
4. 450MW of gas-fired plants (in Ringsend, Poolbeg, Corduff and North Wall) and 136MW of battery plants (in Poolbeg, Ringsend and Inchicore) - to manage periods of high demand - is being proposed by ESB for 2023 [7].
5. Increased flexible demand. In December 2017, 512MW of flexible demand side units bid successfully in the capacity market auction almost doubling flexible capacity from 260MW [2]. In December 2018, 693MW of flexible capacity was successful [99]. It will be assumed that this will increase to 1000MW by 2030 and as in the reference model thatn flexible demand will only operate four hours a day during the peak demand periods.
6. 1.5 million homes 'deep' retrofitted [6]. It will be assumed that this corresponds to a demand reduction of 64% per home [100]. It will also be assumed that 100% of homes will install heat pumps as part of the retrofit. Note Eirgrid seek a lower aim of 17% of residential homes to be

heated through heat pumps by 2030 [4].

7. District heating networks to provide heat to homes and businesses surrounding the Poolbeg waste incinerator and near the Amazon data centre in Tallaght [8].
8. 12% of diesel and petrol by volume to consist of biofuels [6].
9. 300,000 electric vehicles on the road by 2030 [4]. To set up Vehicle to Grid (V2G) in EnergyPLAN data from Genovase et al on the Nissan Leaf was extrapolated to represent all electric vehicles [101]. It was also assumed that only 50% of cars are allowed charge during peak demand and 75% of parked electric vehicles are grid connected.

These stated plans were interpreted as the following inputs in the EnergyPLAN model:

1. 1.3 GW loss of electricity production.
2. 60% increase in electricity demand.
3. 8000 MW of renewable electricity capacity made up of 6704 MW actual capacityThis is equal to 7327 MW of installed onshore capacity due to the 8.5% curtailment factor, 435 MW of offshore[i] and 238 MW of hydro.
4. 2326 MW of new CCGT power plants.
5. 700 MW of added interconnection.
6. Coal generation repowered to gas and peat generation to biomass.
7. 136 MW of battery power with 0.2 TWh of electricity storage.
8. 1000 MW total flexible demand.
9. 1.5 million homes deep retrofitted with corresponding 75% decrease in demand per home.
10. District heating networks installed to distribute heat at Poolbeg.
11. 12% of diesel and petrol by volume to consist of biofuels.
12. 300,000 electric cars on the road, with 50% of cars are allowed charge during peak demand and 75% of parked electric vehicles are grid connected.

This system produced the following results:

5.1 Results

An increased demand of 60% requires a comparable increase in electricity production.

[i] This is equivalent to a 1 billion euro investment in offshore wind

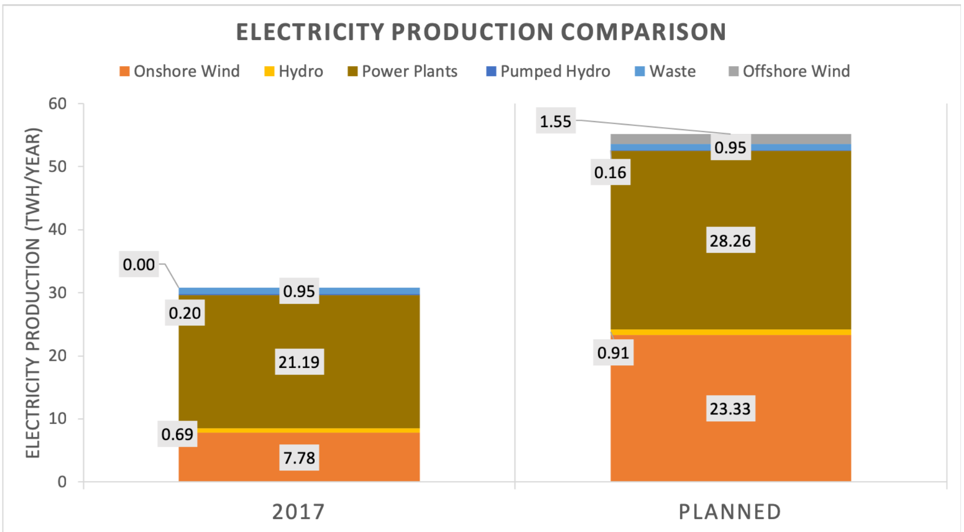

Figure 5.1: Electricity Production Comparison

With peat and coal are both being phased out of electricity production with a switch to biomass and gas, and much of heat production being replaced by heat pumps and district heating fuel consumption drops in spite of the massively increased demand.

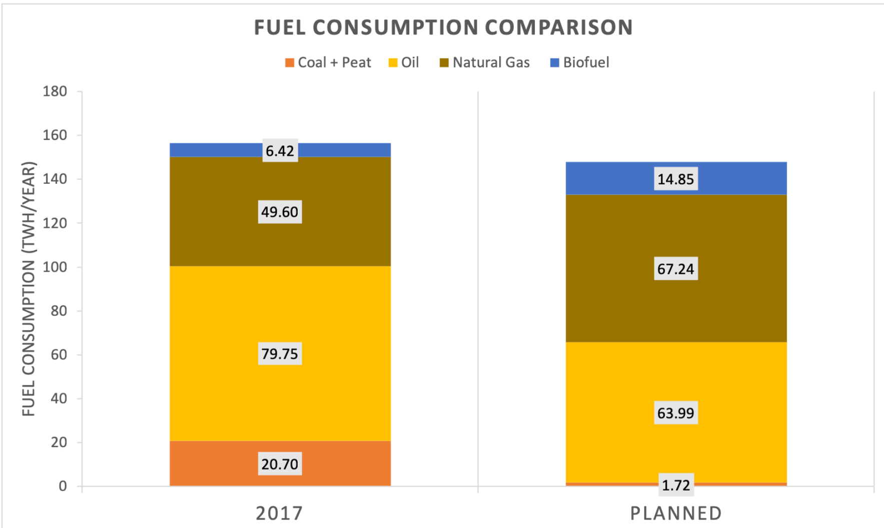

Figure 5.2: Fuel Consumption Comparison

The heat pumps that are used to replace individual boilers in this energy system have an efficiency of 300% (COP=3) and so overall heat demand drops massively with increased heat pump uptake.

Note: The 'geothermal' legend in figure 5.3 below represents heat pumps.

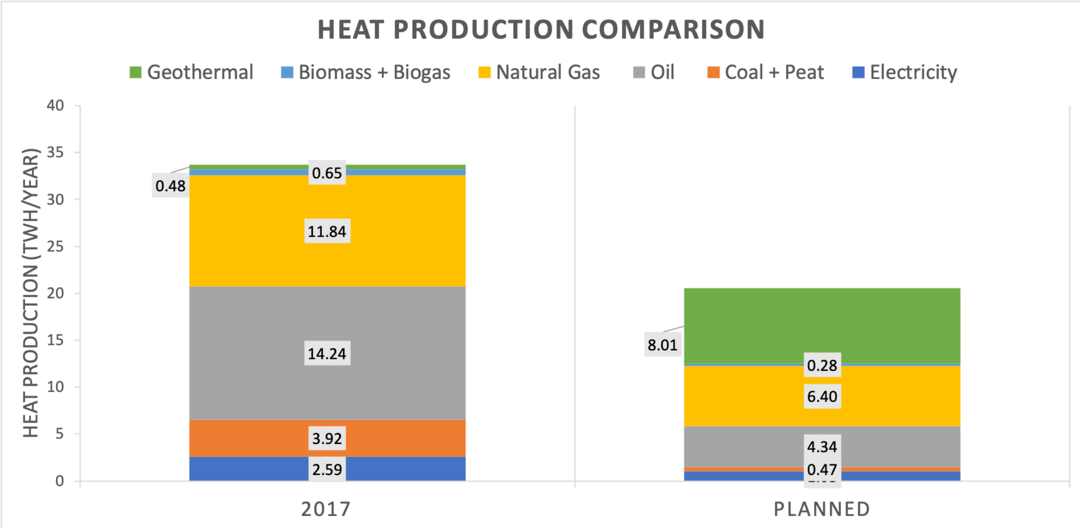

Figure 5.3: Heat Production Comparison

The overall system emissions also drop in spite of increased overall demand due in large part to the electrification of heat with heat pumps.

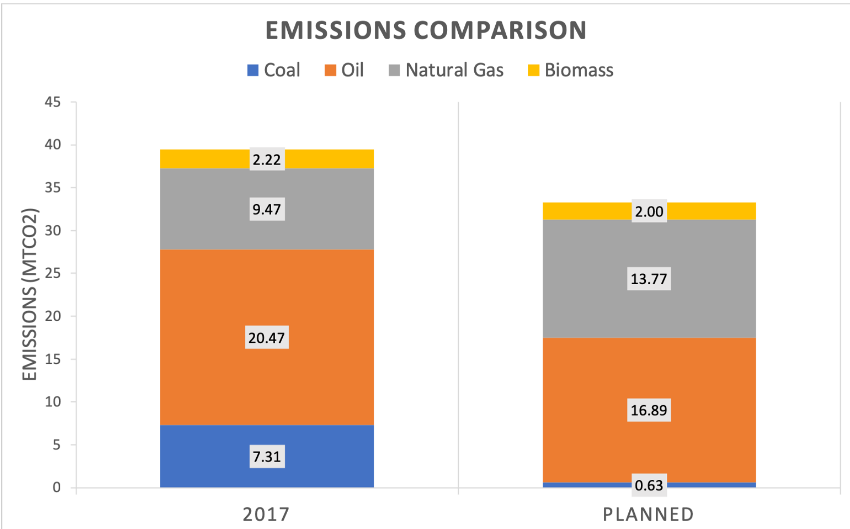

Figure 5.4: Emissions Comparison

The cost of onshore wind far surpasses all other costs at 5.17 billion euros. The required offshore wind may in fact be higher than is used here due to existing barriers to further development of onshore wind in Ireland. Offshore is more expensive than onshore wind so this would push the costs even higher.

Table 5.1: New infrastructural costs needed for current plan

Technology	Cost [Billion Euros]
Onshore Wind	5.17
Offshore Wind	1
CCGT Capacity	2.3
Battery Storage	0.068*
District Heating Network	0.080**
Total	*8.7*

*Estimated by extrapolating from the total cost of the 100 MW battery storage facility setup in southern Australia in 2017 [102]

**Dublin city council estimate the setup cost at 40 million euros for the Poolbeg incinerator [103]. It was assumed that the amazon data centre costs will be equivalent.

5.2 Room for improvement?

This system does not reach the climate committee's 2019 goal of 70% energy from renewable sources. It provides 61.6% with 8000 MW of total renewable capacity, as specified by the climate committee. This corresponds to around 6704 MW actual capacityThis is equal to 7327 MW of installed onshore capacity due to the 8.5% curtailment factor, 435 MW of offshore[i] and 238 MW of hydro. The trend of wind capacity vs. annual wind production in Figure 5.5 below was observed when onshore wind capacity was increased in an attempt to meet this target.

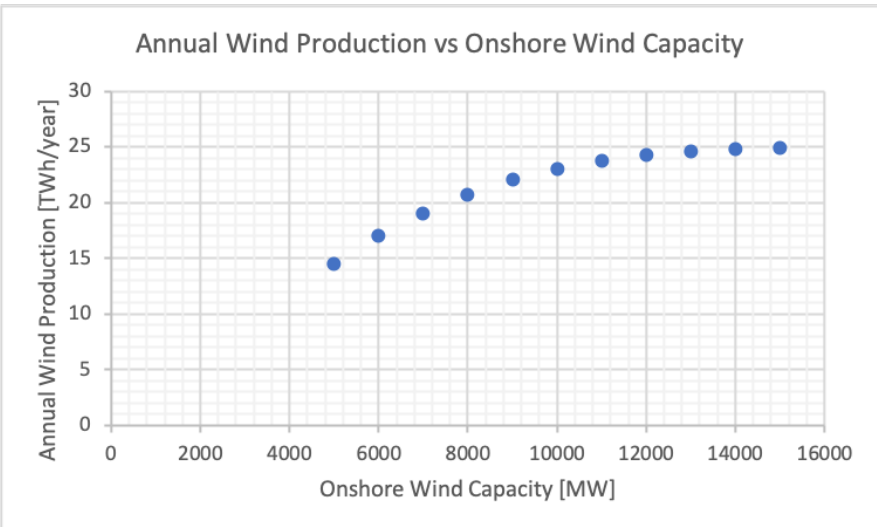

Figure 5.5: Annual Wind Production vs Installed Onshore Wind Capacity

The energy system provides 69.63% of energy from renewables at 13,000 MW of onshore wind capacity and plateaus below 70% at this level. Beyond 6000 MW the potential contribution of additional wind capacity rapidly diminshes, and this is with an extra 700 MW of interconnection installed. In other words the energy system in this form has no use for wind energy beyond a certain installed capacity.

[i]This is equivalent to a 1 billion euro investment in offshore wind

Importantly, even 61.6% of electricity needs being met with renewables the overall primary energy contribution from renewables is still only 23.4%. This is still far off the 2030 target of 32%.
The following options are a useful means of taking advantages of synergies between technologies in the Irish energy system:

1. **Increased electrification of transport will provide a substantial source of electricity storage if V2G is incentivised**. Eirgrid's target of 300,000 electric cars is ambitious for 2030 [4]. It requires an increase of 7500% from 2017. However, there will still be around 1.8 million conventional cars on the road and so the potential of V2G is significantly higher if these vehicles are replaced.

2. **Implementation of district heating in cities**. Although there are already plans to implement district heating for waste heat from incinerators and data centres this does not take full advantage of the district heating's potential. It is possible to either retrofit existing CCGT plants[i] or build future CCGT plants with ability to produce process heat for district heating. Combining this CHP facility with large-scale heat pumps and thermal storage allows for easy and cheap storage of excess renewable energy. Residential heat pumps are efficient but they cannot easily store heat at this scale.

[i] Halligan's paper puts the cost of this retrofit at roughly 9.5 million euros [9]

6 Conclusions & Further Work

Building a model in EnergyPLAN can be a tedious process. The main barriers faced in this thesis in creating an accurate reference model were:

1. Finding the appropriate data.
2. Understanding the EnergyPLAN model:
    (a) Input requirements
    (b) Interactions between inputs
    (c) Model outputs
3. Making appropriate assumptions.
4. Tracking model changes and sources of data

The construction of the reference model system was a long, iterative process. The FIDE guide provided by EnergyPLAN was helpful but not enough on its own as a guide to finding and manipulating data [77].

It was not possible to benchmark any of the system cost data against actual system costs as, despite best efforts, this data could not be found. Therefore the validity of the EnergyPLAN cost estimates made in this thesis are depend wholly on the validity of the sources used. It is hugely important to have reliable cost data as once the model shows that the choice of technologies can technically meet system demands, system costs (and emissions) are the differentiating factor between different technologies.

Analysis of the current direction of the Irish energy system indicates that even if the ambitious targets outlined by the are met Irish progress will still not be sufficient. The model indicates that only 23.4% of primary energy will be met with renewables even though the renewable contribution to electricity will be 61.6%. This thesis has identified two potential areas of improvement that policymakers could explore to take advantage of synergies between technologies in electricity, heat and transport. These are:

- Large scale implementation of district heating in cities. Although there are already plans to implement district heating for waste heat from incinerators and data centres this does not take full advantage of district heating's potential. It is possible to either retrofit existing Combined Cycle Gas Turbine (CCGT) power plants[ii] or build future CCGT plants with the ability to produce process heat for district heating. District heating is more beneficial from an energy system perspective than heat pumps for individual households as it can easily be supplied by thermal storage. This thermal storage can in turn be supplied by intermittent renewables during periods of excess production. Heat pumps cannot be as easily synchronised with storage and so cannot take advantage of excess renewables to the same extent.
- Increased electrification of transport provides a potential source of electricity storage. Eirgrid's recommendation of 300,000 electric vehicles was adopted in an EnergyPLAN model[4]. They added a significant load but also a source of storage for the grid. In order to harness the storage potential of electric vehicles drivers will need to be incentivised to keep them connected to the grid as much as possible. Although increasing the number of vehicles will mean that additional electricity generation is required this type of load is well suited to harnessing renewable electricity.

[ii] Halligan's paper puts the cost of this retrofit at roughly 9.5 million euros [9]

- Using Power to Gas (P2G) to fuel heavy vehicles, freight and aircraft which are not currently considered suitable for electrification. It will be necessary to develop either P2G or hydrogen production to meet the fuel demands of these vehicles [10, 11]. P2G holds advantages over hydrogen as the fuel produced is compatible with existing gas infrastructure and can be stored cheaply and efficiently. Regardless of whether P2G or hydrogen is chosen the electrolysis infrastructure will need to be developed. This need for production of synthetic gas (syngas) from P2G (or hydrogen from hydrogen production) for transportation will, in turn, incentivise the use of this technology to meet long-term electricity storage demands [11].

All of these considerations should be tested for compatibility with the current energy system and measured against current plans. The real advantage of smart energy systems is not for a short-term 2030 system but for a longer term 2050 system. The associated synergy advantages will become more useful as renewable energy contributions to electricity reach the 100% level rather than the 60-70% level.
Finally, the following was also identified as needing further research over the course of this thesis:

1. Active power control (APC) for wind turbines. Wind turbines can contribute to grid stability if they incorporate active power control. APC could be a necessary tool for grid stability in future high renewable electricity grids.

2. Commercial and household solar photovoltaic panels (solar PV) in future energy systems. Whether or not solar PV receives a Renewable Energy Feed-In Tariff (REFIT) or other government funding should be determined by how well it fits in with future energy systems designed to maximise synergies between technologies.

3. Nuclear power in future energy systems. Nuclear power plants produce reliable power with low carbon emissions but do so at a high cost. If uranium harvesting from seawater becomes realised on a commercial scale and carbon prices increase, the capital costs may not be as much of a barrier to uptake.

7 Appendix

7.1 Excel data manipulation

To create an hourly distribution file for 2017:

1. I first found the row positions of the first hour and last hour in the year 2017:
   (a) The search for the position of the cell containing the first hour was initially performed using the MATCH and INDEX functions in excel to find the position and check the result as the spreadsheet contains 166,462 data values. However, this did not produce a perfect result once checked with a manual scroll to guarantee that the resulting position was correct. This was perhaps due to the unusual format of the cells (xx/xx/xxxx xx:xx:xx) being searched.
2. I then used these values to get the average demand for each hour for the entire year:
   (a) Using the row value of the first position (marked with a '01/01/2017 00:00:00' timestamp) and the last position (marked with a '31/12/2017 23:00:00' timestamp) of the year it was possible to access all of the cells in between using the INDIRECT function. This function allows for indirect access to cells using a cell position as an input. This allowed me to create an array of every fourth row position (as every fourth position represents the hourly data point such as '01/01/2017 00:00:00' and '01/01/2017 00:01:00') between the first and last value in 2017. I was then able to find an average hourly value for every four data points and thus a yearly hourly distribution.
3. I finally had to add 12 data points to either side of this distribution as the previous manipulation produced only 8760 data points which is smaller than the required 8784 data points. I pulled these points from before the '01/01/2017 00:00:00' and after '31/12/2017 23:00:00' so that this minor error in the distribution could be spread out either side.

To find the total annual electricity demand for 2017:

- I found the hourly power demand by multiplying each average hourly demand value by 3600 seconds (or one hour).
- The total annual demand is equal to the cumulative sum of these power values.

7.2 MATLAB script for heat demand distribution

```
%% ******* Take in data from text files *********

% Using HDD from https://www.degreedays.net/ for Ireland in 2017

fileID1 = fopen('hdd.txt','r');
hdd = fscanf(fileID1, '%f');


% Using EnergyPLAN's distribution for Denmark:

fileID2 = fopen('Hour_indv-heat-50procent.txt','r');
denmark_dist = fscanf(fileID2, '%f');


%% ******* Create an annual hourly distribution using HDD file  *********

% by mapping the Denmark distribution (hourly fluctuations)
% to the daily demand data or HDD (daily fluctations)

% HDD and Denmark must both be in percent form:

maxHDD = max(hdd);
percent_HDD(:,1) = hdd(:,1)/maxHDD;

maxDen = max(denmark_dist);
percent_Den(:,1) = denmark_dist(:,1)/maxDen;


% Want a distribution where the average demand of every 24 hours  is the HDD for that da
% To correct the denmark distribution so that this is the case need to add/subtract a co

% AVG(24 hours) + correction = HDD
% => correction = HDD - AVG(24 hours)

correction = zeros(8784,1);
check_correct = zeros(8784,1);

for i = 1:1:366

    x = i-1;
    p1 = 1+24*x;
    p2 = 24+24*x;
    m = mean(percent_Den(p1:p2,1));

```

```
    correction(p1:p2,1) =  percent_HDD(i) - m;

    corrected_dist(p1:p2,1) = percent_Den(p1:p2,1) + correction (p1:p2,1);

end


%% ********* Turn the HDD file into 8784 data points *********

percent_HDD_Big = zeros(8784,1);

for k = 1:1:366

    p = k-1;
    p1 = 1+24*p;
    p2 = 24+24*p;

    percent_HDD_Big(p1:p2,1) = percent_HDD(k);

end


%% ********* Plot the data *********

clf;

figure(1)
hold on;
t = 1:1:8784;
plot(t,corrected_dist,'b-')
plot(t,percent_HDD_Big,'r+')
title('Corrected Distribution')
ylabel('Relative Demand')
xlabel('Data Point')


figure(2)
hold on;
t = 1:1:8784;
plot(t,percent_Den,'k-')
plot(t,percent_HDD_Big,'r+')
title('Original Distribution vs HDD')
ylabel('Relative Demand')
xlabel('Data Point')
```

7.3 Government Plans

According to a report by the Oireachtas joint committee on climate action (released in March 2019) [6] the government is currently planning:

1. **Electricity**
    (a) To increase electricity generation from offshore wind, onshore wind and solar PV. The RESS (Renewable Energy Support Scheme), created in July 2018, aimed for renewables to provide 55% of electricity generation by 2030 but this committee recommends that it be revised for a more ambitious target of 70%. In particular it aims to build support for renewable energy projects by sharing ownership through community-led projects. The committee has a preference for supporting offshore wind projects as they are easier to site thanks to a higher public acceptance and have higher capacity factors.
    (b) To encourage the growing of seagrass around offshore wind farms as a means of carbon sequestration.
    (c) Increased interconnection to the European grid through a Celtic interconnector to France to be completed by 2025/26
    (d) To cease energy generation through the use of coal and peat as soon as technically feasible.
    (e) To review the extent to which indigenous biomass and biogas can replace fossil fuel electricity generation.
    (f) To support the uptake of energy storage technology (such as batteries, pumped storage or compressed air storage development) through RESS
2. **Heat**
    (a) To incentivise the retrofitting[i] of around 1.5 million low Building Energy Rating (BER) homes - the majority of which are using oil, coal, peat or gas for heating - to help homes overcome cost barriers. It will also target retrofitting in public buildings, schools and hospitals. There is no specific heat pump or district heating target.
3. **Transport**
    (a) To incentivise active transport such as cycling though improved infrastructure (such as dedicated cycling lanes) and policy (bike to work scheme, Dublin bikes etc.).
    (b) To promote a 'huge' shift away from cars towards public transport through investment in infrastructure (Metrolink, Dart expansion etc.) for all towns and villages. Could be encouraged by implementing a 2:1 investment in public vs. private transport infrastructure in the future.
    (c) To encourage electric vehicle uptake through policy incentives and improved charging infrastructure.
    (d) To allow only low/zero emission buses and hydrogen, LPG or CNG Heavy Goods Vehicles (HVGs) or trucks.
    (e) To increase the biofuel percentage of petrol and diesel to 12% - thereafter it could cause technical problems.
4. **Collaboration with Industry**

[i] Reducing demand by improving energy efficiency through improving insulation of the building envelope and windows and through more efficient heating sources such as heat pumps

(a) The government plans to collaborate closely with ESB, Eirgrid and Bord Na Mona on formulating a plan to balance the electricity grid with increased electricity demand and without coal or peat. It is also necessary to include experts from Irish universities in this planning stage for the sake of 'choice awareness'. In Lund et al's book 'Renewable Energy Systems' they claim that members of industry (such as the ESB) are not well suited to being the sole advisors to government in planning future energy systems [104]. The transition from a fossil-fuel based energy system to a renewable energy system is a radical technological change in that changing this dimension (electricity supply) requires changes in other dimensions (organisational, demand, storage etc.) [104]:

- Renewable energy system technologies benefit from a wide geographical distribution
- The technological solutions differ from one place to another
- The maintenance of these new technologies is dependant on ownership and organisation - such as community ownership of onshore windfarms.

Therefore Lund et al. believe that with the implementation of new technologies, new types of organisations are likely to develop [104]. These organisations are going to be numerous and small with scarce financial or political capital [104]. As this change poses a threat to existing institutions they will not by themselves create and promote the alternatives required to implement change [104]. In the 1980s the power station Nordkraft considered only one alternative in switching from coal power - oil power - as this technology fitted well into the existing organisations of the power companies [104]. The local citizens had to describe and promote a concrete technical alternative representing radical technological change - insulation of houses and expansion of CHP outside the borders of the municipality [104]. This aim of raising 'choice awareness' inspired Lund et al. to create EnergyPLAN to promote public discussion of technical alternatives to identify institutional barriers to be able to design design institutional alternatives [104].

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