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HOW TO DESIGN THE IRISH ENERGY SYSTEM IN ORDER TO BOTH ACHIEVE EFFICIENT CARBON REDUCTIONS AND MINIMIZE NATURAL GAS DEPENDENCY?

TECHNICAL AND SOCIO-ECONOMIC PRE-ANALYSIS

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Abstract

This Master Thesis is a technical and socio-economic pre-analysis of how could the Irish energy system be designed in order to both effectively achieve carbon reductions and minimize natural gas dependency with the help of energy storage and district heating.

Firstly, the power system was modeled through an Excel dispatch model using quarter-hourly time series and then the heat and power system was modeled with the energy analyzing tool EnergyPLAN. Furthermore, a reference model for the year 2020 together with four alternative scenarios for the same year were simulated and compared through their technical output as well as socio-economic costs. Based on the performed analyses it is discussed how the system could be optimized in the most efficient way and the research question is answered. The Irish key energy policies are then addressed and policy suggestions are proposed.

The report concludes on the main findings and the perspectives for future work are also discussed

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PREFACE

This project is written as a Master Thesis for the programme in Sustainable Energy Planning and Management at the Department of Development and Planning at Aalborg University.

FRAME OF PROJECT

Inspired by the completed by the author internship at the energy consulting company Incoteco ApS and his supervisor at Aalborg University, it was his wish to perform a technical and socio-economic analysis of the Irish energy system. This report can be considered as continued work on the topic from previous project by the author, as in this report another energy modeling tool is used and moreover it also covers the heat sector.

THE MODEL

Two energy analyzing tools were used in the project. Firstly in the previous project, an Excel based dispatch model was developed in order to provide the necessary tool to investigate the technical aspects of the Irish power generation system. The model was based on downloaded from EirGrid quarter-hourly time series for the whole 2011. Secondly, the EnergyPLAN model tool was used to simulate the Irish power and heat sectors using again the available 2009 and 2011 hourly distributions. Then results from both models were compared and verified.

READING GUIDELINES

This report provides all the needed information regarding the project and model descriptions which. The attached to the paper DVD provides the electronic copy of the report, both the Excel dispatch model and the EnergyPLAN files as well as results. There is furthermore a bibliography at the end of the report which consists of a list in all sources used in this project. In the appendix are presented the EnergyPLAN simulation results for each of the developed scenarios.

APPRECIATIONS

The author would like to express his genuine gratitude to the to his supervisor Bernd Möller, associate professor at Aalborg University, for his inspiration, enormous help and constantly encouraging feedback throughout the whole project.

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CHAPTER 1: INTRODUCTION

This chapter presents the background of the integration of wind energy in Ireland according to the relevant energy policies and the current status of electricity generation. Next, the chapter reviews the Government's vision for future power generation with low CO_2 footprint together with the key policies, based mostly on wind power and the problems that occur from it, as well as defines several constraints in optimal wind power utilization. Furthermore, Chapter 1 defines the problem formulation, where is clarified the importance of energy storage as a possible solution for achieving optimal wind penetration. The problem formulation defines the research question of the present study, which will be answered at the end of the project. Chapter 1 moreover provides the project's objectives as well as the delimitations of the study.

1.1 BACKGROUND

The climate change is a fact and many studies point that the reason for it is the emission of Green House Gases (GHG) from human activities, such as burning fossil fuels, agriculture, etc. Carbon dioxide, also refered as CO_2, is the most significant GHG, whose concentration has risen with some 30% - from 280 ppm (parts per million) in preindustrial times to almost 398.5 ppm in May 2013 (CO2.org 2013). This is the result of the ever extending use of fossil fuels in the energy sector. In fact, the carbon concentration has increased with 20% only within a decade for the period from 1995 to 2005, which is the biggest change recorded at least for the last couple of centuries. (IPCC 2007)

Once the GHG, such as CO_2 and methane, are built in the atmosphere, they change the Earth's heat balance as they trap the solar radiation, or in other words: more heat is entering the Earth that is leaving it. This is the so called radiating forcing and this causes a constant increase of the temperature around the globe. (Karl, Trenberth 2003, Connolly 2010a)

There are records that unequivocally show that there has been a constant increase of the average temperatures since the measurements started in the middle of the 19th century, as there is notably steep increase beginning after the half of the 20th century (IPCC 2007), which is exactly when the industrialization was strongest around the globe, which means more and more GHG emissions ever since. Moreover, there are records revealing that the ice cap on the northern hemisphere is melting due to the increased average temperature, which also led to another fact: the global average sea level is increasing, both because of more water from the ice caps had joined the global sea waters and because of increasing the water volume with increasing temperatures due to global warming. (IPCC 2007). Yet this increase in sea water levels is much more significant because the former reason and less due to the latter.

If these trends continue unchanged it is expected that this will lead to thrilling climate changes all around the globe, which threaten, not only some cities or even countries to disappear from the Earth's surface, but also fresh water and food supply, together with health, as well as wild life ecosystems to suffer radical problems worldwide (Connolly 2010a). To summarize, it is critical to start climate mitigation measures on global level, such as energy production in a sustainable manner, which will prevent the future generations from suffering very harmful damages. It should be noted that such measures already exist in Europe, where according to the plan EU 20/20/20, amongst others each EU member has a mandatory individual target regarding carbon reductions, renewable energy (RE) production and energy savings, which should be fulfilled by year 2020 (The European Commission). This EU policy measure is considered only the first step of a major change in the energy production and consumption in Europe, which will be followed by different and stricter plans for the coming decades.

Furthermore, with the ever increasing demand for fuels and considering the scarcity of reserves left – according to the most recent study by British Petrolium (BP 2012) if the world production remains the same (which would be very unlikely as IEA predicts increase as big as 30% in 2030 compared to 2007 levels (Connolly 2010a)), there are proven reserves which will be sufficient for only about 54 years of oil, 63 years of gas and 112 years of coal production (BP 2012). However, these periods could be significantly shortened if both the current trend for ever increasing demand for fossil fuels continues and if carbon capture and storage (CCS) technologies become widely used (Connolly 2010a). Moreover, not only that the fossil fuels are depleting and it is more than clear that there will be devastating consequences for the industry worldwide, but there can be expected massive problems for many economies once the production starts to decrease and hence the fuel prises to increase because of the scarcity on the market. This can be expected to happen actually many years before all reserves are depleted (Connolly 2010a).

Next, not only that the scarcity of fossil fuels reserves will be a problem in near future, but the geographic distribution especially of natural gas and oil reserves is a problematic issue now as about 90% of world's oil reserves are located only in 15 countries and 90% of the natural gas reserves are possessed by 20 countries. However the fuel demand is not concentrated in this handful of countries. This combined with the fact that many of the largest oil and natural gas producers are countries in a rather unstable political situation makes the perspective even more concerning and therefore it is clear that the world has to limit its dependency on these fuels, because the future energy supply might become a very political issue. It is fact that already for political reason the whole Western World suffered two big oil crises – in 1973 and in 1979, which led to certain policy changes so the oil dependency to be limited. (Connolly 2010a) It was just recently in January 2009, that again due to political reasons, Russia stopped 60% the gas supply to Europe and left six countries in South-eastern Europe without natural gas supplies in the middle of the winter (Lea 2009).

However a major role on the NG market and development of RE can play the shale gas. Its development has been very rapid in the last decade. For instance, the share of shale gas from the whole NG supply in the US grew from less than one percent in 2000 to about 20% in 2010, as it is predicted that its share will grow to some 46% by 2035. The shale gas "revolution" from the US already pressed down the world natural gas prices because of the amount of liquefied shale gas from the US transported worldwide. There are still many uncertainties regarding the development of shale gas in Western Europe, such as: sceptic prognosis for the levels of technically recoverable shale gas; very high levels of shale gas on the market can replace investments in RE instead of coal. (Stevens 2012) Moreover, shale gas development is also controversial from environmental issues concerning its fracking. For the first, in some cases as a result from unstable concrete leaks of methane might occur, leading to potential fires or explosions. Secondly, the chemicals which are pumped during the drilling process steadily returns to the surface, where it can pollute both water and land. This has already led to many environmental consequences for the people living in these fracking areas in the US. (Harvey 2011) There is currently no shale gas production in Europe, but there are already several countries in Europe which have explored/planning to explore their available shale gas resources, amongst others: Poland, Hungary, UK. etc. It could be considered that shale gas could become a big game changer for energy policies, amongst others in Europe, as with its deployment, it offers both cheaper prices for NG and secondly, the least carbon pollution from a fossil fuel.

For the summary, both present and especially future security of supply is an issue of concern and is expected to be a more politically sensible topic. Therefore the world's dependency on fossil fuels should be eliminated and a more sustainable energy production should be implemented. It could be concluded that making transition from fossil fuels to RE energy generation is not only a question of environment and sustainability, but also of security (Connolly 2010a).

It is considered that fossil fuels generation replacement with renewable energy sources, combined with energy efficiency measures and demand-side management, is a sustainable alternative to the described above unsustainable current situation. Very broadly, sustainability means that humanity should use what is available in a manner that does not threaten the future generations' development. It consists of its three pillars – environmental, economic and social. Development is only sustainable when the three mutually independent pillars are in harmony (UNEP 2010). As shown above though this is not the case now: polluting the atmosphere with GHGs from anthropogenic activities, such as burning fossil fuels for energy generation, and the followed climate change is clearly unsustainable and jeopardizes the Earth's climate. Depleting all fuel reserves and causing deep political and economic crisis in very near future is nonetheless sustainable and will harm the future generation perhaps earlier than expected as it will happen only in a few decades. Hence it could be reckoned that the current development is not at all sustainable and should be changed.

In the European Union (EU) level there are already taken measurements. As previously mentioned, the programme EU 2020, also known as the 20/20/20 plan, is the main plan for development and growth in the EU in the current decade. Along with job creation and stabilizing the Euro targets, there is emphasis on the energy production and consumption. 20/20/20 is a binding legislation, which is supposed to ensure by year 2020: 20% carbon reductions, 20% RE generation and 20% energy efficiency improvements all compared to 1990 levels. These goals are overall for the union and are to be achieved as each member-state fulfills an individual target by 2020. This plan is considered a first step for Europe in a transition towards sustainable development and fighting the climate change and is expected to be followed by more challenging and strict ones in future. (The European Commission)

This project studies the technical and economic aspects of fulfilling the EU target for RE on national level. For a case study is chosen Republic of Ireland, as for brevity it is refered as Ireland throughout the report. Ireland is chosen as a case study both because its energy system is very alike with many other ones of developed countries which are having similar problems with the implementation of RE technologies on national level; because it is an island and therefore an "almost closed energy system" with only limited interconnections to the UK and none to the continent, which emphasizes on the problem with integrating large amounts of fluctuating RE.

Below are briefly described the current energy situation in Ireland, relevant policies and the future vision for development of the Irish energy sector.

1.2 Current status, relevant policies and future vision of the energy system

Ireland is located in North-Western Europe on the island of Ireland, which is sharing with Northern Ireland, which is a part of the UK. Ireland has a population of about 4.4 million and an area of some 70,000 km^2 (Connolly 2010a). Throughout the 1990s and early 2000s experienced a massive economic growth, especially after 1993. In 2007 the country's Gross Domestic Product (GDP) was almost three times bigger than the one of 1990. This large economic growth in the period presumably comes as a result from development of information technologies, services and pharmaceutics (International Energy Agency 2007). In 2008 the Irish economy registered a downturn as a consequence of the global financial crisis, which deepened in 2009. (SEAI 2012b)

1.2.1 The Irish energy system

Figure 1.1 below illustrates the development of the Irish GDP, Total Primary Energy Requirement (TPER) and the energy related carbon emissions during the last twoTripling the GDP in 2007 compared to 1990 levels led to an increase in the TPER with more than 70% and consequently energy related carbon emissions growth of almost 60% for the same time period. It is important to note the relative decoupling of economic growth and energy intensity, as in the early 2000s the economy was growing with a much more rapid rate than the TPER and especially in the period 2009 – 2011, where while the economy made upturn, TPER and CO_2 emissions kept decreasing. This could be explained by reforms in the economy and improvements of the energy efficiency, as well as much milder winter in 2011 than in the previous year. For example, in 2011 the economy grew with about 1.4% but the overall energy use fell by 6.4% because the heat demand was much lower than in 2010. (SEAI 2012b)

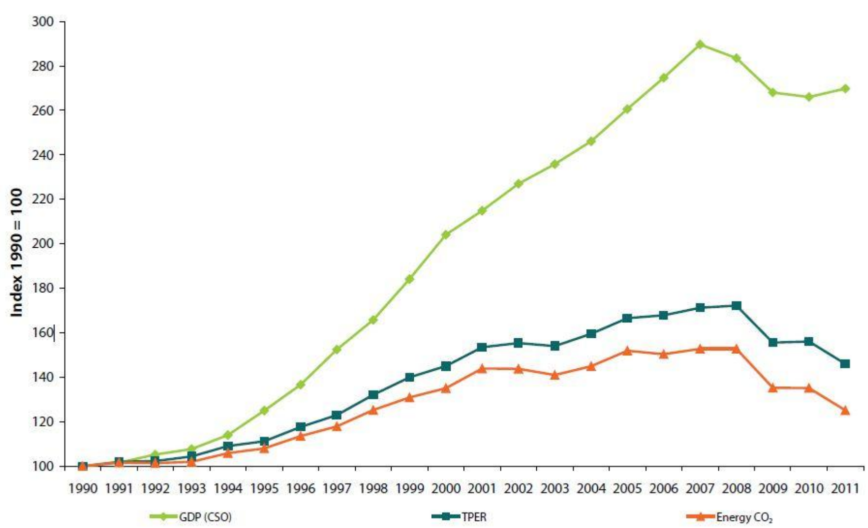


Figure 1.1 – Index of Gross Domestic Product (GDP), Total Primary Energy Requirement (TPER) and Energy related CO_2 emissions for the period 1990 – 2011; Source: (SEAI 2012b)

Despite the decreasing trend for TPER and energy related CO_2 for the last three years which is a result from the global financial crisis, the Irish energy demand is still grown significantly compared to 1990 levels and it should be satisfied. Figure 1.2 visualizes the total energy supply for the period 1990 to 2011. For this period the TPER grew by 46%, mainly due to oil used in the transportation sector, with a peaking growth of 177% in 2008 compared to 1990 levels, followed by power and heat demands with respectively some 67% and 30% in the same year (Connolly 2010a). In 2011 the use of fossil fuels in all energy sectors amounted to 94%, which is also an annual expenditure for importing of fuels of €6 billion for the same year (SEAI 2012b).

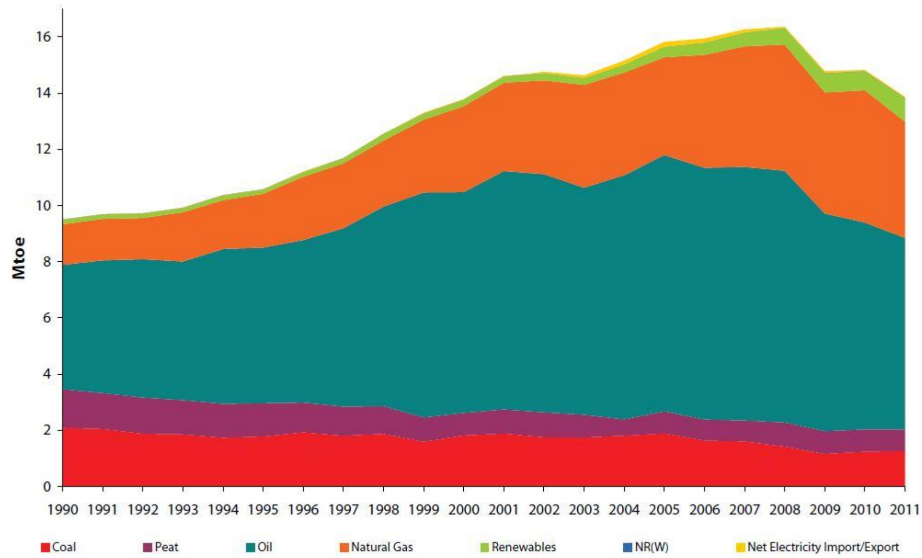


Figure 1.2 – Total Primary Energy Requirement (TPER) for the period 1990 – 2011; Source: (SEAI 2012b)

Clearly the use of fossils in energy generation is dominating. Below in Figure 1.3 is illustrated the energy used for power generation, which is a third of the TPER for 2011. Evidently there is a shift from oil to natural gas in the power generation beginning in 2001 as by now oil is almost phased out – it amounted to only 0.9% in 2011, as all power plants (PP) burning oil will be shut down by 2016, so oil will be only used in the only coal PP Moneypoint as a pilot fuel. Natural gas is the dominant fuel for power generation with a share of 55% in 2011. The share of coal has been halved during the period from 40% share in 1990 to 20% in 2011. Peat is more or less constant in the presented power generation mix with only a decline of about 21%. The RE has been constantly increasing throughout the period from share of just 1.9% in 1990 to 11.5% in 2011. In is interesting that in 2011 there was a 40% increase in RE for power generation, mainly because the increased contribution of wind. (SEAI 2012b)

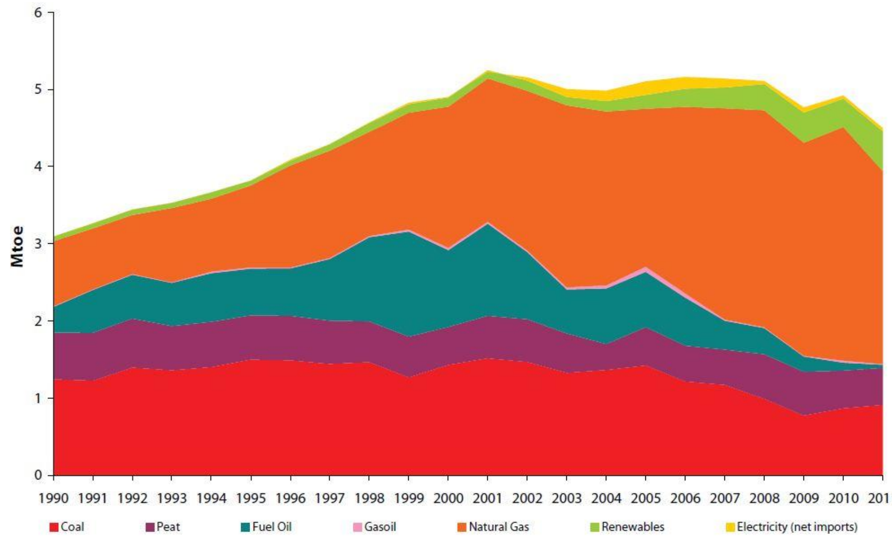


Figure 1.3 – Primary Fuel Mix for Electricity Generation for the period 1990 – 2011; Source: (SEAI 2012b)

Moreover, the increasing trend in natural gas consumption in power generation could be expected to continue. Ireland has indigenous natural gas sources, but their limited amount is expected to supply only about the half of the NG demand until 2017. Furthermore, Ireland has as well indigenous peat resource, which is used for power and heat generation, but is also expected to last for more than 15 years. Evidently from Figure 1.3 above, coal has been constantly used for power generation, driven by both low prices on both the market and on the CO_2 emissions. Yet the tendency is to decrease the coal generation, which is replaced by the NG gas. Clearly from the diagram burning of coal for electricity production has decreased about twice in the period 1990 to 2011. The government, which has objective for diversification in the fuel mix so not to be dependent on only one fuel, invested €368 million in improvements that the plant to meet the NOx and SOx emissions requirement. Nuclear power is considered not an option in Ireland. (International Energy Agency 2007)

To summarize, Ireland uses enormous amount of fossil fuels in its TPER, which amounted to 94% of all energies in 2011. The country has scarce indigenous resources and therefore imports most of the fuels for energy generation, which makes its very volatile to fluctuations on the market (Connolly 2010a). The situation is expected to get worsened as since most of the Irish natural gas is imported from the UK, however the UK's production from indigenous sources is declining and there are certain risks of for the UK's security of supply of natural gas on its own market (Stern 2011). Consequently, there will be inevitable negative effects on the Irish NG supply as the country will be dependent on more distant gas markets. (International Energy Agency 2007) Furthermore, Ireland pays an enormous expenditure on imports of fossil fuels, which amounted to €6 billion in 2011, which in times of deep global financial crisis is even more weakening the economy. From both environmental, security of supply and economic point of view, Ireland has to find a solution to be independent on fossil fuel imports. Moreover, Ireland as EU member has certain obligations regarding EU's 20/20/20 targets, which are discussed in the next subsection of this chapter.

1.2.2 The EU context in the Irish energy policies

As an EU member, Ireland has binding energy and CO_2 emissions targets regarding EU's 20/20/20 plan. Firstly, by year 2020 16% of the gross final energy supply in Ireland should come from RE sources, distributed in the three energy sectors: RE electricity (RE-E), RE heat (RE-H) and RE transport (RE-T). While the 2020 target for RE-E is 40%, as 37% will come single by wind, which is the highest wind contribution in any EU member-state (Connolly 2010a), in 2011 the contribution was 18%, mainly from wind energy. The RE contribution to thermal energy (RE-H) was 4.8% in 2011, while in 2020 it should amount to 12%. RE in transport achieved a share of 2.6% in 2011, compared to a target for 2020 of 10%. (SEAI 2012b)

Secondly, according to the same Climate and Energy EU package Ireland has to all EU Emissions Trade System (EU ETS) companies have to cut their carbon emissions based on 2005 levels with 21% by 2020 and also the non-EU ETS Irish carbon emissions should be reduced by 20% for the same time horizon (SEAI 2011). Evidently from Figure 1.4 below the energy-related CO_2 emissions are the most significant GHG polluter in Ireland. It is interesting to note that not only the overall Irish GHG emissions have risen with about 2 $MtCO_2$ annually in the period 1990 to 2011, but also the energy related carbon emissions share has increased from 55% to 64% for the same time period. (SEAI 2012b)

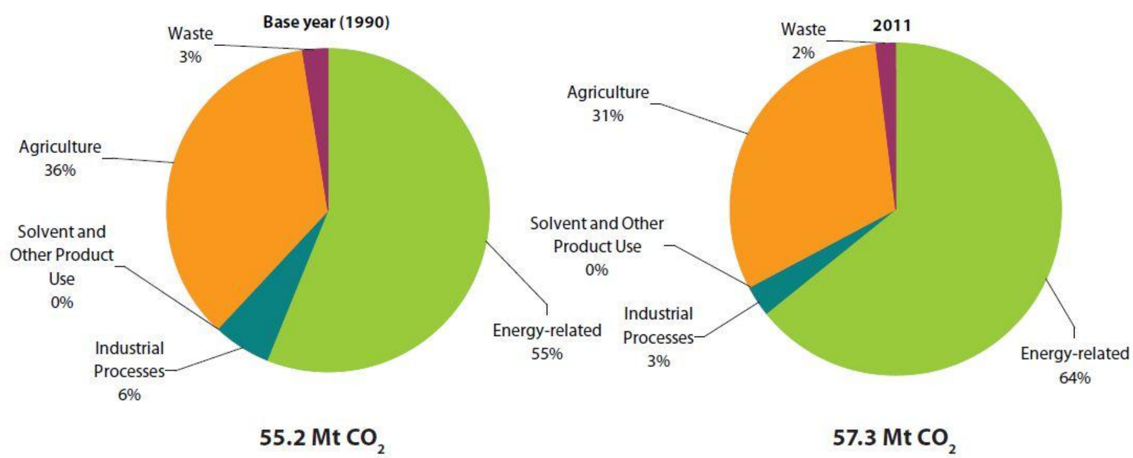


Figure 1.4 – Greenhouse Gas emissions by source; Source: (SEAI 2012b)

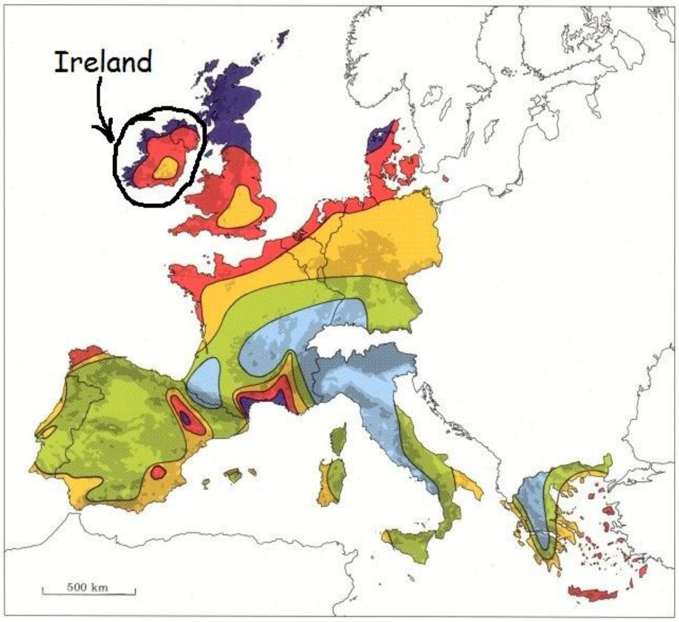
Furthermore, the Irish government has more energy orientated goals both intermediate and for 2020, which will support achieving the overall 2020 EU targets. Amongst others, there is a target to use 30% biomass fuel in the three peat power plants by 2015; cogeneration of heat and power (CHP) should be expanded to 800 MW of industrial CHP and a maximum of 50% natural gas for overall electricity generation, both by 2020. Lastly, a 20% reduction overall in the energy demands by 2020 is planned. (Connolly 2010a)

In summary so far, not only Ireland has to put its import dependency on fossil fuels to a halt by replacing it with more climate benign technologies, such as RE, from environmental, security of supply and economic point of view, but Ireland has binding targets as an EU member regarding both growth in the RE share, reduction in GHGs and energy efficiency improvements. Obviously from the figures, the country is making progress regarding the transition to RE technologies, but there are several constraints which hinder the progress. Firstly, peat and coal generators are ran as a base load continuously throughout the year with very small seasonal and daily variations, which limits the system's flexibility, which results in a problem of optimal utilization of wind power. Secondly, the same peat and coal generators are also heavy carbon polluters, nearly twice as intensive as natural gas. Thirdly, it is clear that the Government has objectives to keep these PPs for several reasons: cheap fuel as well as CO_2 prices, already made large investment in Moneypoint in order to decrease NOx and SOx emissions (which also leads however to efficiency reduction), energy diversity, jobs creation (in the case of peat). There are clearly policies for increasing of wind power, but there are not policies regarding optimizations in the existing energy system in order to effectively utilize the installed wind turbines output and hence decrease fuel consumption and carbon emissions.

1.2.3 Renewable Energy and future vision of the Irish energy system

Ireland has already done a lot regarding transition to renewable energy, but a lot more has been planned to come. The government has proposed incentives, such as RE feed-in tariffs, which aim to increase the onshore wind power, hydro power and biomass landfill gas (Sustainable Energy Authority of Ireland 2012). For fulfilling the plans biofuels, hydropower and marine energy will play an important role in future. However, each of them is due to some reasons constrained. For example, Ireland has about 212 MW of installed hydro power capacity, which represents about 75% of the country's potential and is only about 3% of the overall installed generation capacity, therefore hydro power will always be constrained and cannot play the major role in the future RE supply (Connolly 2010a). Apart from hydro power, there are other RE sources which are in the Government's plans, such as wave power. Ireland has one of the world's best accessible wave resource (Connolly 2010a). The Government has planned 500 MW of installed wave power by 2020, but so far apart from testing wave power prototypes on the shore of Ireland as well as worldwide, there is still not a functioning device anywhere up to date. Moreover, despite the fact that Ireland is a leader in manufacturing of tidal power turbines, it is considered that there are not appropriate sites in Ireland for tidal power as well as some economic constraints. Photovoltaics (PV) are also considered uneconomic way to produce power in Ireland and therefore are not subsidized the the Government.

On the other hand Ireland possesses a source of renewable energy in abundance – wind power. Evidently from Europe's wind map, presented in Figure 1.5, Ireland has some of Europe's best wind locations.



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

Figure 1.5 – Europe's wind map; Source: (The world of wind atlases)

Wind energy is the obvious choice for Ireland. There is plenty of it, it replaces fossil fuels and hence both import dependency, expenditure and CO_2 emissions. Wind energy is also an advanced and mature technology in our days. (Connolly 2010a) Furthermore, Figure 1.6 below quantifies the accessible wind resource by cost, amount of installed wind power and social feasibility for year 2010. The diagram shows that with increasing of wind capacity also the marginal price of wind production increases. This occurs firstly because of system constraints at about 1,000 MW installed capacity and then because of social constraints (e.g. available geographical locations, vision and sound pollution, etc.) at about 5,000 MW wind power capacity. Clearly the marginal wind production price grows from almost €0.07 to nearly €0.09 per kWh of wind generation for installed capacities of respectively 1,000 MW and 5,000 MW. It could be concluded that in 2010 the wind energy was competitive with fossil fuels power generation on prices (SEI 2004a), and furthermore the installed wind power at the end of 2010 was 1,392 MW (EWEA 2011). Secondly it could be concluded that the highest wind penetration at the current fossil fuel prices is about 5,000 MW.

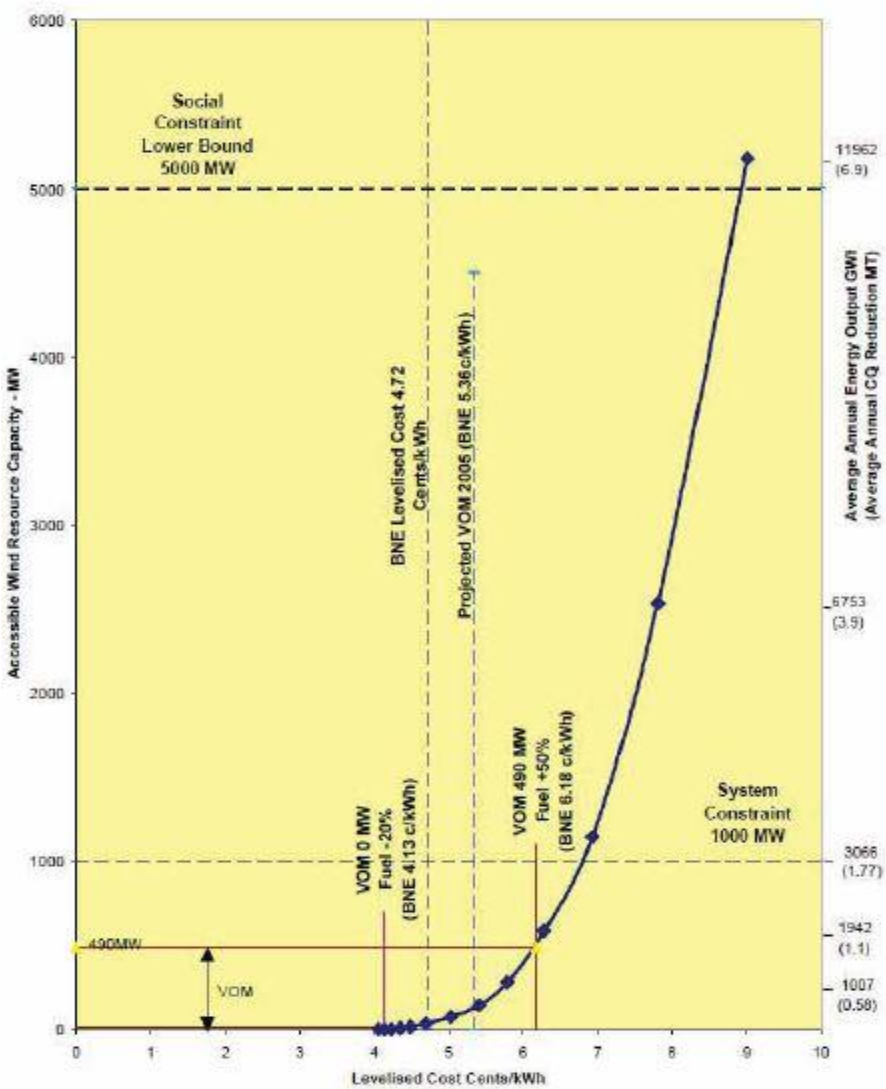


Figure 1.6 – Resource cost curve for wind power 2010 with at 2004 price levels; Source: (Forfas 2010)

In fact, wind power already plays an important role in Ireland's energy mix. Figure 1.7 below illustrates the rapid development of wind power in the country in the period 1990 – 2011, especially from 2003 onwards. The diagram shows that while generation from hydro power has been decreasing over the period and is almost halved in 2011, the wind power generation is booming as its contribution in 2011 was thirteen times the one in 2001 as the total amount of installed wind power capacity was 1,631 MW by the end of 2011, as by 2020 the installed wind power capacity is predicted to be between 3,500 and 4,000 MW. (Sustainable Energy Authority of Ireland 2012) These figures account for onshore wind power, as currently there is only one offshore wind park with a capacity of 25 MW (Connolly 2009) as there are plans to build it to 500 MW in future (NOW Ireland).

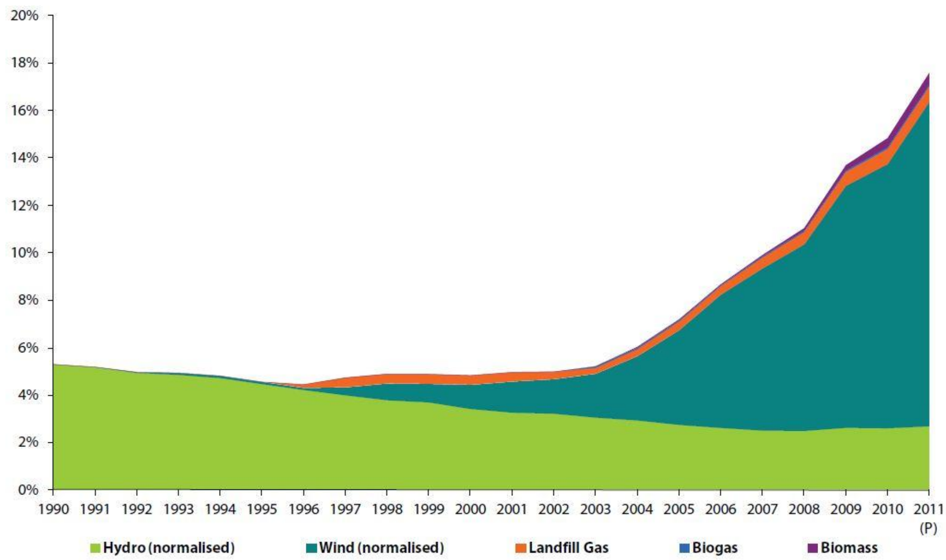


Figure 1.7 – RE contribution to the Gross Final Energy Consumption from 1990 to 2011; Source: (Sustainable Energy Authority of Ireland 2012)

Looking a bit further, Ireland has the potential to achieve onshore wind deployment of 11 – 16 GW and offshore wind capacity of 30 GW by 2050 according to (Sustainable Energy Authority of Ireland 2013). This could create about 20,000 jobs in both in installation as well as operation and maintenance (O&M) by 2040. And as the Irish Wind Energy Roadmap to 2050 (Sustainable Energy Authority of Ireland 2013), thousands of jobs could be created from the wind industry in the next decades.

To summarize, Ireland is planning a transition from conventional to renewable energy generation. Drivers for this is on one side striving for sustainability in energy generation, which would grant clean environment, savings on fuel imports, independent and secure energy supply from indigenous source and jobs creation. Additionally, as an EU member-state, Ireland has obligations regarding EU's plan for development Europe 2020, which has to fulfill and as shown above, already there are policies and incentives for development of RE as well as intermediate targets, which will help to meet the overall 2020 goals. At first sight, the enormous available wind resource and the vast development of wind power in Ireland in the recent years suggests that these obligations will be easily met. However, wind power has one major drawback – it is a fluctuating RE source, which not only cannot be called upon will, but is both unpredictable and its output does not coincide with the daily power demand, which is on the other hand fairly predictable. All these lead to certain concerns and considerations, which are described in the following subsection of this chapter – Problem formulation.

1.3 Problem formulation

Unlike with the dispatchable RE sources, such as biomass and hydro power storage, the fluctuating character of wind could become concerning for large wind penetrations as very fast the power produced by wind turbines could become times bigger than the demand. Production and consumption of electricity should be balanced instantenously. If one of these increases or decreases the other one should do the opposite. Power demand follows normally hourly curve on 24 hours basis, of course depending on the time of the year, which is predictable. However, wind energy is stochastic, following however daily and seasonal changes. Changes in wind speeds appear fast because wind power is a function of the cubic of wind speed and hence, unlike the demand, wind energy is fairly unpredictable. (IEA 2011a)

Figure 1.8 below is an example of the challenging character of utilizing wind power in a weekly period, with highly variable wind speeds. The red (upper) curve is the power demand, which is evidently similar on a daily basis. The black (lower) curve follows the net load (demand – RE supply), which clearly is not coinciding with the demand and is filled with contrasts due to variations in wind speeds. When generation from wind and PV is lower than the demand (positive net load), the difference should be covered by dispatchable power plants. On the other hand, it is noticeable that sometimes the net load is below zero, meaning that wind and solar power alone produce more electricity than the demand. Evidently on the 14th of April only within a few hours more than 12,000 MW of capacity should be shut and part of the excess production from wind turbines should be curtailed, stored or exported, or otherwise there will appear imbalance in the electrical system.

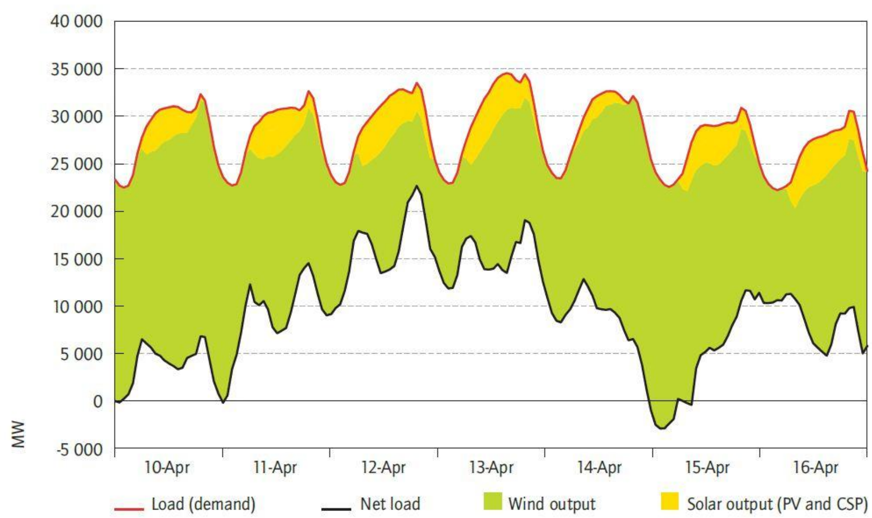


Figure 1.8 – Variability in demand and net load (demand – RE supply) in a challenging week; Source: (IEA 2011a)

It is clear that balancing a power system with large wind power penetration is a difficult challenge, particularly for islands, such as Ireland, which have a limited interconnection (500 MW) to the UK (The Irish Times 2012), which by the way is also an island and is currently installing enormous amount of wind capacities offshore which could also lead to the same balancing problems (The Crown Estate 2012). Furthermore, not only that it is hard for Ireland to export any excess power, but is currently also uneasy task to store it, as there is currently only one hydro pumped energy storage (HPES) with a capacity of 292 MW, which could be maintained for up to six full load hours (ESB Ireland 2012). Moreover, the third option for handling the problem of excess, namely curtailment of wind turbines, decreases their economic efficiency. It is clear that curtailment of wind power should be avoided, but it is also a possible solution of a capacity problem and should be used sparsely (< 100 hours/year).

To cope with large penetrations of fluctuating RE source, such as installing an overall capacity of 4,000 MW wind power in Ireland by 2020, is essential the energy system to be flexible, so to respond quickly enough to the variations in wind speed and keep the system balanced (IEA 2011a). Especially in the case of Ireland, as described above, cause of the limited/unacceptable three alternatives to the flexible power system: export, storage and curtailment. The Irish power generation system is rather flexible, with domination of Combine Cycle Gas Turbines (CCGT), which corresponded to approximately 58% of demand in 2011 (Wheatley 2012). The CCGT installed capacities are mostly new (commissioned after 2001) and efficient (up to 59%), which also have a high ramping ability (4.5 %capacity/minute) and do not wear off from this as they are made for ramping (Rangelov 2013). However, there are also several inflexible elements in the Irish power generation system. Evidently from Figure 1.3 – Primary Fuel Mix for Electricity Generation, the base load is covered by peat and coal. The three state owned power plants, with an overall net capacity of just below 350 MW, are a "must-run" and they operate on their maximum availability. The government does not have plans for decommissioning of them because of several reasons, amongst others: maximal utilization of its indigenous sources, employment, fuel diversification. Next, the only coal power plant, namely Moneypoint, with a net capacity of almost 900 MW, is ran nearly as a base load, with only some seasonal variations. The power plant is the largest Irish CO_2 polluter (Limerick Clare Energy Agency 2012, EnviroSolutions) with annual amount of carbon emissions in 2007 of about 4.7 MCO_2 (EnviroSolutions). The Government's recent large investment in retrofitting it, does mean that it will continue operating in near future, which could be explained by several drivers: low fuel and carbon costs, fuel diversification. (Rangelov 2013)

This is in a clear contradiction with the necessity of maximal flexibility when deploying large wind power capacities, as described earlier. Despite the majority of flexible CCGT in the system, there is a constantly running load of more than 1 GW of power. This defines **Problem 1**: Currently limited flexibility of power generation system and consequently more troubled power balancing with high wind penetrations.

Next, some studies, namely (Sharman 2011) and (Udo 2011), disputably accuse wind power in Ireland alone that due to the higher ramping rates in CCGTs and the consequently higher carbon emissions from natural gas, the CO_2 intensity increases. This however was argued by (Rangelov 2013), whose model proved that firstly the ramping rates of CCGTs are yet not utilized on their available maximum, and secondly that the carbon emissions rise from single from ramping is only minor. Another recent study for the Irish carbon emissions from power generation in 2011 (Wheatley 2012), suggests that wind power does not replace fossil fuels in Ireland as efficiently as expected, because due to constant running of the peat and coal power plants (PP), CCGTs balance the demand, which means that at higher wind speeds, wind power replaces natural gas. Taken that a unit of electricity produced by NG has half the emissions of peat and slightly more than the half of a unit produced by coal in Moneypoint (Carbon Trust 2011), higher carbon intensity per unit of produced energy occurs in the system. (Wheatley 2012) also suggests that this effectiveness is likely to fall as wind power capacities increase by 2020 2 to 2.5 times the wind power capacities of

2011. Another study (Méray 2011) also observes that as a consequence the low fuel and CO_2 prices, generation from coal is cheaper than from natural gas. The merit order of the electricity market suggests that when there is more generation from wind in the system it replaces the most expensive marginal producers, which happens to be NG generators. Given the nearly twice higher CO_2 emissions from coal than NG, wind energy replaces not the biggest environmental polluter, but generation from the most benign one. Furthermore, the modeled annual carbon emissions from power generation in Ireland for 2011 in (Rangelov 2013) show that with replacing by a single replacement of coal and peat plants with new CCGT capacities and the present wind turbines, carbon emissions would fall with some 37% compared to the reference model. The author also concludes that striving to decrease the Irish CO_2 emissions from power generation, it is not only necessary to build more wind turbines, built is actually more important to replace coal and peat PPs first.

To summarize, the primary goal of wind power is to replace fossil fuels and hence decrease carbon emissions. However, this becomes problematic and less effective for Ireland as long as the biggest polluters coal and peat power plants operate more or less on a constant level. Moreover, wind power practically replaces NG power generation, and therefore carbon reductions are not effectively achieved in the present Irish power generation system, which is the definition of **Problem 2**.

Furthermore, due to variable character of wind power, it has a low capacity credit from 5% to 40%, whereas dispatchable conventional power plants have a high capacity credit between 90% and 97%. The wind is not dispatchable power generator and therefore it should be "backed-up" with a dispatchable source of energy, which to secure power supply when there is not sufficient wind power. It is estimated that this "back-up" capacity should amount to about 80% of the installed wind capacity. (Méray 2011) For the case of Ireland at first sight it can be considered that the best option of backing-up wind power is to dispose a sufficient amount of CCGTs, because of their enhanced flexibility and comparatively low carbon emissions. Nevertheless, if CCGTs are used extensively in the current system, more natural gas will be consumed and hence the dependency on NG imports will be increased (Rangelov 2013). Next, Ireland has a goal of limiting generation from NG to 50% by 2020 (Connolly 2010a) as NG's share in this sector was 55% in 2011 (SEAI 2012b). Consequently there occurs **Problem 3**: Extensive use of natural gas as a partner for wind energy increases natural gas consumption and import dependency.

For summary, while Ireland is chasing its EU and national targets for year 2020, three relevant problems have been defined. Since wind is currently the best available renewable energy source in the country, there has been a vast expanding of the wind power capacities in the last decade. Up to 2020 is expected however even stronger deployment of wind turbines, as their overall capacity is expected to expand from the currently installed 2,200 MW (IWEA 2013) to about 4,000 MW in year 2020. Because of the variable character of wind energy, this large penetration is expected to cause challenging power balancing. For the latter is clearly needed a very flexible power generation system, which is currently constrained by the base load operation of peat and coal power plants. It was determined that these plants not only complicate the overall flexibility of the power generation system, but also worsens the effectiveness of carbon reductions, as wind power replaces mostly natural gas, but the biggest polluters – peat and coal PPs generate rather constantly according to their availability. Nevertheless, if these problems are solved by replacing peat and coal power capacities with natural gas ones, then the NG use in power generation will increase and hence the import dependency will also rise, as well as Ireland will not achieve their goal of maximum 50% NG for power generation by 2020.

The above elaborated consequence of events deriving from problems 1, 2 and 3, formulate the main **Research question** in this project:

> *How can the Irish energy system be designed in order wind energy to both reduce CO_2 emissions and minimize natural gas imports?*

1.4 Project objectives

The first objective of this project is to create a robust model, which can replicate the figures from the annual energy balance for year 2011. Secondly the study tends to analyze the Irish heat and power sectors from technical and socio-economic points of view with a reference for the year 2020, as it is a corner-stone in the EUs climate and energy package, but it is also to review the development of the system after year 2020 (see Chapter 5: Analyses). Thirdly this report strives to optimize the current energy system in terms of energy balance, fuel balance, carbon emissions, system operation and socio-economic costs through comparing different technical modifications in order to improve the system's performance (see Chapter 5: Analyses). Next, it studies the proposed technical modifications in two different models – the EnergyPLAN model tool and developed by the author Excel based dispatch model (see Chapter 2: Methodology) in order to verify the study results. Furthermore, this project performs a preliminary policy analyses in order to address the constraints for completing the 2020 targets most effectively and proposes new policy measures in order to achieve best results (see Chapter 6: Policy Analyses). The last, but not least objective of the report is to analyze the research question through the described analyses in this subsection and answer it (see Chapter 7: Conclusions).

1.5 Project's main delimitations

In order the project to be carried through in the time frame, there are several delimitations, the main of which are described in this subsection. It is important to note that the ones, which are not shown here are present in Chapter 2: Methodology.

Firstly, a delimitation of this study is to investigate only the heat and power sectors in Ireland, instead of studying the coherent energy system, where should be added transportation as well. This is both because of the limited project time frame and the rather slow development of EVs and hybrids. However, when performing energy system analyses all three sectors should be studied together as they are parts of the whole energy system. In this way they complement rather than oppose each other and synergies occur, which leads to higher integration of RE in the whole system and better results. Moreover, looking at all sectors grants greater flexibility of the system than studying each one separately.

Secondly, the study uses historical time series for import/export of electricity from 2009, despite that it is expected that they will be different in the studied year 2020, where the installed wind power is predicted to be about three times the one in 2009. Because of the increased wind penetration the marginal price of electricity is expected to decrease as well as at times of high excess production will be very low and hence attractive for the neighboring UK to import. It should be mentioned that import/export is not only driven by power price, but also by power demand and local power supply in the interconnected regions of the importing country. Therefore a thorough study of the markets should be also provided in order to determine the real import/export figures.

Thirdly, again because of the limited timeframe, the compressed air energy storage technology (CAES) is not considered in Ireland, despite that in Chapter 3: Energy Storage Technologies it is defined as one of the two ES technologies (together with HPES), which are capable to provide enough storage for large scale integration of power. In order to study CAES, geographical locations should be analyzed as well as appropriate place for CCGT next to it (see Chapter 3). Yet there is already a study which analyses possible HPES sites in Ireland (Connolly, MacLaughlin 2010) and therefore this is the ES technology studied in this report.

Fourthly, despite that a rather crude Stakeholders analysis and implementation plan is suggested as well as general policy suggestions in Chapter 6: Policy Analyses, detailed ones should be proposed, which analyze all stakeholders thoroughly, determines implementation bottlenecks, proposes a business plan and ownership schemes. Moreover, the Irish job market and job creating opportunities also have to be analyzed in order to study the job creation from implementing the proposed new energy technologies.

Fifth, despite the new EU Directive for energy efficiency from the end of 2012 (European Commission 2012), the obligations for the member states are not included in the analyses, due to the lack of official response to it from the Irish state officials. Yet the directive includes a compulsory decrease of power demand by 2020 as well as district heating (DH) and CHP for all member states.

In summary, despite the above mentioned project delimitations, a possibly more detailed models in both EnergyPLAN and Excel were created and described in the next chapter: Methodology. Reflection on the delimitations is provided in Chapter 7: Conclusions, where are amongst others discussed possibilities for future work.

The next chapter describes the methodology used in this report in order to address the described in this chapter issues and research question.

CHAPTER 2: METHODOLOGY

This chapter introduces the reader to the overall report structure, reveals the methodology used in this project, where amongst others are discussed: description of the EnergyPLAN energy analyzing tool, data gathering and theory regarding developing of the Reference model, the main assumptions in the model, discusses on the analyses made in this report.

Previously, in Chapter 1, it was presented the main drivers for shift from conventional to renewable energy in Ireland together with the Irish key policy issues and energy targets. It was also determined that wind power is the most significant available RE source in the country. Nevertheless, several problems were defined in the current system design that can be considered problematic when harnessing large amounts of fluctuating wind power in the energy system. Hence, it was defined the main research question of the study. The present chapter reveals, amongst others, the methodology used in order to answer the research question.

Firstly in the chapter, it is graphically presented the overall structure of the report and it is as well elaborated on the contents and connections of the chapters. Secondly, this chapter deals with the models used for analys es in order to answer the Research Question, where it amongst others elaborates on: pre-analyses of the Irish power generation system, performed by the author in (Rangelov 2013), where quarter-hourly Excel based dispatch model was built; the scenarios analyses of this pre-study, including the conclusions, which are taken into account and are a point of departure of the current project; the used energy tool EnergyPLAN, the Reference models, data gathering process and the Reference model's main assumptions.

2.1 REPORT STRUCTURE

The overall structure of this report is illustrated below in Figure 2.1. The whole paper consists of six chapters, which as the connections between them are drawn on the picture. To begin with, **Chapter 1** introduces the reader to the general problems with burning of fossil fuels and the need to switch to RES, discussing the problems of harnessing fluctuating renewables. The chapter furthermore presents the scope of the project, namely energy analyses on a national level as well as the project's objectives. As Ireland is chosen as a study case, some general energy trends in the country are presented as well as its future targets and the key energy policies, which have to accomplish them. The chapter ends with the Research Question of the paper as a result of the defined concrete problems in the problem formulation. Next, **Chapter 2**, the present chapter, elaborates on amongst others, the previous work on the topic by the author and presents the previously developed Excel dispatch model. Next, it discusses the tool used in this study, namely EnergyPLAN, together with the motivation for its use. The chapter furthermore presents the main assumptions in developing the Reference models, for instance data gathering process, technical and costs data used. Furthermore, **Chapter 3** presents the presently commercially available storage technologies and discusses the ones chosen to be included in this study's analyses. Moreover, **Chapter 4** tests the Reference 0 model built in EnergyPLAN, which simulates the Irish heat and power sectors' operation in 2011, to the actual recorded data for the year. After validating the model's accuracy, the Reference 2020 model is built, which represents the anticipated system operation in year 2020, according to the forecasts for base scenario with the current Irish energy policies. It is then used in **Chapter 5**, where it is compared to alternative scenarios for the same year in order to find technical and socio-economic optimization. It is worth mentioning that the results of the analyses are then compared to the results of the previously used for analyses dispatch model. Next, **Chapter 6** provides policy analyses and suggestions, as well as a crude stakeholder analysis and implementation study. Lastly, **Chapter 7** concludes on the report, based on the provided analyses. It also discusses on shortcomings from both models used in the study as well as perspectives for future work on the topic.

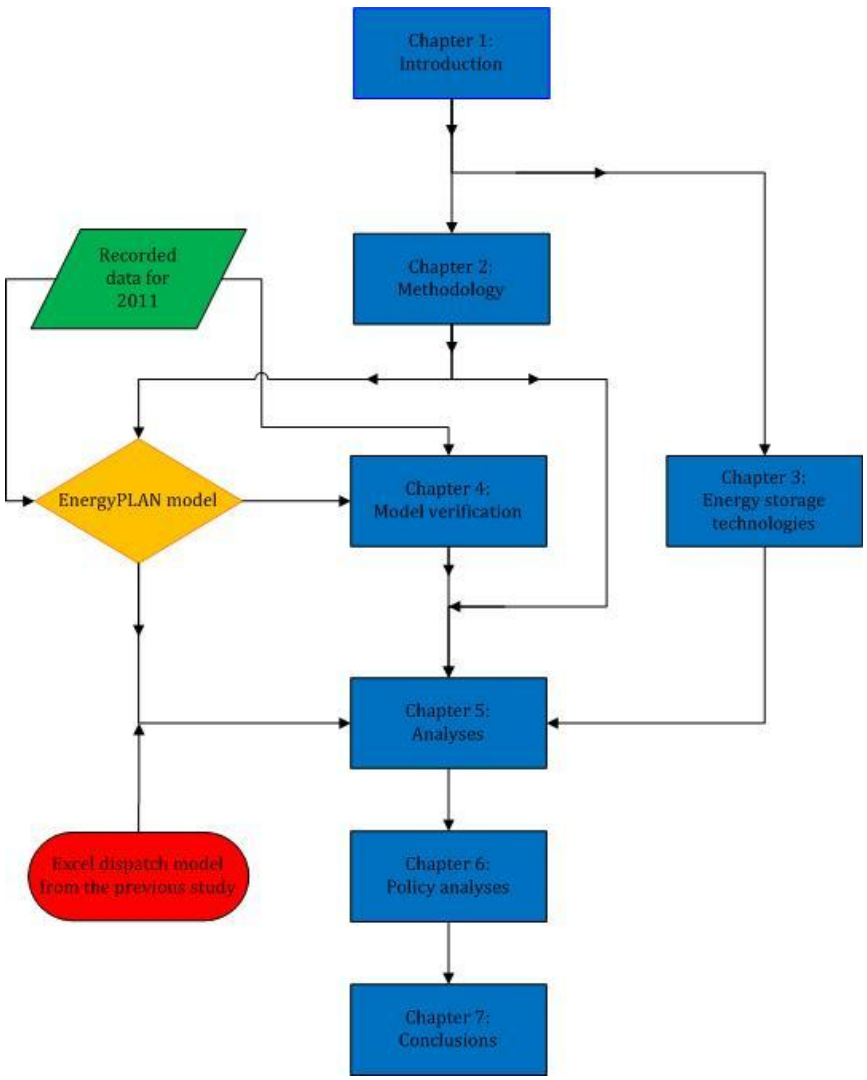


Figure 2.1 – Report structure; Source: Own drawing

2.2 WORK -FLOW

This project could be interpreted as a "follow up" study of a previous recent study by the author, namely "How to efficiently achieve carbon reductions in the Irish power generation system" (Rangelov 2013), which is a point of departure for this report. Since both studies are relevant and moreover part of a whole workflow, it is essential to briefly present the analyses provided in the previous investigation as they are relevant for this study as well. This section elaborates briefly on the main features and analyses provided in (Rangelov 2013), which as remarked as valid for the current paper. Firstly, the drivers for investigating the topic by the author are explained and pre-analysis are shown. Secondly, data gathering and modeling are elaborated. Thirdly, model verification of the build dispatch model is provided. Fourthly, scenario analyses are discussed, together with policy suggestions and sensitivity analyses. The section concludes on the presented study as these conclusions can be pecepted as a point of departure for the current project. It should be noted that only the essence of the mentioned parts of (Rangelov 2013) are presented in this section, for more details, the full report should be consulted by the reader.

2.2.1 PRE-ANALYSIS

The initial inspiration for start working on the topic were two studies, namely (Sharman 2011) and (Udo 2011), which argue that mainly due to ramping of the CCGT power plants because of wind generation fluctuations, the carbon intensity in CO_2/MWh of produced electricity for the whole generation system increases for utilized wind power capacity of above approximately 1,100 MW. This paradox is illustrated in Figure 2.2. The data used in the study was downloaded from the Irish TSO (Eirgrid) for the period from 16th December 2010 until 20th December 2011. The R^2 in the correlation suggests however a poor fit. Next Sharman also suggests that the specific CO_2 emissions from the Irish thermal PPs are increasing steadily with the amount of utilized wind capacity for the same period. It should be noted that this correlation has even poorer fit than in the previous figure. The author further suggests that the CCGT PPs will suffer a shorter lifetime because of extra wearing from ramping, which proved to be not the case in (Rangelov 2013) as it turned to be that these power plants not only ramp on a rate lower than their technical specifications, but actually they are made for ramping and this should not worsen their technical operation.

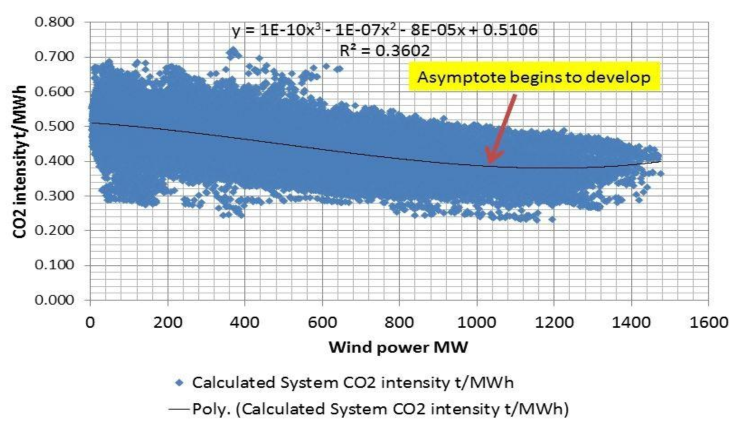


Figure 2.2 – System carbon intensity; Source: (Sharman 2011)

Despite the presented above suggestions, a causal relationship cannot be established only by studying regression curves, but it is needed to model the system in order to explain this paradox. Furthermore, in a preliminary analysis of the same time series by (Eirgrid) it turned that the above suggestions by Sharman are incorrect, because a polynom of fourth an higher orders than the used in (Sharman 2011) third order give opposing results with even higher fit. It was furthermore suggested that the explanation of the shown above paradox of wind power is because of the constantly running peat and coal power plants, which have only seasonal change in their operation, namely they are used more in the winters, but on a 24-hour basis they are operated evenly. This means that when wind generation is high, it replaces mostly natural gas generators. This is suggested also by (Méray 2011), which studies wind power integration on North-Western Europe. Moreover, Möller's suggestion was later validated by two different and mutually independent studies: firstly by (Wheatley 2012) and then by the author of this report in (Rangelov 2013).

2.2.2 *DATA MODELING*

In order to study the suggestions from the previous subsection, it was decided to develop an Excel based dispatch model with the same data series, which were used in the shown regression curves in the previous subsection. Therefore quarter-hourly time series for system demand, wind generation, CO_2 intensity and CO_2 emissions for the whole 2011 were downloaded from (Eirgrid). Unfortunately, Eirgrid did not provide the actual records for operation of all plants for the studied period upon author's request, therefore data regarding the existing capacities of the different power generators in Ireland was gathered from several sources, amongst others: Electricity Supply Board (ESB Ireland 2012), (Eirgrid, SONI 2012) and (Power Plants Around the World). Next, the actual figures for annual fuel inputs for power generation were gathered from the Energy Balance (SEAI - Energy Balance 2012) available at the Energy Statistics Section at Sustainable Energy Authority of Ireland's website (SEAI 2012c). The next subsection elaborates on the model's main assumptions and features.

2.2.3 *MAIN ASSUMPTIONS AND FEATURES OF THE EXCEL BASED DISPATCH MODEL*

To explain shortly, after revising the available data recourse and for simplification, some smaller generators, such as waste-to-energy or biomass, and moreover import/export were neglected. Then all power generators in the dispatch model were divided into two groups: not dispatchable and dispatchable. Both are presented below in Tables 2.1 and 2.2. It should be noted that in fact the coal plant is "partly dispatchable", which means that it has very small variations on 24-hours basis and moreover seasonality, as it is used more in winters, which can be noted from the available monthly energy mix diagrams at (Eirgrid).

Table 2.1: Not dispatchable units; Source: (Rangelov 2013)

	Wind	Peat	Hydro (not dispatchable)	CHP (gas fired)	Coal 1	Coal 2	Coal 3
Net capacity, MW	1,500	346	106	151	283	282	282
Availability, %	-	68%	54%	40%	95%	55%	0%
Ramping rate, % of capacity per minute	-	0.00	0.00	0.00	2.00	2.00	2.00
Efficiency, %	-	37%	-	40%	35%	35%	35%
CO_2 emissions, tCO_2/MWh of fuel; Source:(Carbon Trust 2011)	0.00	0.39	0.00	0.18	0.37	0.37	0.37

Coal 1, Coal 2 and Coal 3 = the three coal units at Money Point coal power plant, as they are not dispatchable in the model;

Table 2.2: Dispatchable units; Source: (Rangelov 2013)

	New CCGT	Old CCGT	Hydro (dispatchable)	Peak GT	HPES	DO	HFO
Net capacity, MW	2,803	622	114	314	292	324	806
Availability, %	71%	40%	76%	20%	0%**	50%	50%
Ramping rate, % of capacity per minute	4.00	4.00	6.67	0.00	6.67	0.00	0.00
Efficiency, %	58%	50%	-	40%	64%	40%	38%
CO_2 emissions, tCO_2/MWh of fuel, Source: (Carbon Trust 2011)	0.18	0.18	0.00	0.18	0.00	0.27	0.28

New CCGT = Combined Cycle Gas Turbine plant commissioned after year 2000;

Old CCGT = Combined Cycle Gas Turbine plant commissioned before year 2000;

Peak GT = Open Cycle Gas Turbine plan used only for peak demands.

In tables 2.1 and 2.2 are shown all modeled power generators in Ireland, which are modeled respectively not dispatchable and dispatchable. The merit order is from left to right, starting with the dispatchable units and hence prioritizing production from left to right standing units. Hydro power is divided into two almost equal parts: not dispatchable run-of-river, and dispatchable dams. It is important to note that the place in the merit order of the HPES is chosen in order the capacity only to shave the peak loads and generate power in the peak demands, but it is only assumption and in reality it is operated through market mechanisms, which are not considered in neither (Rangelov 2013), nor the present study. Hence different placing of the HPES in the merit order will seriously influence the annual production from this unit.

The generated capacity of each not dispatchable unit for every quarter-hour from the modeled period year 2011, excepts for the wind generation where real quarter-hourly time series is used, is calculated by the formula:

$$P_{NET,n} = C_{NET,n} * Availability_n, MW$$

where,

$P_{NET,n}$ – *net generated power by the n – power generator*, MW;

$C_{NET,n}$ – *net capacity of the n – power generator*, MW;

$Availability_n$ – *availability of the n – power generator*, %.

Or in other words, the not dispatchable in the model units operate continuously throughout the year without any variations.

The dispatchable units operate through the following formula:

$$
\begin{aligned}
&If\ D_{n-1} > 0\, and\ D_{n-1} > P_{NET,n}\ then:\\
&P_{NET,n} = C_{NET,n} * Availability_n, MW; unit\ n+1 is\ also\ dispatched;\\
&f\ D_{n-1} > 0\, and\ D_{n-1} < P_{NET,n}\ then:\\
&P_{NET,n} = D_{n-1}, MW; unit\ n\ is\ the\ last\ activated\ power\ generator;\\
&where,\\
&D_{n-1} - residual\ system\ demand, MW;\\
&P_{NET,n} - net\ generated\ power\ by\ the\ n - power\ generator, MW;\\
&C_{NET,n} - net\ capacity\ of\ the\ n - power\ generator, MW;\\
&Availability_n - availability\ of\ the\ n - power\ generator, \%.
\end{aligned}
$$

This means that their production varies according to: the residual system demand, the n-generator's capacity and availability.

It is essential to emphasize, that not dispatchable capacities in the model constrain system's flexibility and hence the more not dispatchable units are being operated, the more constrained is the system's response to increased wind generation and due to this inertia, curtailment of wind power might be necessary in order to keep grid stability. The necessity of maximum flexibility in order to harness fluctuating RES, such as wind power, is documented in several studies, amongst others: (IEA 2011a), (Lixuan, Möller & Lund 2012) , (Østergaard 2011a), (Connolly 2010b), and others.

Furthermore, since time data series were not provided by Eirgrid for all operating generators, and hence the model could not be verified through reproducing correctly the system's operation quarter-hour by quarter-hour for the whole year, the dispatch model was built to reproduce the annual amounts of fuels used for power generation in Ireland and hence annual CO_2 emissions from electricity generation.

The annual amount of fuel burned in each power generator was calculated through the formula bellow:

$$
\begin{aligned}
&G_n = \sum P_{NET,n} / 1000 * Ef_n, GWh\\
&where,\\
&G_n - annual\ amount\ of\ fuel\ used\ in\ the\ n - generator, GWh;\\
&P_{NET,n} - net\ generated\ power\ by\ the\ n - power\ generator, MW;\\
&Ef_n - efficiency\ of\ the\ n - generator, \%.\\
&Note: all\ efficiencies\ are\ shown\ in\ tables\ 2.1\ and\ 2.2
\end{aligned}
$$

Moreover, for the CO_2 emissions calculation is used the following formula:

$$C_m = \sum_1^n P_{NET} / Ef * conv., tCO_2;$$

$$where:$$

$$C_m - system\ CO_2\ emissions\ in\ the\ m - quarter\ hour\ for\ power\ generators\ from\ 1\ to\ n;$$

$$P_{NET} - net\ generated\ power, MW;$$

$$Ef - power\ generator\ efficiency, \%;$$

$$conv. - conversion\ factor, tCO_2\ per\ MWh\ of\ burned\ fuel.$$

$$Note - all\ efficienci\ es\ and\ conversion\ factors\ are\ given\ in\ tables\ 2.1\ and\ 2.2$$

It is also important to mention that partial load operation of the CCGTs was taken into account in the model, which was the main argument of both (Sharman 2011) and (Udo 2011) for higher carbon intensities from power generation with increasing the utilized wind power capacity (see the previous subsection 2.2.2). Figure 2.3 below describes the law according to which the CCGTs in the model operate, meaning that their efficiency decreases with the decreasing of the load. Start-ups of the power plants are not considered in the model.

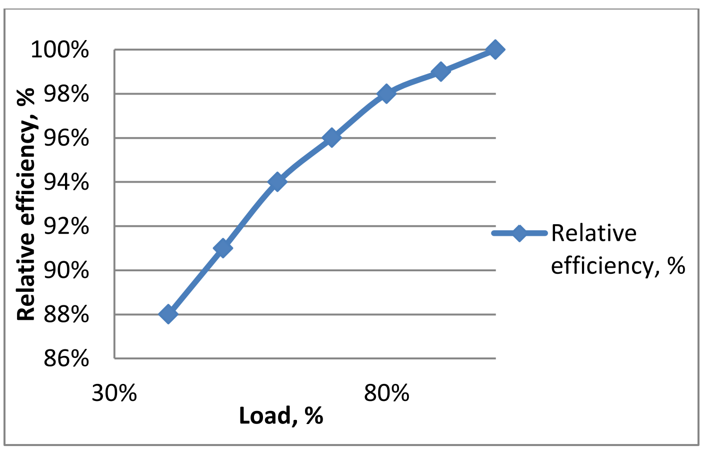


Figure 2.3 – Part load efficiency of Gas Turbine Power Plant. Source: (Tauschitz, Hochfellner)

To summary, with all above mentioned assumptions and uncertainties a Reference model for 2011 was developed representing the operation of the Irish power generation system on quarter hourly basis. Next, the model was tested for accuracy and validated, which is presented in the next subsection.

2.2.4 *VERIFICATION OF THE DISPATCH MODEL*

The first test criteria was the annual amount of fuel used for power generation in the model. Table 2.3 below presents comparison on annual level between the modeled fuel inputs and the recorded ones in (SEAI - Energy Balance 2012).

Table 2.3: Annual fuel mix comparison; Source: (Rangelov 2013)

	Annual fuel balance for power generatio, GWh; Source: (SEAI - Energy Balance 2012)	**Modeled annual fuel balance (energy statistics), GWh; Source: Model**	**Difference, %**
Peat	5,582	5,571	-0.21%
Coal	10,618	10,611	-0.07%
Gas	29,075	29,281	0.71%
Hydro	709	702	-1.02%
Oil products*	640	1,013	58.30%*
Wind**	4,385	4,256 (=Eirgrid)	-2.93%**
Imports	488	neglected	-

* The difference is rather high between the recorded and modeled annual amounts of oil products, however this could be explained by the neglection of imports and hence more oil generators producing power, as they are the last in the merid order (see tables 2.1 and 2.2 from this chapter);

** The difference in wind generation annual figures is expected to come from the fact that the modeled wind out is the same as the downloaded annual from (Eirgrid) and the annual figure here derives from the (SEAI - Energy Balance 2012) and hence possible minor variations in the data bases.

The results in Table 2.3 clearly show that despite minor variations, the Excel base dispatch model with accurately reproduced the annual fuel input for electricity production in Ireland for 2011.

Next, using the carbon factors shown in tables 2.1 and 2.2 for each of the fuels, annual CO_2 emissions comparison between the quarter-hourly CO_2 emissions by (Eirgrid), carbon emissions from the (SEAI - Energy Balance 2012) and the modeled ones. Evidently from the results, the modeled annual carbon emissions from power generation reproduced correctly the recorded ones from two other sources with only minimal deviations.

Moreover, the Reference model was further tested for accuracy on quarter-hourly level in order to check if it is valid also for distribution of the power generation throughout the year. It was proven that there are significant variations between the quarter-hourly extreme values of CO_2 emissions between the records and the model. The model's lowest CO_2 emissions per hour are nearly twice the actual ones. The maximum CO_2 emitted per hour in the Reference model is with more than 26% lower than Eirgrid's maximum. However, on average comparison the error is only 3.6% which is fairly low. Furthermore, the average amount CO_2 per hour is nearly the same in the model as it is in Eirgrid's time series, with an error only within 0.3%. This shows the model's incapability of replicating results on quarter hourly level, due to the lack of actual time series by power generators, as described earlier. It should be noted, that more tests were performed to check the model's performance on quarter-hourly level, which for brevity are not included in this short description, such as CO_2 regression curve, HPES regressions curve, etc, which were compared to actual ones and all proved that the Reference model cannot be used to investigate the power system on hourly level. For more details consult please (Rangelov 2013).

In summary, several validation tests proved that the Excel based dispatch model reproduced accurately the Irish power generation system performance in 2011 on annual and on 24-hours average basis, but incorrect on quarter-hourly level. Hence the model was verified to perform analysis only on annual level and on 24-hours average basis. These are shortly presented in the next subsection.

2.2.5 Scenarios' analyses

This subsection briefly describes the developed scenarios with the quarter-hourly dispatch model. It furthermore presents the results from the performed simulations for different scenarios, as each scenario is based on the Reference model, but upgraded with different assets, which are relevant to the expected system development according to the Irish TSO's prediction and evaluation of the whole system capacity (Eirgrid, SONI 2012). Lastly, the subsection provides sensitivity analyses, which were made in the report, in order to analyze further the development of wind power in the country and possible constraints for achieving efficient carbon reduction through wind power in Ireland. It should be noted that the presented here analyses are very synthesized and show only the essence of the performed study. For detailed information regarding the simulations results and analyses the reader is kindly asked to consult the whole report (Rangelov 2013).

A. Scenarios presentation

Reference Scenario

This scenario represents the Reference model of the Irish power generation system in its operation during the whole year 2011. The Reference Scenario was used to verify the Excel based quarter-hourly model (see the previous section 2.2.4 Model verification)

Scenario 1: Natural Gas

This scenario steps on the Reference Scenario, but all coal, peat and oil power capacities are replaced with new CCGT power plants.

Scenario 2: Natural Gas + Wind

The scenario only differs from Scenario 1: NG with the installed wind power capacity, where this scenario presents the system with 3,500 MW of wind capacity, as according to (Eirgrid, SONI 2012) the wind power levels in Ireland by 2020 should be somewhere between 3,500 and 4,000 MW.

Scenario 3: Natural Gas + Wind + Storage

Again this scenario is almost the same as the previous one, but the only difference is the installed HPES capacity. While in Scenario 2 it is assumed that the HPES capacity remains the same as presently, namely 292 MW, in this scenario it is doubled and is 600 MW.

B. Scenarios simulation results

Below are briefly illustrated the results from the quarter-simulations on annual level for each of the above described scenarios. Firstly, the balance of the power system is discussed, followed by the fuel mix for power generation studies for each scenario. Thirdly, annual CO_2 emissions are simulated and presented in the subsection. Lastly is investigated the quarter hourly ramping of the CCGTs.

Power system balance

The results suggest that the power system as it is in Scenario 1 is most balanced with no higher extremes in peak excess production and shortage of power for each quarter-hour of the year, and overall annual generation is positive. The high wind level scenarios 2 and 3 have both high power deficits in times of low wind speeds and high surplus power at extreme wind speeds. The doubled HPES capacity in Scenario 3 is not sufficient to act as a buffer in the power system for the specific time of the maximum excess power production due to its incompleteness of operation due to uncertainty regarding the HPES place in the merit order of the dispatch model. (Rangelov 2013)

Annual fuel balance

The results reveal that cutting the coal and peat generation and replacement of the capacity with new CCGT would increase the NG consumption with about one third in Scenario 1 compared to the Reference model and with some 18% in Scenarios 2 and 3 and hence import dependency, despite the more than doubled amount of wind power capacity - from 1,500 MW to 3,500 MW for the high wind power scenarios 2 and 3. (Rangelov 2013)

Annual CO_2 emissions

With just abolishing the peat and coal capacities and replacing them with natural gas ones, the CO_2 emissions in the electricity sector would decrease with some 37%. Further carbon reduction with about 15% is realized with building more wind turbines in the high wind scenarios 2 and 3. Because of the uncertainties regarding the place of HPES in the merit order and hence its operation, it remains unclear what amount of CO_2 would be avoided annually if the storage capacity is doubled. Nevertheless it could be anticipated the doubled storage to contribute for system's flexibility and therefore higher RE share, which enables to achieve additional fuel savings and hence further carbon reductions.

Ramping

In order to study the system ramping performance on a quarter-hourly basis, the maximum ramping as a percentage of the capacity for every 15-minutes period of the year. The results show that the maximum ramping rate for quarter-hour has lowest value in Scenario 1, just below 20% and is nearly equal in all other scenarios – about 26%. These results also show that despite the model allows ramping rate of 4% of the capacity per minute, only about 2% are used. The reason for this though is very likely to be that all CCGTs operate as only one unit in the model, but in reality only one or two plants would be set to ramping, as all others would operate rather stable on constant load. (Rangelov 2013)

Sensitivity analyses

In order to study the CO_2 emissions from power generation as a function of installed wind power, sensitivity analysis was performed. As illustrated under this paragraph in Figure 2.4, the dynamic specific carbon reductions were analyzed as a function of installed wind power. Points of departure are the same as in the previous sensitivity study about CO_2 (see above), namely Reference Scenario and Scenario 1: NG. *"The dynamic specific CO_2 reductions are calculated as each of the simulated* *annual amounts of system CO_2 emissions for both scenarios was distracted from the modeled present one in the reference model and then divided by each simulated amount of installed wind power capacity from 1,500 to 4,000 MW with step of 50 MW and hence the dimension is tCO_2 per MW of installed wind power. The results illustrate that if wind turbines capacity increases from the existing one to 4,000 MW with running coal and peat power generators in the Reference Scenario, then the carbon reduction per MW of wind turbines increases and reaches its maximum at about the 2,900th installed MW at some 280 tCO_2/MW and remains at the same levels despite the increasing amount wind power. In contrast, in Scenario 1 without the coal and peat capacities, the maximum specific carbon reductions maximum appears to be at the current installed capacity amounting for some 2,800 tCO_2/MW, which is explained by the sudden disappearing of the largest carbon emitters peat and coal. Then the curve steadily decreases with rather sharp slope, ending with a minimum value of about 1,400 tCO_2/MW at the 4,000th MW of installed wind power."*[1] These results underline how important is to shut coal and peat power generators in Ireland while installing more wind power in order to achieve optimal carbon reductions, because the minimum specific carbon reduction per MW of installed wind turbines of Scenario 1: NG (without peat and coal) is five times the maximum one in the Reference Scenario (with running peat and coal).

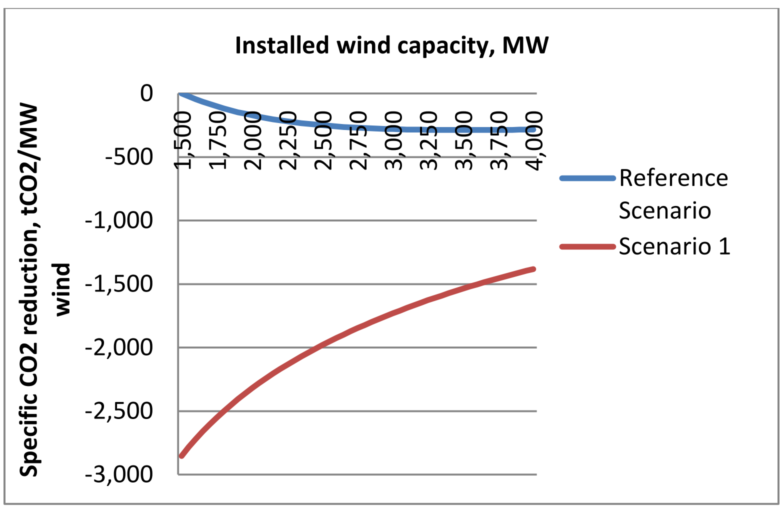


Figure 2.4 – Sensitivity dynamic specific carbon reduction; Source: (Rangelov 2013)

Summary on the analyses

To summarize in a few words, all investigated scenarios in (Rangelov 2013) would satisfy the power demands. However, only by replacing coal and peat power generators with new CCGT, not only the annual CO_2 emissions from power generation would decrease with some 37% for wind power capacity of 1,500 MW and further 42% for wind capacity of 4,000 MW, but also closing the base load peat and coal plants would grant the system greater flexibility, which is necessary for harvesting large scale wind power. Furthermore, the role of storage could not be satisfactory studied through the developed model, due to the uncertainty of its placement in the merit order. Next, ramping of the CCGTs was identified to be in much lower levels than suggested in (Sharman 2011) and moreover the decreased partial load effectiveness operation of the CCGTs due to

[1] p. 52 and 53 from (Rangelov 2013)

ramping has only minor and neglectable effect on the annual CO_2 emissions from electricity generation. Despite the positive environmental and technical effects on the power system from replacing of coal and peat generators, the import dependency on natural gas is increased even for the high wind scenarios with some 18%. (Rangelov 2013)

The study (Rangelov 2013) suggests that if carbon reductions are to be achieved in the most effective manner for the Irish power generation sector, it is not sufficient only to install massively wind turbines, but it is even more important to stop the largest CO_2 emitters, namely peat and coal capacities, which at the same time also constrain optimal wind power utilization because of their low or no variation and hence limits system's flexibility.

Furthermore, the project could not identify the role of energy storage and how can it assist to design a power generation system, which not only effectively decreases the carbon emissions, but does not increase natural gas import dependency. Next, (Rangelov 2013) also points that it is important to study the inclusion of other energy sectors, such as heat, in order to utilize greater amounts of fluctuating RES.

Moreover, the previous study by the author was made through the self-developed dispatch model in Excel, which robustness was proven, but it was also very time consuming to create and also rather difficult to model in energy system in detail in Excel. It was also considered necessary to study the Irish energy system with a proven energy analyzes computer tool, which was developed by experts in the field and was used for other similar studies and proved to be working properly and providing easy access to a number analyses tools, such as different regulation for example. Last but not least, it was also considered necessary to include the heat sector in order to determine possible synergies between the two sectors and implementing large scale wind power, which is the case for amongst other Denmark (Lund, Mathiesen 2008), (Lund 2009).

In order to study the Irish energy system deeper than the previous study and include the above described points, taking into account the results from the analyses in (Rangelov 2013), as well as to answer the research question, which was outline din the previous chapter, it was decided to use energy computer model, which is described in the next subsection.

2.3 The tool used in this project

The main reason to model a national energy system, such as the Irish energy system, is to describe the energy system operation, which is a complicated issue, since energy systems on regional and national level comprise from many different systems and elements, which cooperate in order to maintain the system balance. It is furthermore harder task, as regional and national energy systems are operated by people and are part of our human habitat (Illum 1995).

Furthermore, a crucial element of analyzing the transition towards RE, including system design as it is the case in this project, is to investigate the effects of its implementation on the other elements of the energy system. In order to generate answers of how implementation of RE would change the technical or/and economic aspects of the current or future energy system, energy models are being developed, usually with the help of various energy software tools. (Connolly et al. 2009) The first subsection of this section shortly elaborates on the different available computer tools for energy modeling and discusses which type is considered most appropriate for the present study.

2.3.1 TYPES OF COMPUTER TOOLS FOR ENERGY MODELING

Firstly it should be mentioned, that a recent study, namely (Connolly et al. 2009), reviews the available computer tools for modeling national energy system. The project initially considered a number of 68 energy models, but 37 were finally included in the analyses. The review concludes that there is not a single tool, which addresses all the issues for integration of renewable energy, but rather the choice of using the "ideal" for every case tool depends of what are the main objectives which has to be fulfilled by the concrete study. Several factors, amongst others: energy sectors included, investigated technologies, studied time scale, system complexity, type of analyses, availability, and others, alter enormously the choice of appropriate energy tool. (Connolly et al. 2009)

Generally, seven types of energy tools could be distinguished according to (Connolly et al. 2009), in this number are:

1) Simulation tool
   This tool connect supply to a given energy demand and maintains energy balance, it uses allocation by least fuel demand. Normally this is made on one-hourly resolution for a period of one year;
2) Scenario tool
   This type of tool combines time series into a long term scenario. Typically, the step is one year and scenarios are being developed for periods of 20 to 50 years;
3) Equilibrium tool
   This is an economic tool, which goal is to explain the behavior of supply, demand and prices in general or part of the economy;
4) Top down tool
   This is a macroeconomic tool, using economic data to determine growth in energy prices and demands. Normally these tools are also equilibrium tools;
5) Bottom up tool
   The bottom up tool analyses the specific energy technologies and then detects investment options and alternatives
6) Operation optimization tool
   This tool optimizes the operation of the energy system by means allocation by least fuel demand. These tools are normally also simulation tools;
7) Investment optimization tools, which are typically also scenario tools, optimize the investments in an energy system.

For the case of this study, namely energy system design, a simulation modeling approach is the most appropriate. This is a rather more engineering and concrete approach to study the operation of an energy system on hourly basis than on for instance aggregated annual demand basis. Furthermore, for a national energy system design, the author also believes that the tool should be deterministic, which with certain inputs will always come to the same results, but not stochastic.

Furthermore, to study the energy system more in technical details is necessary and hence the optimization should be based on investigating the given system elements, rather than optimization of the investments. Another important aspect was identified as the tool should be able to provide easily accessible regulation strategies in order to study the optimal regulation of the energy system with increasing RE share. The regulation options are amongst others: technical and market optimization strategies (described further in subsection 2.34); CEEP regulation, such as: reducing RE production, replacing CHP with boiler and el. heating, others; import/export regulation; electric grid stabilization; external el. markets. Next, the tool should also encompass the heat sector, as it was considered in (Rangelov 2013) necessary to study eventual synergies between power and heat sectors and the necessity to study the coherent energy system in order to achieve best results of RE implementation. Last, but not least, the tool for the project should be easily accessible, or in other words could be downloaded for free, because of the purpose of the project, namely Master Thesis.

In order to satisfy the above described description of the necessary tool for analyzing of the Irish energy system in the present report it is chosen to use the EnergyPLAN tool, as below it is elaborated on the motivation to use particularly this model, its structure and main features.

2.3.2 Motivation for using the EnergyPLAN model

In order to determine how the Irish energy system works and to study the technical consequences of large scale RE integration in the system in different scenarios it was required to model the system. The author had already modeled the Irish power system in an Excel quarter-hourly dipatch model, which model is described briefly above and in details in (Rangelov 2013). For the current study it was chosen to use the energy analyzing tool EnergyPLAN for several reasons, amongst others the main ones are:

- EnergyPLAN encompasses all the three sectors on a national energy system: power, heat and transportation. Ireland has still not integrated its energy system and therefore its three sectors are completely segregated (Connolly et al.). However, in order to facilitate the integration of large amounts of fluctuating RE it is crucial to integrate the power, heat and transport sectors (Lund, Mathiesen 2008) as in the present report is studied only the integration of the power and heat sectors due to amongst others project time frame;

EnergyPLAN is a computer model which simulates the energy system on an hourly resolution, which is very important when studying integration of variable renewables, such as wind power (Lixuan, Möller & Lund 2012)

- Another major advantage of the tool is that it can identify the optimum technical as well as economic operation of the energy system. There are many of energy modeling tools that can optimize a system based on costs, but EnergyPLAN can optimize the system performance based on its technical components by means of meeting the demands and maintaining energy balance, therefore the model uses allocation by least fuel demands. In this way the model eliminates the constraints from existing financial infrastructures when analyzing future alternatives. Moreover, EnergyPLAN can model the system according to the costs if necessary, hence it can perform analyzes with or without the existing infrastructures; (Connolly et al.)

- EnergyPLAN eases the users to study a national or regional energy system on amongst others: energy and fuel balances, critical excess electricity production and import/export through different regulation strategies, etc.

Moreover, the EnergyPLAN model had already been used in a number of relevant studies for integration of large scale RE in Ireland, such as: (Connolly 2010a); in Denmark, such as: 100% renewable energy systems in Denmark (IDA2030 plan 2006) and (Lund, Mathiesen 2008); large scale integration of RE in Denmark amongst others: (Lund 2005) and (Lund 2004); in China: (Lixuan, Möller & Lund 2012) and other countries; energy storage, such as: (Blarke, Lund 2007), (Lund, Salgi 2009), (Østergaard 2011a) ; RE strategies for sustainable development: (Lund 2007); district heating and RE in Denmark: (Lund et al. 2009), and other related to this project studies. EnergyPLAN proved to be appropriate and robust tool for all the mentioned studies and therefore it is believed that it also can be applied for the case of Ireland in the present project.

It should be underlined that EnergyPLAN was used in 2009 for modeling the Irish energy system in 2007 in the study (Connolly 2010a). However, the present study and (Connolly 2010a) model the system in essentially different ways. Firstly, in this project it is modeled only the power and heat sectors in 2011, while in (Connolly 2010a) it is modeled the coherent energy system in 2007. Secondly, as explained further below, the major point of this report is to study the effect on the Irish energy system from running base load of coal and peat power plants and therefore they were modeled in the EnergyPLAN tab "nuclear power" with their original distribution for 2009 separately from the other power plants. In contrast (Connolly 2010a) models all power generators as one power whole power plant, which does not allow comprehensive investigation of the effects of semi dispatchable PPs such as coal and peat in Ireland on the increasing wind power capacity and aims for carbon reductions (Rangelov 2013).

To summary, because of EnergyPLAN's complexity and versatility, wide variety of technologies included, studied time period, different analyses enhancement, maturity and reliability, availability (the tool is free to download from (Lund)), the tool was chosen to be used in the present study.

2.3.3 Overall structure of EnergyPLAN

EnergyPLAN is a deterministic input/output model. General inputs are demands, power station capacities, RE sources, costs and a number or optional regulation strategies, which emphasize import/export and CEEP. The outputs are energy balances, including annual energy production, import/export, CEEP, fuel consumption, carbon emissions, cost balance, RE share. (Lund). The model simulates hourly system operation over a period of one year. EnergyPLAN's structure is illustrated below in Figure 2.5.

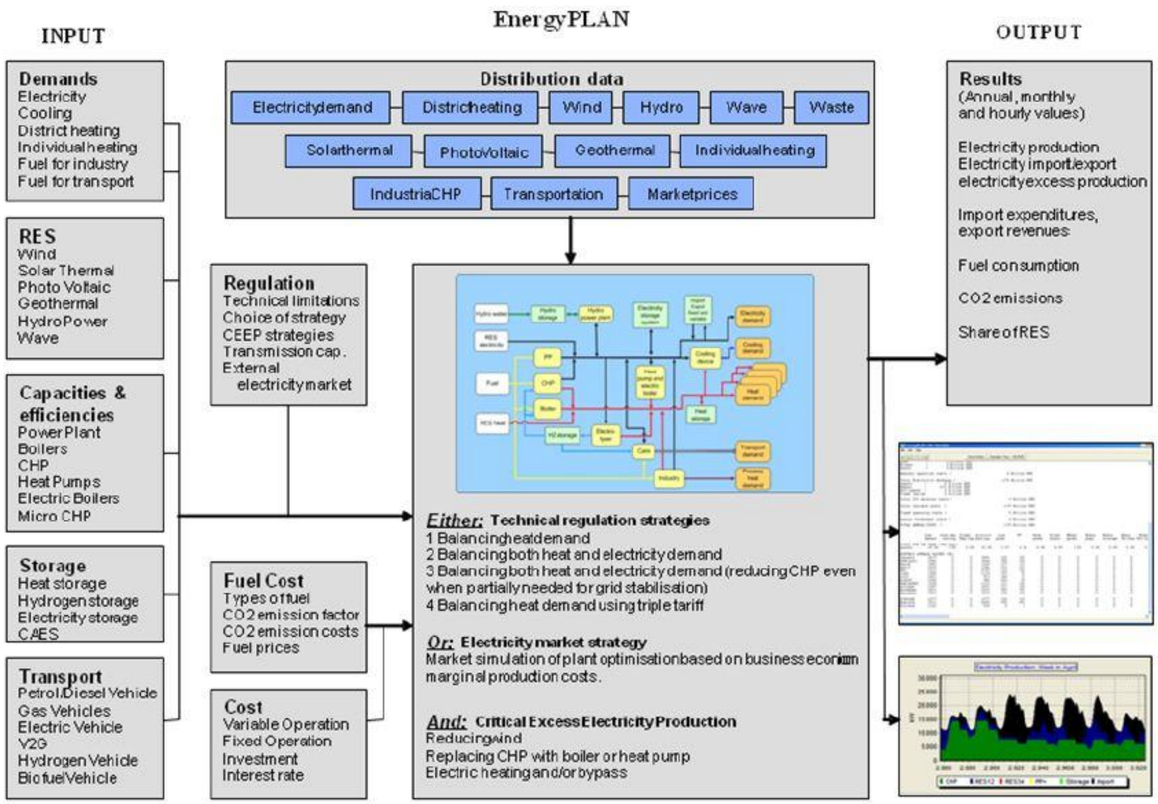


Figure 2.5 – Structure of EnergyPLAN; Source: (Lund 2009)

Furthermore, the model requires annual hourly distributions for all inputs in order to simulate accurately the operation of the energy system throughout the year. Each distribution file should consist of 8,784 data points, corresponding to one for each hour of the year presuming that the year is leap as the hours in a normal year are 8,760. Normally the data point value is between 0 and 1, which represents the demand or production from 0% to 100%[2]. However, if a value higher than 1 is given, the model will index it. This is done by dividing each value in the distribution by the maximum value, which means that historical data can be used. (Connolly 2009) In other words, it means scaling of the distribution and hence scaling of the output. For instance, if a 100 MW wind turbine plant has an annual production of, say 400 GWh, using a certain distribution, then if the wind park capacity is 200 MW (doubled), its production will be also doubled – 800 GWh if the same distribution is being used. This rule applies also to the demands.

Nevertheless, scaling the power production according to increase in the wind power capacity is not fully accurate. If it is presumed that the sites with best wind conditions are occupied firstly, then after a certain installed capacity, especially as it is the case with Ireland to double the installed capacity in the next seven years, every next wind park would have worsened capacity credit. In other words, increasing the wind penetration, the capacity credit is very likely to reduce. However, with improvements of the wind turbine technology, as for instance using higher wind turbines, this is not always the case. This is suggested also from the study (DENA 2005) in Figure 2.6 below,

[2] This is not valid for the price distributions in EnergyPLAN, where real figures are being used.

where is illustrated the effect on wind turbine capacity credit from expected technology improvements.

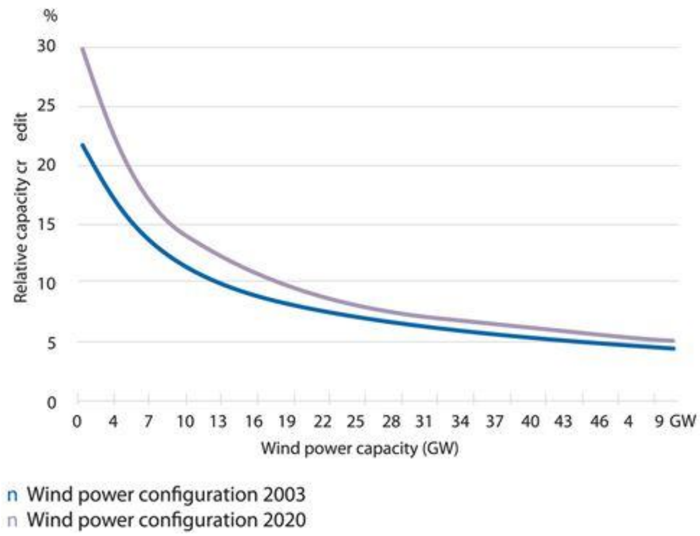


Figure 2.6 – Installed wind power and capacity credit in Germany; Source: (DENA 2005)

To summarize, in this subsection it was very broadly described the overall structure of the EnergyPLAN model tool. For detailed information, the reader can see website (Lund) and the currently latest documentation version 10.1 (Lund 2012).

2.3.4 ENERGYPLAN DEVELOPMENT AND PURPOSE

The model has been continuously used and improved since 1999, when it was developed by Henrik Lund, professor at Aalborg University, Denmark, (Lund 2012) in an Excel spreadsheet. Due to growing too large file, the model was re-programmed twice as it is programmed in Delphi Pascal presently. (Lund 2012) It uses analytical programming, but not iterations and hence calculations are performed very quickly – it requires only a few seconds on a normal computer, even for a very detailed and complicated national energy systems (Lund).

Next, the main purpose of EnergyPLAN is to help to design national/local energy planning strategies based on technical and economic analyses for the investigated system development scenarios. (Lund), (Lund 2012) The tool can be used for several applications:

- <u>Technical analysis</u>
  Design and analysis of a complex national/regional energy system under several regulation strategies. This analysis strives to optimize system's fuel use. The input consists of description of energy demands, production capacities, efficiencies and fuel types. Outputs are energy balances, fuel consumption and CO_2 emissions;
- <u>Market exchange analysis</u>
  In this case the model analyzes the trade and exchange on international electricity markets, constrained by the system's interconnection capacities. Hence additionally input is required, such as different prices and taxes, in order to determine the marginal market

prices reaction to changes in the import/export. This regulation is based on the fundamental assumption that power plants operates according to business-economic profits;

- Feasibility studies
  Here the model calculates the feasibility of the analyzed energy system in terms of annual expenditures under different regulations. Therefore more additional inputs are required, such as investments and fixed O&M costs, together with the lifetime of the facilities and interest rate.

To conclude this subsection, EnergyPLAN eases the user to design and analyze a national/regional energy system by the means of several different types of analyses and regulation strategies described above. These are used to analyze the Irish energy system in this study.

2.4 The Reference models' main assumptions

In order to study the technical and economic consequences of the Irish energy system according to the Government's and EU's policies, which amongst others is the main objective of this report, a Reference model was developed using the EnergyPLAN model, which represents the heat and electricity sectors operation according to the current plans and objectives. Since year 2020 is a cornerstone for the European renewable energy development (see Chapter 1), and moreover there are concrete objectives on both national and EU level, it was chosen to create a Reference model for the year 2020, which in this report is referred as Reference model 2020, and is compared to alternative system designs and regulation in order to optimize the energy system design.

In order to assure that a built model is working correctly, the so called Reference 0 model was developed for year in the past. Since 2011 was the latest year for which there was accessible online data, it was chosen to test the Reference model for validness. The results were compared to the recorded ones from the Energy Balance (SEAI - Energy Balance 2012) as well as data from Eirgrid (Eirgrid). The model verification is thoroughly explained in Chapter 4: Model verification further in this report.

Once the Reference 0 model for year 2011 was verified, the Reference model 2020 was developed, which represents how the Irish energy system could be expected to operate in 2020 according to the Irish Governments current policies and targets. This subsection of Chapter 2 elaborates on how the Reference 0 model was developed and hence the Reference model 2020, which amongst others includes data gathering, main assumptions and model operation.

2.4.1 Technical data used

As mentioned above here it is described the data gathering process for the Reference 0 model and furthermore for the Reference 2020 model, beginning with the technical data. Several technical inputs in EnergyPLAN are required, amongst others: power demands, power plants capacities and efficiencies, renewable energy production, individual heat demands, industrial heat and power demands, carbon emission factors, hourly distributions, and others. Below is briefly elaborated how all used inputs were gathered, their sources and main assumptions.

A. The Reference 0 model

1) Electricity demand 2011

To simulate the electricity demand, EnergyPLAN requires as input both the annual electricity system demand and the hourly distribution. Firstly, the total electricity demand was obtained from the Irish TSO (Eirgrid) and was set at 25.875 TWh/year. Secondly, the hourly distribution was also needed with 8,784 data points, however from Eigrid it is only available quarter-hourly distributions which means that there are 34,041 data points. Therefore a macro function in Excel was developed in order to create average values for each whole hour, which derive from each former four quarter-hours. This is illustrated below in Figure 2.7.

SUM =AVERAGE(B6:B9)

	A	B	C	D
1	Time	Quarter-hourly System Demand, MW	Hourly System Demand, MW	Time
2	1/1/2011 0:00	3,167.0		
3	1/1/2011 0:15	3,141.0		
4	1/1/2011 0:30	3,091.0		
5	1/1/2011 0:45	3,043.0	3,110.5	1/1/2011 0:00
6	1/1/2011 1:00	2,970.0		
7	1/1/2011 1:15	2,903.0		
8	1/1/2011 1:30	2,840.0		
9	1/1/2011 1:45	2	=AVERAGE(B6:B9)	
10	1/1/2011 2:00	2,723.0		
11	1/1/2011 2:15	2,672.0		
12	1/1/2011 2:30	2,619.0		
13	1/1/2011 2:45	2,563.0	2,644.3	1/1/2011 2:00
14	1/1/2011 3:00	2,518.0		
15	1/1/2011 3:15	2,459.0		
16	1/1/2011 3:30	2,429.0		
17	1/1/2011 3:45	2,399.0	2,451.3	1/1/2011 3:00
18	1/1/2011 4:00	2,365.0		
19	1/1/2011 4:15	2,323.0		
20	1/1/2011 4:30	2,300.0		
21	1/1/2011 4:45	2,269.0	2,314.3	1/1/2011 4:00
22	1/1/2011 5:00	2,243.0		

Figure 2.7 – Quarter-hourly and hourly el. demand distribution; Source: (Eirgrid)

2) Power generation 2011

Firstly (1), it is important to note that despite the fact that cogeneration of heat and power plants (CHP) and district heating are key elements in EnergyPLAN. However, up to date there are not any district heating systems in Ireland (Connolly 2009). Moreover, the operational cumulative capacity of all CHP plants in 2011 is 284 MW (SEAI 2012a), as about 150 MW from them are industrial (Eirgrid, SONI 2012) and the rest are in the public and commercial sector. Most CHP plants run on natural gas as there are a few small ones on biomass.

Secondly (2), as discussed in the previous section of this chapter and moreover in details in (Rangelov 2013), the power generation in Ireland is partly based on coal and peat power plants, which are ran as base load with almost no variations on 24-hour basis and with small variations in the seasons. Next, the flexible element of the system is the CCGTs fleet ran on NG, which are the dominant power source currently. However, EnergyPLAN simulates all power plants as one big power plant with same distribution, which is not the case here. Moreover, the programme does not provide tab for the peat. Therefore, peat and coal was modeled as one fuel – coal, as the proportion is: coal~61% and peat ~39%.

Furthermore, it is essential for this study to simulate properly the different operation profile of coal&peat and CCGTs altogether with the CHP units which are not dispatchable. In order to solve the problems described in (1) and (2), the following steps were taken:

a) CHP in group 3 in EnergyPLAN (large scale CHP extraction plants) was modeled the 284 MW of operational CHP (SEAI 2012a). Distribution for operation of all CHPs is not available, due to the very different character of their operation in the time, but they were rather modeled as constant operation in such a way that their annual production is equal to the one from (SEAI - Energy Balance 2012);

b) All natural gas, biomass and oil conventional power generators were modeled as one plant in the same group 3 of CHP, but utilized in 100% condensing mode, hence operating as a conventional power plant. The overall condensing capacity of these generators amounts to 4,600 MW (Eirgrid, SONI 2012). The annual fuel inputs in EnergyPLAN were taken from (SEAI - Energy Balance 2012);

c) The coal and peat generators were modeled in the EnergyPLAN tab for nuclear power in order to differentiate from the other generators. Their overall net capacity is 1,193 MW (coal=847 MW and peat=346 MW) (Eirgrid, SONI 2012). The distribution for both fuels was taken from half-hourly time series for the year 2009 from the Irish TSO (Eirgrid) and converted to one-hourly values with the help of almost identical macro as the one described earlier in this section (see subsection 2.4.1 A of this chapter). Then the distribution was averaged for both fuels proportional to their annual fuel shares, respectively coal~61% and peat ~39%.

Next, all efficiencies of the different power generators are needed input for EnergyPLAN. These are presented below in Table 2.4:

Table 2.4 Electrical efficiencies power generators, %	
Coal/Peat*	33%
Natural gas**	54%
NG based CHP***	35%

* Coal and Peat generators are modeled as a single fuel in EnergyPLAN;
** In the efficiency for CCGTs is also biomass and oil generators efficiency, but due to their insignificant quantity in the energy mix they are neglected;
*** Includes only the electrical efficiency for the cogeneration of heat and power.

All efficiencies were calculated from (SEAI - Energy Balance 2012) and then compared to the ones already used in modeling the Irish energy system in (Connolly 2009) and in (Rangelov 2013). The first crucial point is that generation from coal/peat was modeled as nuclear power, as outlined above, using the time series for 2009. Therefore in order to reproduce the annual fuels in 2011 the efficiency was adjusted to 33%, which is actually the efficiency of a nuclear power plant (EIA 2013). From the Energy Balance for 2011, their efficiencies of coal and peat are respectively 40% and 41%. The second crucial point is the efficiency of CCGTs. From (SEAI - Energy Balance 2012) they showed to be about 52%. However, 54% was used in EnergyPLAN in order to reproduce the actual annual fuel inputs. It should be underlined that a single new CCGT has efficiency of about 59% (PEI 2010). Hence 54% is clearly a high efficiency for annual performance of all CCGTs in Ireland. Assuming that all input data for the model is correct, which is further validated in Chapter 4: Model verification, a possible reason for the need of too high efficiency of CCGTs might be that only the newest CCGTs were used to cover the demand in 2011, which is logical as they have highest efficiencies and hence lowest marginal costs and moreover given that there is overcapacity installed, this seems logical. Lastly, the electrical efficiency of a NG based cogeneration of heat and power plant was acquired from (Østergaard 2011b) and is 35%.

3) Renewable energy 2011

Three parameters are needed as RE inputs in EnergyPLAN, namely: type of renewable energy system in question, installed capacity and annual hourly distribution.

a) Onshore wind

According to (EWEA 2011) by the end of 2010 there were 1,392 MW and by the end of 2011 1,631 MW of installed wind power in Ireland. Therefore it was decided to specify the overall installed wind capacity throughout the year of 1,500 MW, of which 1,474.8 MW onshore and 25.2 MW (NOW Ireland) offshore wind power. The distribution for 2011 was obtained from (Eirgrid) on a quarter-hourly resolution, as with the help of macro in Excel (see point 1) from this subsection) was converted into hourly values.

b) Offshore wind

The installed amount of offshore wind power capacity is 25.5 MW (NOW Ireland). For distribution was used the same distribution as with onshore wind and also the correction factor in EnergyPLAN was used for adjustment to the actual production. The reason for using the same distribution is that it gives a good description of the moving of air masses over the island of Ireland. It should be however noted, that in reality the offshore distribution could be expected to be more even with smaller variations in the wind speeds than onshore wind, which is though not accounted in the model. As a result it could be expected that for scenarios with higher offshore wind power capacities, the simulations show higher production peaks and lower levels than would be in reality.

For Ireland it is estimated that the average capacity factor for an offshore wind park is some 40%, which corresponds to 0.88 TWh/year. (Connolly 2009) In order to achieve this annual production the correction factor in EnergyPLAN was used.

c) Hydro power

Two types of hydro power are specified in EnergyPLAN. The first one is “River Hydro” which is run-of-river and the produced energy must be used as water is supplied, and “Hydro Power” where the water is stored in dams and dispatched when most appropriate. The installed hydro power capacity was obtained from (ESB Ireland 2012) and amounts to 216 MW, where it is divided by almost equal parts of run-of-river hydro and dams. However, due to uncertainties in the “Hydro Power” distribution, all hydro power was simulated in this study as run-of-river, and hence not dispatchable, with even production throughout the year amounting to 0.71

TWh/year. Nevertheless, the author acknowledges that for future studies the hydro power should be examined separately in order to optimize the dispatch.

4) Energy Storage 2011

The only large scale energy storage facility in Ireland is the HPES at Turlough Hill (ESB Ireland 2012). Despite it was under reconstruction during the whole 2011, it was included in the Reference model, because it is further needed for exploring the other scenarios. The needed parameters were acquired from (Connolly 2009) and are as follows: pump capacity is 272.8 MW; turbine capacity 292 MW; round trip efficiency 63.9%; storage capacity 1,752 MWh.

5) Individual heating 2011

Here needs to be specified the energy for residential and commercial sectors, as only heat needs to be accounted because electricity is already included at the electricity demand. The required inputs for EnergyPLAN are: total annual fuel consumption by type for heating, boiler efficiencies for every type of fuel, hourly heat distribution for 2011.

The total fuel consumption for heating in the commercial and residential sectors were acquired from (SEAI - Energy Balance 2012) and for the boiler efficiencies were taken from the Building Energy Rating published by (SEAI-DEAP 2013). Both are provided below in Table 2.7.

Table 2.7 Individual heat consumption and boiler efficiencies

Fuel	Total individual consumption (residential + commercial), TWh/year	Thermal efficiency boiler, %
Coal/Peat	5.501	60%
Oil	7.129	75%
Natural gas	10.862	89%
Biomass	0.454	65%

Furthermore, there are no records of what part of the electricity is used for heating. However in (SEI 2008) it was suggested that some 14% of residential electricity is used for space heating and more 23% is used for domestic hot water (DHW). Next, it was also found that in the report (Cumarsaide, Nadurtha 2006) about 12% electricity in the commercial sector in Ireland is used for heating. Since the total individual consumption is a sum of the residential and commercial sectors heating and hence available from the (SEAI - Energy Balance 2012), they are respectively 8.281 TWh and 6.513 TWh in 2011. Hence it was calculated: 0.37*8.281 + 0.12* 6.513 = 3.84 TWh of electricity were used for heating in the individual consumption in Ireland in 2011.

Finally, hourly heat distribution was acquired from a previously developed model of the Irish energy system for 2007, namely (Connolly 2009). It assumes amongst others, that DHW is used constantly throughout the year and space heating is not needed in the summer months.

6) Solar thermal 2011

Three EnergyPLAN inputs were required to simulate the solar thermal energy in 2011: annual solar thermal production, hourly distribution and a solar thermal share. The first one was obtained from (SEAI - Energy Balance 2012) and amounted to 0.02 TWh/year. Next, for annual distribution was used a constructed curve output curve for Denmark from the study (Lund, Mathiesen 2008). The same curve was used before to describe solar thermal hourly distribution in Ireland in the study (Connolly 2009), namely because of the very similar climate and average annual amount of sun radiation in both the countries: 989 kWh/m^2 for Ireland, and 976 kWh/m^2 in Denmark (Connolly 2009). The used distribution provides production from a 4.4 m^2 solar thermal panels installation during a typical year in Denmark. It is based on a consumption of DHW heated from 10^{o}C to 55^{o}C and amounts to consumption of 150 litres per day. Lastly, the solar thermal share was needed, which represents the percentage of dwellings in Ireland, which have a solar thermal installation. In order to estimate this, firstly the installed solar thermal panels area was acquired from (Connolly 2009), which amounted to some 33,600 m^2 in 2007. The same source suggested that a typical domestic solar thermal installation in Ireland is 5 m^2. Hence, it was calculated 33,600/5 = 6,720 homes have a solar thermal system. Secondly, from the housing section at (CENSUS 2012) it was obtained that all homes in Ireland in 2011 amounted to 1,654,208. Therefore it was calculated that 6,720/1,654,208 *100% = 0.41% of all homes in Ireland have a solar thermal installation.

7) Industry 2011

Next, in order to simulate energy use in the Industrial sector, several parameters are required for EnergyPLAN, which are: annual fuel consumption for each fuel, industrial CHP electricity and heat production, hourly distribution. The first one, fuel consumption is showed below in Table 2.8.

Table 2.8 Annual fuel consumption industry; Source: (SEAI - Energy Balance 2012)

Fuel	**Industrial consumption, TWh/year**
Coal/Peat	1.105
Oil	4.885
Natural gas	7.257
Biomass	1.675

Furthermore, the annual electrical output in 2011 by industrial CHP was 2.01 TWh. No heat is being exported to district heating networks from CHPs in Ireland, so this tab was left blank. Lastly, no distribution data is available for industrial, so it was modeled as a constant load throughout the year, resulting in the annual exported to the grid production.

8) Import/export 2011

EnergyPLAN simulates the amount of imported/exported electricity. Two paramteres were needed: the annual amount of import/export and its distribution. From (SEAI - Energy Balance 2012) it was obtained that Ireland imported 0.488 TWh of electricity from its only interconnection at the time with Northern Ireland. This input has a minus sign, as respectively export has plus. For hourly distribution it was used the one from 2007, which was collected from (Connolly 2009).

9) Interconnection capacity 2011

The existing in 2011 interconnection capacity of Ireland with Northern Ireland was 1,440 MW. However, after revision of 2006 and 2007 data time series for electricity trade, it was clear that import/export capacity never exceeded 220 MW. Therefore in the Reference 0 model the import/export capacity was set at 220 MW.

10) CO_2 emissions factors

EnergyPLAN requires carbon emissions factors for three fuels, namely: coal, natural gas and oil. However, in this paper coal and oil amount for a group of fuels, but not a single one. The fuel coal in EnergyPLAN represents coal and peat products, while oil accounts for heavy fuel oil (HFO) and distillate oil (DO). Therefore, based on the annual shares of single fuels in each of the fuels groups, available from (SEAI - Energy Balance 2012), and moreover on carbon emissions factors for each single fuel available from (SEAI 2012b), overall CO_2 emissions factors for each group of fuels were chosen and are presented in Table 2.9 below.

Table 2.9 CO_2 emissions factors for EnergyPLAN; Source: (Connolly 2009)

Fuel	CO_2 emissions factors, kg/GJ
Coal/Peat	100.63
Natural gas	57.1
Oil products	73.2

B. The Reference 2020 model

The Reference 2020 model "steps" on the same assumptions as the Reference 0 model, but is further developed with projections data for the Irish energy system in year 2020. It is important to note that the projections taken into account are the ones, which are expected to happen if the current key energy policies remain the same as in 2010 (see Chapter 1). The forecasts for the Irish energy system in this are based on (Clancy, Scheer 2011) and (Eirgrid, SONI 2012).

Since all the steps for technical data handling in EnergyPLAN remain the same as in the Reference 0 model in the previous subsection, here they only refer to the already described ones as it is also elaborated on each assumption for system modification up to year 2020.

1) Electricity demand 2020

According to a median electricity demand growth by year 2020 according to (Eirgrid, SONI 2012), the electricity demand in Ireland is expected to grow with some 6.9% from 2011 to 2020, which results in expected annual electricity demand of 27.657 TWh/year. It was used the same hourly distribution as the demand for 2011 (see the previous subsection).

It is important to mention that in October 2012 the EU adopted the new Directive 2012/27/EU on energy efficiency (European Commission 2012), which amongst others provides measures for a common framework across the EU members for increasing the energy efficiency in order to achieve the 2020 targets. It moreover contributes to establishing individual indicative energy efficiency (EE) targets for year 2020. This could be interpreted that each member state, including Ireland, will have to revise its EE goals and make certain improvements in order to reduce the demands through EE measures. However, despite the fact that these targets are mandatory, this paper does not take into account any response to this EU directive on Ireland, such as expected electricity savings, because of lack of data and discussion, which is result of the relatively short period between issuing the EU directive and performing the present study.

2) Power generation 2020

Most of the elements of the power generation system in 2020 remain as they were in 2011, such as main power generation dispatchable capacities, efficiencies, partly dispatchability of peat and coal operators and their capacity, hourly distributions, etc., which were explained in the previous subsection. Here are mentioned only the differences.

Firstly, the operating CHP capacity is expected to rise to 800 MW_e (SEAI 2012a). Secondly, all oil generators are decommissioned by 2016. Thirdly, a few Gas Turbine power plants are replaced with new CCGTs, but the overall capacity of CCGTs and GTs is lower than in 2011, amounting to some 3,807 MW (Eirgrid, SONI 2012) with almost 800 MW, because of some of the old open cycle gas turbines are decommissioned.

3) Renewable energy 2020

Firstly, the Hydro power remains the same as it was in 2011. Secondly, onshore wind power capacity is grown to 3,593 MW in 2020 (Eirgrid, SONI 2012) from 1,475 MW in 2011. Thirdly, offshore wind power has also a significant growth from 25 MW in 2011 to some 325 MW in 2020 Q. The hourly distributions for both offshore and onshore wind power remain the same. Fourthly, 75 MW of installed tidal/wave power is also predicted to be installed by 2020, as it is not specified what is the share of each system (Eirgrid, SONI 2012). It should be mentioned that up to date there is not a commercial wave power system available. Therefore it was assumed that all 75 MW will be tidal power as hourly distribution was taken from (Connolly 2009).

4) Energy storage 2020

Currently there are not plans for installing new large scale energy storage facilities, and therefore it is assumed that the only one of this type presently, namely the HPES at Turlough Hill, is the only energy storage in the Reference 2020 model.

5) Individual heating 2020

The forecasted individual consumption is taken from the Base 2020 Scenario from the study (Clancy, Scheer 2011) and are presented below in Table 2.10. They are furthermore compared to the ones in 2011. All boiler efficiencies remain the same, but it could be expected the new EU Directive on EE (European Commission 2012) to require improvement in boiler efficiencies.

Table 2.10 Individual heat consumption and boiler efficiencies 2011 and 2020; Sources: (SEAI - Energy Balance 2012), (Clancy, Scheer 2011)			
Fuel	**Total individual consumption 2011, TWh/year**	**Total individual consumption 2020, TWh/year**	**Δ, %**
Coal/Peat	5.501	2.5	-54.55%
Oil	7.129	6.15	-13.73%
Natural gas	10.862	15.863	46.04%
Biomass	0.454	0.673	48.24%

The forecasts suggest a clear decrease of using of coal and peat in the individual sector, which is falling with more than half. There is also a decline in using of oil products with almost 14%. Nevertheless, almost 50% increase in the NG and biomass consumption is forecasted, where the former has the highest share of all fuels used in individual installations, namely some 63%. A possible explanation is that despite NG's higher price compared to coal and peat, it is a much easier fuel to handle a heating system and to maintain appropriate temperatures of the indoor environment, as it is very often almost fully automatic and there is nearly no need the owner of the installation to maintain it manually. This is not the case with coal and peat burners, which have to be loaded, unloaded and the burner must be cleaned on a daily basis. Moreover that with a natural gas burner, there is no need for seasonal or monthly storage, as one is a must for coal and peat. Last, but not least NG installations do not sully the room where the boiler is, which is the case with coal, for example.

6) Solar thermal 2020

It is assumed that production from solar thermal installations remain the same as in 2011, as there are currently not any incentives to establish new installations, which is also the case with the other type of solar cells – PVs. A possible explanation is that because of the Irish not particularly sunny climate, the RE from sun is currently out of the Governments objectives.

7) Industry 2020

From the energy forecasts for Ireland up to 2020 (Clancy, Scheer 2011) were taken the anticipated annual fuel consumption in industry for 2020. It is presented below in Table 2.11, together with the ones from 2011 and both are compared in percentage.

Table 2.11 Annual fuel consumption industry in 2011 and 2020; Source: (SEAI - Energy Balance 2012), (Clancy, Scheer 2011)			
Fuel	**Industrial consumption 2011, TWh/year**	**Industrial consumption 2020, TWh/year**	**Δ, %**
Coal/Peat	1.105	1.082	-2.08%
Oil	4.885	4.11	-15.86%
Natural gas	7.257	6.536	-9.94%
Biomass	1.675	3.646	117.67%

The figures suggest that coal and peat consumption remains more or less the same in 2020 as it was in 2011. They furthermore anticipate a rather small decline in oil and NG consumption with respectively some 16% and 10%. Lastly, biomass consumption is however more than doubled in 2020, namely with almost 118% more than what it was in 2011. This probably is coming as a result from the incentive for thermal RE in the services sector (ReHeat) in Ireland (see Chapter 1).

8) Import/Export 2020

According to (Clancy, Scheer 2011), because of the significant wind penetration in Ireland up to year 2020 the marginal price of electricity production is expected to be very low and therefore the export is expected to increase. The forecasts are for about 1 TWh/annual export and this number is set in the model as for hourly distribution is used the same as in the Reference 0 model reproducing 2011.

9) Interconnection capacity 2020

Since 21st of December 2012 the East-West interconnector between Ireland and Britain is already operating commercially with a capacity of 500 MW (Eirgrid 2012), which should be added to the previously existing capacity with Northern Ireland as well as Scotland of 1,440 MW in 2011. According to (Eirgrid, SONI 2012) a further expansion of the interconnections to the UK up to 2020 with a capacity of 440 MW is under planning. Because of all the new interconnectors, which will operate commercially and the above described projections for low marginal electricity price and moreover in times of higher excess production from wind, it could be expected that the interconnection capacities will be utilized more than they were in 2011. On the other hand, if the total interconnection capacity of some 2,400 MW is set as input into EnergyPLAN the capacity set in EnergyPLAN, then the interconnectors would be utilized all the time through the year, which would not lead to accurate results, because the distribution time series are based on 2009 (as discussed in the delimitations in Chapter 1). Therefore the overall interconnection capacity in the model is set to 900 MW.

2.4.2 COSTS DATA USED

This subsection describes the main cost assumptions used in the Reference 0 and Reference 2020 models, respectively for years 2011 and 2020. It is important to note that all costs are forecasts for year 2020 made in 2011.

Moreover, it should be noted that the costs in this study are socio-economic. This means that they include externalities, such as CO_2 pollution.

EnergyPLAN simulated the energy related costs in four main categories, namely:

- Fuel costs:
  This includes fuel purchasing, processing and taxes, including related CO_2 costs;
- Investments:
  Includes money required, units lifetime and payment interest rates;
- Operational costs:
  This input accounts for fixed and variable O&M costs;
- Additional costs

Accounts for any costs, which are not included in EnergyPLAN so far, for instance installing preinsulated district heating (DH) pipes for establishing a DH system.

1) Fuel costs

The costs for purchase of fuels for years 2011 and 2020 suggested by (IEA 2011b) and (DEA, Energinet.dk 2012) and are presented below in Table 2.12.

Table 2.12 Fuel prices in years 2011 and 2020; Sources: (IEA 2011b), (DEA, Energinet.dk 2012)						
€/GJ	**Crude oil ($/bbl)**	**Crude oil**	**Fuel oil**	**Coal**	**Natural Gas**	**Biomass**
2011	98	11.94	8.36	2.54	5.65	6.3
2020	118	14.38	10.06	3.03	8.29	7.45

Furthermore, concerning the CO_2 costs in EnergyPLAN, it became clear that currently there are not any carbon taxes for power generation, but all power generators above 23 MW participate in the European Union Emissions Trading Scheme (EU ETS). From (Neuhoff, Schopp 2012) it was obtained that the price for a tonne of CO_2 in 2011 was about €8. Next, from (IEA 2011b) was suggested that in 2020 the tonne of CO_2 will cost €30. These two numbers were then used in EnergyPLAN for the respective years.

It is crucial to be noted that because of the way of modeling the coal and peat power plants, namely as nuclear power, for reasons explained thoroughly in subsection A. 2) from section 2.4.1 of this chapter, the calculation of marginal production price does not include most of the carbon emissions from power generation, because coal and peat are not consider carbon polluters in the present model, but in reality they are the largest and most intensive CO_2 emitters. Because of this shortcoming of the model, the negative socio-economic effect from peat and coal power plants could be expected to be seriously underestimated in the analyses of this study.

Lastly, fuel handling costs were acquired from (DEA, Energinet.dk 2012) and are presented in Table 2.13 below.

Table 2.13 Fuel handling costs; Source: (DEA, Energinet.dk 2012)				
€/GJ	**Fuel Oil**	**Coal/Peat**	**Natural gas**	**Biomass**
Central Power Stations	0.228	0.067	0.428	1.16
Distributed CHP, industry, individual	1.914	0.067	2.945	6.118

2) Investments and O&M costs

All specific investments, fixed and variable as well as total O&M costs were obtained from (DEA, Energinet.dk 2012), (DEA, Energinet.dk 2010) and (Connolly 2009) and are presented below in Table 2.14. In the table are also shown the installed power generation capacities (Eirgrid, SONI 2012) of each technology used in the Reference 0 model and the Reference 2020 model.

Table 2.14 Investment and O&M costs and installed Irish power generation capacities in years 2011 and 2020; Sources: {{93 DEA 2012}}, {{95 DEA 2010}}, {{42 Connolly, David 2009}}, {{3 Eirgrid 2012}}

	Investment costs	Fixed O&M costs	Variable O&M costs	Total O&M costs		Ref. 2011 installed Irish capacity	Ref. 2020 installed Irish capacity
Plant type	M€/MW	€/MW/year	€/MWh	€/MW/year	€/MWh	MW/fuel type	MW/fuel type
Steam turbine, coal fired, advanced steam process	2.03	61,600	2.20	-	7.00	852.5/Coal 806/Oil	852.5/Coal
Steam turbine, coal fired advancedsteam process, 20% co-firing of biomass	2.20	66,000	2.50	-	7.00	345.6/Peat	345.6/Peat
Gas turbine single cycle, (40 - 125 MW	1.20	9,300	3.80	-	7.00	719/Gas	719/Gas
Gas turbine combined cycle (100 - 400 MW)	0.82	30,000	1.80	-	2.50	2806/Gas	3807/Gas
Gas turbine combined cycle (10 - 100 MW)	1.45	30,000	2.50	-	-	208/Gas	208/Gas
HPES	0.60	3,000	3.00	-	-	292	292
Hydro power	1.765	-	-	70,600	-	216	216
Onshore wind	1.32	-	-	-	13	1500	3593
Offshore wind	2.4	-	-	-	17	25	325
Tidal	3	-	-	-	7	-	75

Lastly, investments and O&M costs for the Irish individual heating systems in 2007 were acquired from (Connolly 2009). They are shown in Table 2.15 below.

Table 2.15 investments and O&M costs for the Irish individual heating systems in 2007; Source: (Connolly 2009)				
Fuel type	**Size, kW**	**Cost (incl. installation), €**	**Lifetime, years**	**O&M costs, €/year**
Oil	26	14,750	15	110
Biomass	19	19,500	15	110
Natural gas	26	14,750	15	110
Solid fuel	21	15,300	15	110
El. Boiler	12	15,500	15	0
El. Heater	20	6,000	20	0
Solar thermal	2400 kWh/year	5,900	35	55

2.4.3 Regulation

In order to simulate the power generation system more accurately, two regulations for each scenario have been used. Firstly, it is assumed that 30% from the power in the Irish grid comes from facilities that provide grid stabilization. Secondly, electricity to the grid from industrial cogeneration of heat and power (CHP) is ran constantly throughout the year for all scenarios, as it is 229 MW, which results in an annual production of 2 TWh.

2.4.4 Summary on the Reference models and assumptions

Based on the assumptions described in this section were developed the Reference 0 model, simulating the Irish power and heat sectors in 2011. It was checked for accuracy with the historical data further in Chapter 4: Model verification and considered credible for further analyses and optimizations in this study. Next, it was developed the Reference 2020 model based on the same assumptions as it simulates the forecasts of the anticipated Irish energy system in year 2020 based on the current key energy Government policies. Furthermore in Chapter 5: Analyses are provided modifications of the system in order to optimize its operation, based on technical and socio-economic studies as well as sensitivity analyses. Amongst others, the results from the EnergyPLAN model in this study are compared to the ones in the previous study, namely (Rangelov 2013), which used Excel based dispatch model.

2.5 Summary on the chapter

This chapter provided detailed data about amongst others: general report structure, previous work on the problem, motivation for using the EnergyPLAN energy analyzing tool for this study as well as description of the programme. Moreover, the main assumptions, data gathering process, tools and methods used for developing of the Reference 0 and Reference 2020 models.

Following, in Chapter 3 are described the currently available energy storage technologies as well as discussion for their role in the present study.

CHAPTER 3: ENERGY STORAGE TECHNOLOGIES AND SYSTEMS

This chapter tends to present rather broadly the concept of energy storage and the main drivers for building it. Furthermore, it also reviews only the currently commercially available storage technologies and systems of a very large scale, which can be anticipated to be relevant within the project reference year 2020 and also appropriate for the Irish case.

3.1 WHY ENERGY STORAGE?

Increasing the installed wind capacity is not only the case for Ireland, but also on European and global level. Despite the global financial crisis, in 2008 wind power was the power generation technology which was installed more than any other in the EU, amounting to some nearly 8.5 GW of new wind capacities in that year (Swiercinsky et al. 2010) as by the end of 2011 the total amount of installed wind power capacity in the EU almost reached 94 GW (EWEA 2011). Considering the drivers for switch to renewable generation, amongst others climate mitigation, fuel prices and security of supply, as well as the maturity of wind power technology, this growth is likely to continue both in Ireland and the EU. However as outlined earlier in this report, harnessing wind energy requires a flexible power system on both the generation and the consumption sites. This flexibility can be achieved by adding energy storage (Swiercinsky et al. 2010, Connolly, Leahy 2010) unless we have an advanced CHP system.

Energy storage (ES) can be used for a number of applications in the power system which facilitates utilization of wind power. Firstly, ES can be used for number of technical applications, amongst others: load leveling and peak shaving, meaning to store the excess wind generation in times of excess production due to low demand and to use the stored electricity when demand exceeds wind generation. The character of fluctuating renewables, such as wind power, is of use-it-or-lose-it character so if wind production exceeds demand it must be curtailed (Østergaard 2011a). In this way ES can assist to store the excess wind power for other times of the day, where there will be not enough wind generation to cover demand. Furthermore, when a blackout occurs in some power generator it requires a certain amount of time for the unit to recover and start exporting again power to the grid. ES facility can significantly decrease this time period, known also as black start (EPRI 2003). Moreover, the best wind conditions are often found in rural areas, which are far from energy dense urbanized areas, such as large cities with a lot of industry. Example for this is China, where the best wind conditions are in the Northern and Western provinces, which are sparsely populated, while the biggest consumers are located on the East coast (Lixuan, Möller & Lund 2012). This means that strong transmission lines are needed to transport power from the far-off wind power plant to the consumers. Presently there are economic, public acceptance and other constraints for building the required transmission grid, but an ES can facilitate the wind park to preserve the energy it cannot transfer to the grid and to transfer it at times of lower wind generation, so the transmission grid will not suffer any damages, while all the wind energy is utilized. More, when wind speeds are decreasing, wind power generation is decreasing much faster[3], which creates problems as other generators from the primary reserve should be dispatched,

[3] Since the theoretically available power in wind can be expressed by: $P = 1/2\ \rho\ A\ v^3$, where: P-power and v-wind velocity (The Engineering Toolbox) This means that wind power is a cubic function of wind speed, or in other words: wind power is very sensitive to changes in wind velocity.

followed by secondary and tertiary reserves. However, if ES is available on the site, then this stop can be softened and hence dispatch of other generators can be more flexible and efficient. Next, energy storage can be used commercially, such as energy arbitrage, operating as both consumer, buying and storing cheap electricity (from excess wind generation), and then work as a generator, selling electricity when it is expensive, also known as time shifting. (Swiercinsky et al. 2010, ESA) Furthermore, if installed solely at the consumers, the ES can reduce their electricity expenses again through time shifting of the bought cheap electricity and used when is most expensive (usually at peak load hours occurring in mornings and early evenings) (Rodriguez 2011).

To summarize, there exist many types of ES technologies for various applications. <u>However for this project it is only of interest to investigate only the ES technologies, which are capable to be used for energy management</u>, so to be able to accommodate large quantities of fluctuating RE. Figure 3.1 below shows a diagram of ES classification through modes of application. It is clear for the diagram that the only two types of ES, which can store large amount of power for hours are CAES and HPES. Therefore they are the only ones, which are considered suitable for the scale of the project and hence the only ones, which construction and operation is described in this chapter.

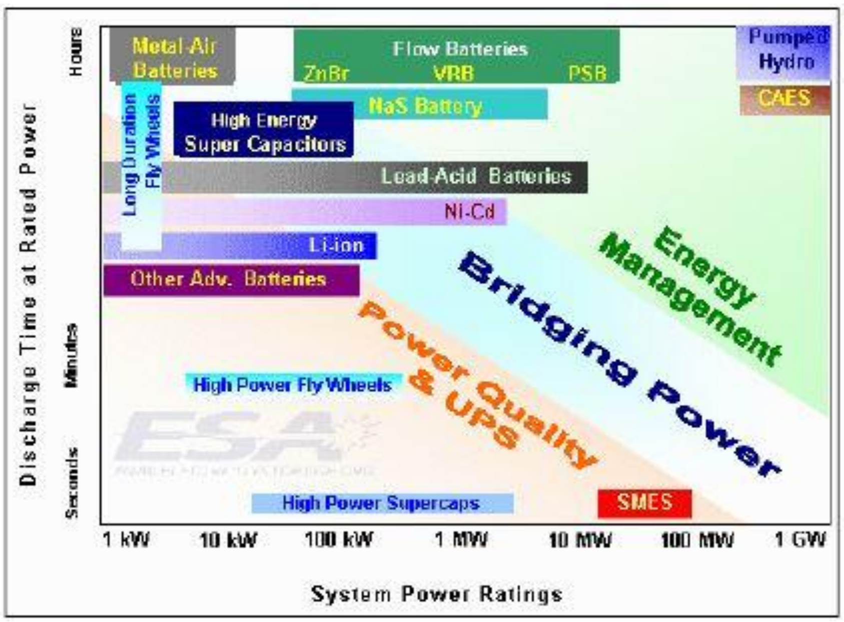


Figure 3.1 – Energy Storage by application time/power; Source: (ESA)

3.2 Energy Storage for Energy Management

This section describes how the above defined ES technologies for Energy Management operate.

3.2.1. Hydro Pumped Energy Storage (HPES)

A HPES plant consists mainly from two separated water reservoirs placed with a vertical distance between them. When there are off peak hours resulting in excess electricity, water is pumped from the lower to the upper reservoirs. And reverse, when there is higher demand, then water is released from the upper to the lower reservoir and transformed into power. Both processes are done by a reversible pump-turbine. (Connolly, Leahy 2010, ESA) Figure 3.2 below illustrates how a typical

HPES plan operates. The power capacity depends on the size of the hydrolic head and the storage capacity on the volume of the reservoirs.

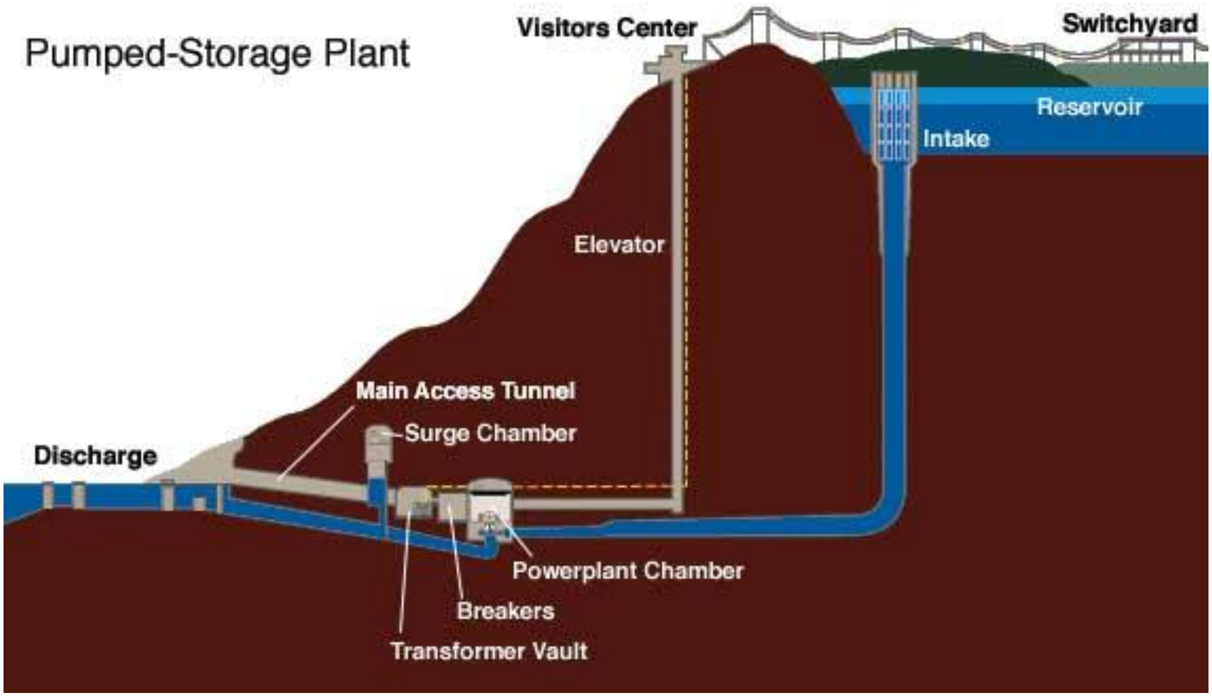


Figure 3.2 – Hydro Pumped Energy Storage Plant; Source: (Wikipedia 2013)

HPES is the most mature and widespread ES technology with about 240 working facilities and installed power of more than 90 GW. A single HPES can operate at power capacity from 30 MW till up to 4 GW and storage of up to 15 GWh (SEI 2004b). The power and storage capacities are both dependent on the reservoirs hydraulic head and volume. However, usually the facilities are built with greatest hydraulic head possible and not the largest volume due to higher costs. The overall efficiency varies from 70 to 85% and is dependent on the efficiency of pump-turbine unit (Connolly, Leahy 2010, SEI 2004b). Nevertheless, devices with variable speed are currently used to improve this (Anagnostopoulos, Papantonis 2007). Until recently HPES was typically freshwater application, men in 1999 a seawater facility was built as corrosion was prevented by painting and cathodic protection (Fujihara, Imano & Oshima 1998).

HPES has a fast response time of 10 minutes or less if full shutdown or up to 30 seconds if kept in standby. This makes this ES technology ideal for load leveling, as well as other applications such as peak generation and black start. The costs vary from about $600/kW (SEI 2004b) to $2000/kW (Connolly, Leahy 2010), depending on size, location and grid connection (Connolly, Leahy 2010). Disadvantage of HPES is that it is dependent on appropriate locations. There should be present suitable geological formations: two reservoirs with a sufficient hydraulic head between them. Not only that these are rare to find, but usually they are situated in remote unpopulated areas without existing transmission grid. However, several studies, amongst others (Fujihara, Imano & Oshima 1998), (Connolly, Leahy 2010) and (Connolly, MacLaughlin 2010), point that it turns to be that there are more appropriate sites for HPES than formerly anticipated, amongst others in Ireland, which were found with the use of a specially designed geographic software (Connolly, MacLaughlin 2010).

There is a design of underground HPES (UPHES), where upper reservoir is at ground level meaning that the other parts of the plant are deep in the Earth. This creates enormous problems regarding its construction with the current technologies and therefore it is just a concept. (Connolly, Leahy 2010) A possible solution is the usage of old mines, where the digging work is already done. Despite that with a more developed technologies UPHES would be a perfect solution for building a plant where there are not available sites, this technology is dismissed from the present study as it is not likely to play a role in the time period till 2020.

In summary, HPES is clearly an ideal energy storage solution for facilitation the integration of large scale fluctuating RE sources, which although is to some extent constrained by available locations for now, can be expected to be built more in near future, after locating new sites with the help of specially designed software (Connolly, MacLaughlin 2010) as well as further use of sea water locations (Fujihara, Imano & Oshima 1998). Single in the EU is proposed building of about 7 GW of HPES capacity in the period 2009 to 2020 (Deane, Ó Gallachóir & McKeogh 2010) and there is also discussion about expanding HPES capacities in several power systems in the U.S. (ESA).

3.2.2 Compressed Air Energy Storage (CAES)

When using CAES compressed air is being stored in an underground cavern. The system is a modification of a gas turbine (GT) technology where when air is compressed at off peak hours and when demand is high then the air is heated and expanded in the GT and producing electricity. (Lund, Salgi 2009, ESA) The system consists of generally of compressor, high and low pressure turbines (in a GT plant), generator and a cavern (Connolly, Leahy 2010). The cavern for compressed air lays typically under salt rocks, or is abandoned hard rock mine or a natural aquifer (SEI 2004b). The principle of work of CAES with GT is presented in Figure 3.3 below.

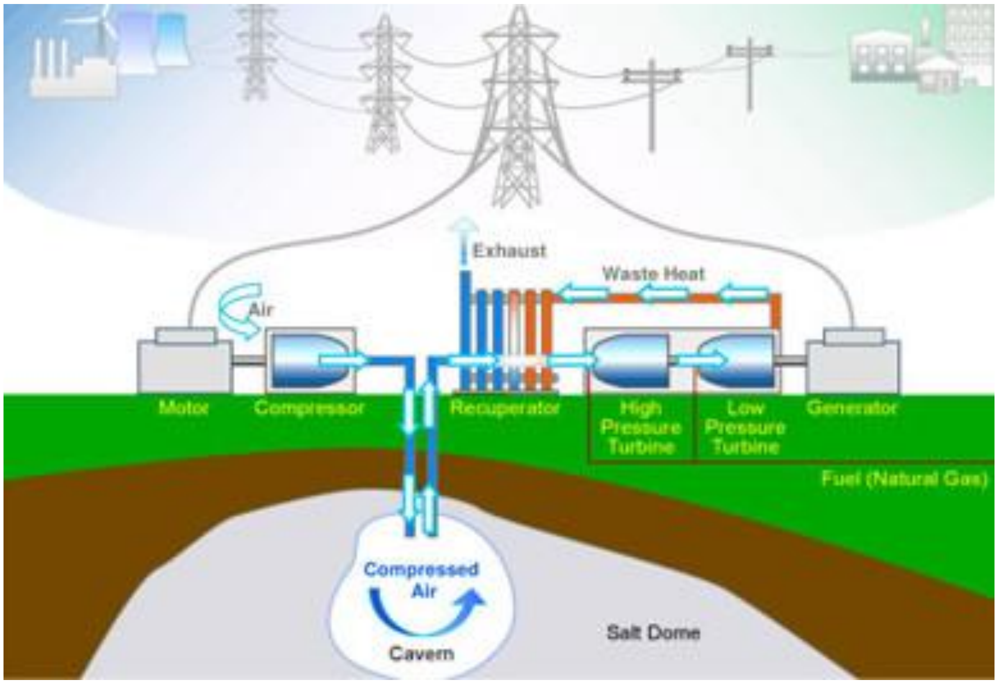


Figure 3.3 – Compressed Air Energy Storage (CAES) Plant; Source: (Salt Cavern Information Center)

In conventional GTs about 66% (SEI 2004b) of the natural gas is used to compress the air, while in a GT combined with CAES the air is pre-compressed by the compressor using cheap off peak electricity. Despite that a small amount of NG is mixed with the air before entering the turbine in order to maintain appropriate temperature and pressure, a GT unit operating with a CAES can produce three times more electricity than a one working on its own while using the same amount of natural gas. (Connolly, Leahy 2010)

Just like HPES, CAES is also a mature, reliable and well known energy storage technology although there exist only two facilities in the world up to date: one is Germany with 380 MW capacity, and another one in USA with a capacity of 110 MW (Lund, Salgi 2009), mainly to back-up slow acting nuclear power plants (Rodriguez 2011). CAES has a very fast response time as is capable of going from stop to full power in less than 10 minutes and from half capacity to full power within seconds (SEI 2004b).

CAES is the only technology other than PHES that can be used in a very large scale (Connolly, Leahy 2010). It has a very fast response time as is capable of going from stop to full power in less than 10 minutes and from half capacity to full power within seconds (SEI 2004b). Consequently it is ideal solution for load following and voltage control (Connolly, Leahy 2010). With the larger deployment of RE technologies, CAES is further analyzed to optimize the inclusion of fluctuating large amounts of renewable energy in the power system. CAES is one of the energy storage systems with greatest flexibility and can facilitate for the integration of RE (Lund, Salgi 2009). The initial investments costs vary from $425/kW (SEI 2004b) to $450/kW (Connolly, Leahy 2010). Similarly to HPES, a drawback of CAES is the need to suitable locations as it is hard to define an underground cavern, which is appropriate to contain compressed air, is near grid and has the sufficient size. (Connolly, Leahy 2010) A number of CAES plants are at different stages of planning and will be constructed in future (Connolly, Leahy 2010, ESA).

To summarize, CAES is a mature and reliable ES technology which can be used for a variety of applications and despite that it still uses some natural gas to be mixed with the air before to enter the GT, it can facilitate integration of large scale RE.

3.3 Thermal Energy Storage System

The difference between energy storage technology is that the ES systems consists of several technologies and their construction is more complicated and unique. In general there exist three types of energy storage systems: Hydrogen Energy Storage System (HESS), Electrical Vehicles (EVs) and Thermal Energy Storage (TES). Despite that the first one is one of the most promising future technologies, because of its immaturity presently (Connolly, Leahy 2010) it is dismissed from this classification. Because of delimitation of this report of not including the transportation sector, the second one is also dismissed. Therefore this section describes only the operation of TES.

The general principle of the Thermal Energy Storage (TES) is like every other storage technology to store excess energy for a later use. (Dincer 2004) However, when storing excess electricity from wind turbines for example, the energy is transformed from power to thermal energy. If district heating is introduced, then TES can encompass both electricity and heat sectors, using Cogeneration of Heat and Power (CHP) (Connolly, Leahy 2010). Despite the various applications of TES in industrial heating and cooling, this project will only consider it as an ES system, which adds flexibility to the system as converts excess power production through heat boilers or heat pumps into heat, stored as hot water in tanks and later used for district heating, which provides space heating and domestic hot water (DHW).

Figure 3.4 shows two scenarios of an example of TES system working with a wind park and a CHP plant. When wind speeds are low (scenario a) the CHP is covering the electrical demand and producing excess heat in times of low heat demand which is stored in water tanks. When the wind speeds are high (scenario b), wind turbines satisfy the electricity demand, while the heat demand is covered by the thermal storage. In scenario b the CHP production is minimal. This given example is of a TES of short term, where short means hours to a day. There exist also long term annual thermal storages (Dincer 2004).

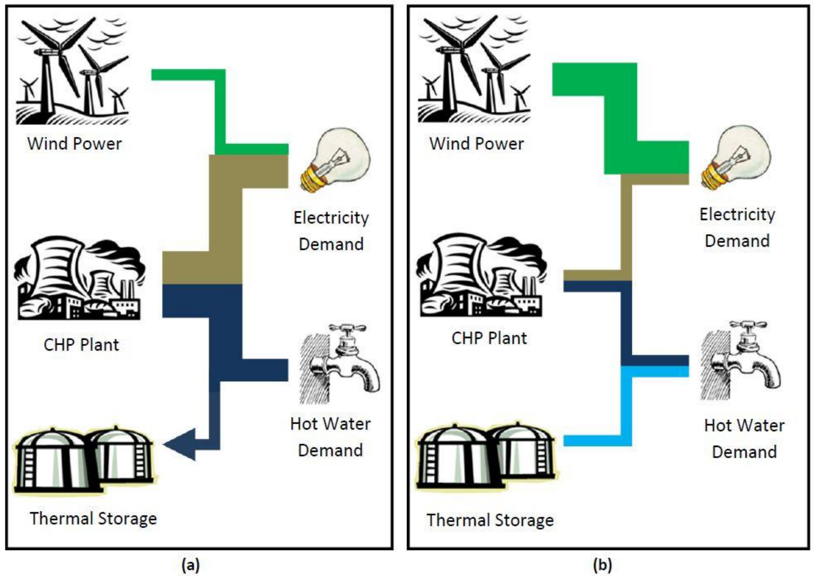


Figure 3.4 – Thermal Energy Storage System working in a) low wind speed and b) high wind speed scenarios; Source: (Connolly, Leahy 2010)

This type of TES system operates in Denmark, which has the highest wind penetration in the world, which amounted to 28% of the electricity consumption in 2011 as it is planned to grow to 50% by 2020. (Energinet 2012) Moreover, there is a roadmap for Denmark to be with 100% RE supply by 2050 (Lund, Mathiesen 2008).

TES system has one major disadvantage: the initial costs for establishing the system, which include CHPs, installing of preinsulated district heating pipes, as the latter encompasses many related costs for infrastructure, and therefore is investigated in this report only for very heat intensive and populated areas in Ireland. On the other hand TES has plenty of advantages: Firstly, it works perfectly already in Denmark, so it is a mature and reliable technology. Secondly, when cogenerating heat and power the overall efficiency is in the range of 80% - 90%, while generating only power in the conventional power plants results in only about 40% efficiency. Next, it is in compliance with the Irish 2020 goals for building 800MW CHPs. Furthermore, once installed, the district heating infrastructure can be used for heat supply not only from CHP, but also from other generators, such as geothermal sources and heat pumps[4].

In summary, TES is a mature and reliable energy storage system, which could be expected to grow around the world, together with the higher efficiency improvements. It works already in Denmark and the Danish wind power case (Energinet 2012) points at the highest in the world wind power penetration with the given flexibility of TES. (Connolly, Leahy 2010)

[4] This depends on for what temperatures the inlet/outlet pipes are designed for, because when using water as a heat carrier, then the higher the temperature, and hence potential, the smaller pipe diameter is required. Given this, if the district heating pipes are designed for high temperatures (>80°C), then these diameters will not be sufficient in the colder periods of the season to supply sufficient amount of heat if the heat carrier temperatures are medium (~50°C to 60 °C), such as heat pump or some geothermal. The tendency is to lower the temperature in the district heating, because of the also lower transmissions heat losses to the ground.

3.4 Summary of the presented Energy Storage Technologies

This chapter presented the energy storage technologies which can be expected to have future in integration of large scale fluctuating renewable energy and could be relevant for the Irish wind power case within the project reference year 2020.

Table 3.1

Energy storage/system technology	*Main advantages*	*Main disadvantages*
HPES	✓ can accommodate very large amounts of excess power; ✓ mature and reliable technology;	× dependent on geological formations
CAES	✓ can accommodate very large amounts of excess power; ✓ mature and reliable technology;	× dependent on geological formations × still uses natural gas
TES	✓ encompasses both heat and electricity sectors; ✓ makes power generation more efficient through cogeneration; ✓ mature and reliable technology.	× requires a specific infrastructure

All presented ES technologies and their main advantages and disadvantages are summarized above in Table 3.1.

The author acknowledges that the only criterias to evaluate the listed technologies are maturity, scale, time perspective up to 2020 and anticipated integrity to the Irish power system. Hence economic and environmental issues are not considered. Furthermore, all technologies listed in this chapter are chosen in order to be applicable for energy management and to very large scale. Moreover, as explained in the beginning of section 3.3 of this chapter, several technologies which are considered promising in future, such as HES and EVs were also not review.

In the next chapter the results from the Reference model are presented and compared to the actual data in order the model to be verified.

CHAPTER 4: MODEL VERIFICATION

In this chapter is provided a number of different analyses in order to validate the Reference 0 model. The results from the hourly simulation of the modeled Irish energy system for 2011 through the tool EnergyPLAN are presented and compared to the actual figures recorded in the Energy Balance for 2011 and also data by the Irish TSO (Eirgrid)*. The main characteristics of the built Reference 0 model, amongst others: electricity balance, fuel balance, CO_2 emissions and electricity distribution, are provided and compared to the actual recorded ones.*

In the previous chapter it was discussed the need of Energy Storage for the case of Ireland and were reviewed the currently available technologies, amongst which it was determined which would be most appropriate for this study. The present chapter, on the other hand, tends to discuss on the overall accuracy of the developed with the energy analyzing tool EnergyPLAN Reference 0 model, which strives to represent the operation of the Irish power and heat sectors in 2011. Below it is discussed on the validity of the model as several key system factors are being compared to the actual records.

4.1 ANNUAL ELECTRICITY BALANCE

Amongst the most important features of the energy system is the electricity balance. The EnergyPLAN model tool simulated correctly the electricity output in the Irish power generation system for 2011, amounting to just below 28 TWh/year (including electrical heating) over one-hourly resolution.

The electricity demand is covered in each hour of the year as there is no critical excess electricity production (CEEP) or other imbalances between generation and demand.

Table 4.1	Annual electricity production		
	Actual 2011 data, TWh/year; Source: (SEAI - Energy Balance 2012)	**Modeled data, TWh/year**	**Δ, %**
Electricity generation in PPs	20.42	22.00	7.73%
CHP electricity production	2.01	2.01	-0.10%
Hydro power generation	0.71	0.71	0.00%
Wind power generation	4.38	4.42	0.81%
Imports	0.05	0.00	100.00%
Electrical heating	-3.85*	-3.85	0.00%
Annual electricity balance	**23.74**	**25.29**	**6.54%**

*The electrical heating consumption is not available from (SEAI - Energy Balance 2012) and hence it was assumed to be the one used in the model.

Clearly from Table 4.1 above, the Reference 0 model figures are very close to the recorded ones in (SEAI - Energy Balance 2012). However, the model overestimates the production from power plants and at the same time neglects the imports, which occurred in the actual system operation. A possible reason is that the model does not take into account the availability of the PPs.

Figure 4.1 below furthermore illustrates the share of contribution of each power generator in 2011. The conventional thermal power plants contributed with almost three quarters share of the total power demand, followed by wind power with some 16%. Imports had a neglectably low share (0,18%) from the total demand.

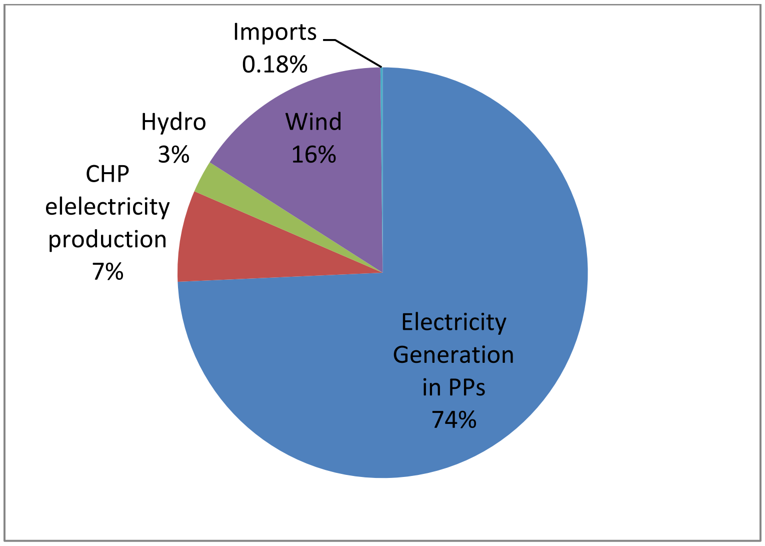


Figure 4.1 – Power production by type of generator; Source: Modeled data

To summary, the built Reference 0 model represents the Irish power generation system in year 2011. The simulation shows that the system is in balance and moreover, the produced figures by the model for electricity generation are close to the actually recorded ones in (SEAI - Energy Balance 2012).

4.2 Annual fuel balance

Next, another important factor is the fuel balance of the modeled energy system. The annual fuel input in the Reference 0 model, which includes electricity and heat sectors, is also revised and compared to the figures from (SEAI - Energy Balance 2012).

Table 4.2	**Annual fuel balance:**		
	Actual 2011 data, TWh/year; Source: (SEAI - Energy Balance 2012)	**Modeled, TWh/year**	**Δ, %**
Coal/peat	23.92	23.93	0.03%
Natural gas	47.19	47.30	0.22%
Oil products	12.65	12.7	0.37%
Renewables	5.18	5.14	-0.86%
Biomass	2.48	2.52	1.73%
Total annual fuel balance	**91.43**	**91.6**	**0.18%**

*Due to the lack of peat input field in EnergyPLAN, peat is modeled as part of the coal, because of their similarities in amongst others: net calorific values, emission factors and plant efficiencies (see Chapter 2: Methodeology).

It is evident from Table 4.2 that the annual fuel inputs in the Reference 0 model are nearly identical with the recorded actual 2011 figures in (SEAI - Energy Balance 2012). EnergyPLAN reproduces correctly the annual fuel balance, as the biggest inaccuracy amounts to 0.86% and occurs at the renewables part. It is explained by the difference in the thermal solar share, where according to (SEAI - Energy Balance 2012) it produced 0.09 TWh of heat in 2011, while in the Reference 0 model this number is only 0.02 TWh. However, these differences seen as general can be considered unimportant as the total annual fuel balance is reproduced with accuracy of just 0.17%.

Furthermore, Figure 4.2 below presents the shares of each fuel in the modeled energy system. Not surprisingly the highest share in power and heat generation sectors in Ireland has the natural gas, which amounts to about 52% of all fuels used in these sectors, followed by coal and peat amounting to just above a quarter part.

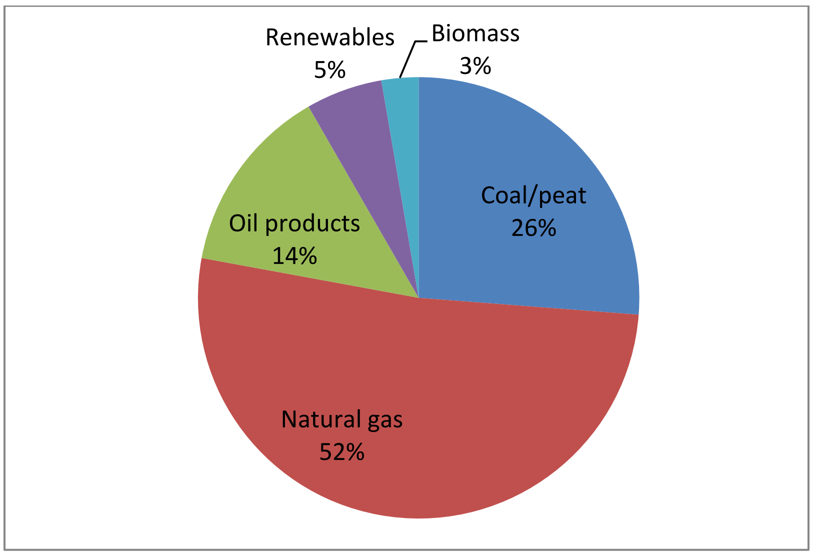


Figure 4.2 – Annual fuel inputs; Source: Modeled data

To summarize, the Reference 0 model accurately reproduces the annual fuel inputs of the modeled Irish power and heat sectors in 2011.

4.3 Annual CO_2 emissions

Furthermore, the carbon emissions in the modeled energy system were studied. Firstly, the actual carbon emissions were calculated using the annual fuel records from (SEAI - Energy Balance 2012) and carbon emissions factors from (SEAI 2012b). Then using the same emissions factors were calculated the modeled CO_2 emissions from power and heat generation using the fuel balance from the model. Finally, the numbers were compared to the provided CO_2 calculation in EnergyPLAN, which is expected to be more accurate as the emission factor input is more precise than the one performed in this estimations (see Chapter 2: Methodology). The results are provided below in Table 4.3.

Table 4.3	Annual CO_2 emissions				
	Fuel balance, TWh/year	**Modeled, TWh/year**	**Carbon emissions factor, tCO2/MWh; Source:** (SEAI 2012b)	**Annual CO2 emissions Energy Balance, tCO2/year**	**Annual CO2 emissions model, tCO2/year**
Coal/peat*	23.92	23.93	0.36	-	8,614.60
Coal	14.42	-	0.35	5,047.42	-
Peat	9.50	-	0.42	3,990.72	-
NG	47.19	47.45	0.2	9,438.91	9,490.00
Oil products	12.65	12.63	0.26	3,289.89	3,283.80
Total			**Σ**	**21,766.94**	**21,376.80**
Calculated by EnergyPLAN					**21,695.20**
Δ, %					**-0.33%**

*Coal and peat are modeled as one fuel in EnergyPLAN

For the first comparison between self-estimated carbon emissions from the fuel balance records and the modeled one, there is a slight difference, where the modeled fuels underestimate the annual CO_2 with about 1.79%. However, the more precise because of more detailed carbon emissions factor input EnergyPLAN calculation number is almost identical with the calculated one from (SEAI - Energy Balance 2012) and is with only 0.33% below it.

From the performed checks, it can be concluded that the Reference 0 model accurately reproduces the annual CO_2 emissions from the modeled power and heat generation in Ireland in 2011. This was confirmed firstly by a rather rough carbon emissions calculation using the modeled fuel balance and secondly by the more precise CO_2 estimation in EnergyPLAN.

4.4 Electricity distribution

Next, it was checked if the developed in EnergyPLAN Reference 0 model simulates accurately the distribution of generated electricity throughout the year. Therefore actual data for the demand was downloaded in the form of quarter-hourly series for the electricity demand during the whole 2011 provided by the independent Irish TSO (Eirgrid). Using these time series the average monthly power demand was calculated. Then it was compared to the reproduced one in EnergyPLAN for each month of the modeled 2011. The results are presented below in Table 4.4

Table 4.4	Average monthly electricity demand, MW		Difference, MW	Δ, %
Month	**Actual 2011; Source:** (Eirgrid)	**Reference 0 model**	**Ref. 0 model - Actual data**	**Difference/Actual data**
January	3,385	3,385	0	0.00%
February	3,255	3,256	1	0.03%
March	3,111	3,106	-5	-0.17%
April	2,815	2,790	-25	-0.90%
May	2,761	2,780	19	0.70%
June	2,712	2,705	-7	-0.25%
July	2,646	2,634	-12	-0.47%
August	2,695	2,712	17	0.62%
September	2,803	2,798	-5	-0.19%
October	2,894	2,904	10	0.34%
November	3,090	3,100	10	0.31%
December	3,203	3,186	-17	-0.52%
Total average	2,948	2,946	-1	-0.04%

Clearly from the results, EnergyPLAN distributes correctly the generated electricity. For each month the simulated el. demand average is nearly equal to the actual one as the biggest difference is in April where the Reference 0 model underestimates the demand with 0.90%. The total average difference between the records and the model is only 0.04%. Next, Figure 4.3 illustrates the average el. demand by months in the model. It shows that in the winter months the demand is higher than in the summer, which is logical and further proves the validity of the simulated distribution.

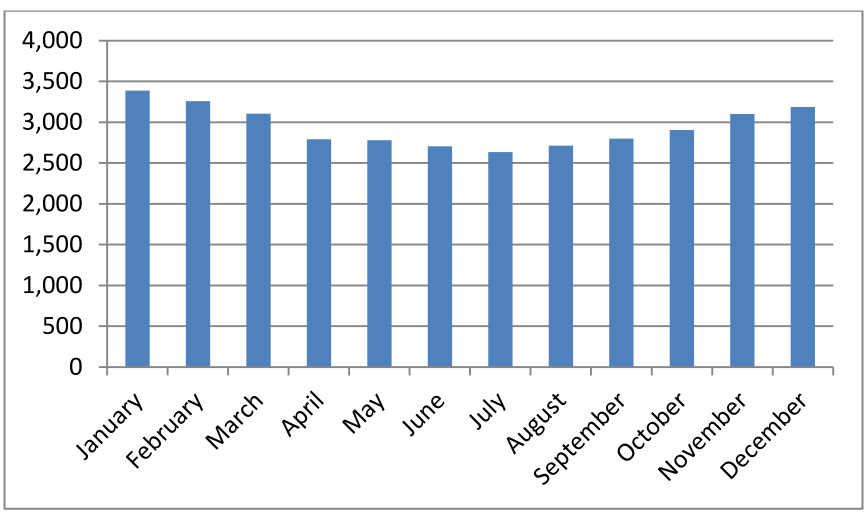


Figure 4.3 – Average electricity demand by months in the Reference 0 model; Source: Modeled data

The extremes and the average modeled electricity demand were also checked for accuracy. The results are shown below in Table 4.5.

Table 4.5	Annual electricity demand, MW		Difference, MW	Δ, %
	Actual 2011; Source: (Eirgrid)	**Reference 0 model**	**Ref. 0 model – Actual data**	**Difference/Actual data**
Minimum	1,561	1,586	25	1.60%
Maximum	4,644	4,607	-37	-0.80%
Average	2,946	2,946	0	0.00%

The presented results moreover assure about the correctness of el. distribution in the Reference 0 model. There are only slight differences in the extremes between the actual 2011 data and the simulations – the modeled minimal demand is with about 1.60% higher and the modeled maximal demand was with 0.80% lower than the recorded ones. This small variation in the extremes is because the Eirgrid's time series are for period of a quarter hour, but they were averaged into one-hourly through a developed Excel macro, because the requirement of EnergyPLAN each distribution to have 8,784 hourly points (see Chapter 2: Methodology). The average electricity demand is identical in the model as it was recorded by Eirgrid.

To summarize, the modeled monthly average electricity demand distribution is very similar to the recorded ones by the Irish TSO (Eirgrid) and logic moreover follows rule of a thumb, that in the winter months demand is higher than in the summer months. Next, the average annual demand in the Reference model is identical to the actual one and the extremes are also very similar. Hence it can be concluded that EnergyPLAN simulated correctly the distribution of generated electricity throughout the year.

4.5 Reference 0 model validation

From all above subsections of the present chapter it was illustrated that the developed Reference 0 model using the energy analyzing tool EnergyPLAN is a balanced model, with no excess power production and the production of each power generator reproduces the actual one with only minor variations. Next, the simulated annual fuel balance reproduces correctly the one from the Energy statistics at (SEAI - Energy Balance 2012). Furthermore, the modeled annual carbon emissions in EnergyPLAN are also with only minor difference between the ones calculated on the fuel balance. Last, but not least, it was presented that the Reference 0 model accurately reproduces the electricity distribution throughout the year as the simulated average monthly demands were compared to the Irish TSO's (Eirgrid) data and considered correct.

Therefore, the developed with the EnergyPLAN tool Reference 0 model, which simulates the power and heat sectors in Ireland in year 2011 was considered credible for the purposes of the present project and was further used to create Reference 2020 Scenario and other alternative scenarios. These are thoroughly studied and presented in the next chapter, namely Chapter 5: Analyses.

Chapter 5: Analyses

This chapter provides the analyses made in the project using the energy modeling tool EnergyPLAN as well as with the developed by the author Excel dispatch model in (Rangelov 2013)*. The study investigates overall five scenarios for development of the Irish heat and power sectors with a reference year 2020, which are compared through technical and economic analyses as well as sensitivity studies.*

The verified Reference 0 model in the previous chapter was a basis to develop the Reference 2020 model of the Irish energy system (see Chapter 2: Methodology). This model is used as a reference to compare different scenarios for technical development of the system to the forecasted one using the current energy policies in Ireland.

Firstly in the chapter are defined the studied scenarios in details. In the second subsection are given the technical analyses, which compare all scenarios on the system's technical performance on amongst others: energy balance, fuel consumption, CO_2 emissions, energy storage operation. These parameters are also compared through the previously built Excel dispatch model. Next, the third subsection analyses the economic impacts of each scenario, amongst others: annual investment costs, variable and fixed O&M costs, fuel costs, CO_2 costs. Lastly, in the fourth subsection are presented the sensitivity analyses.

5.1 Scenarios definition

This subsection presents to the reader the technical parameters for all studies scenarios in this report. There are overall five scenarios for the Irish heat and power sectors in 2020, as the first one the Reference 2020 scenario and the other three are its modifications. The annual net power and heat demands for all scenarios are respectively: 27.656 TWh and 23.72 TWh, as it should be noted that about 4 TWh from the el. demand has accounts for el. heating.

5.1.1 The reference 2020

This is the base scenario, which as described in details previously in Chapter 2 and is the expected Irish energy system in 2020 with the current key energy policies. Distinguishing for this scenario is that about a third from the power generation comes from peat and coal power plants, which are ran as a base load with insignificant variations, mainly in the different seasons. Next, more than half of the electricity production is from mostly new (submissioned after year 2000) dispatchable CCGTs, which are the flexible element of the system. There are about 800 MW_e of gas fired CHP, mostly industrial, which is partly not dispatchable (it can be stopped in case of CEEP, but cannot be called upon will), but running constantly throughout the year with some 644 MW, resulting in annual amount of 5.66 TWh electricity generated. Moreover, about 4,000 MW of wind turbines both onshore and offshore supply fluctuating electricity to the grid. There is also 75 MW of tidal power. The only Energy storage is the HPES at Turlough Hill with power capacity of 292 MW and storage capacity of 1,752 MWh. There is not any district heating (DH) systems in Ireland, as the heat is generated in central coal, oil, NG and biomass boilers as well as electrical heating.

5.1.2 *Scenario 1: NG*

This scenario derives from the Reference 2020 model, but the only modification is that all peat and coal power generation capacities are abolished. In order to keep the system in balance new capacity of 800 MW of CCGTs is built. All other system properties remain the same as in the Reference 2020 model.

5.1.3 *Scenario 2: storage*

This scenario is also based on the Reference 2020 model, but with the modification that the HPES capacity is trippled. So the overall HPES power and storage capacities are respectively 900 MW and 5,400 MWh.

5.1.4 *Scenario 3: DH*

This scenario derives from the Reference 2020, but with the only modification that it includes DH for the defined by the Heat Roadmap Europe (Möller 2013) areas defined as feasible for DH with more heat intensity of more than 50 TJ/km^2, which is a part of Dublin's net heat demand, which is 7.38TWh, which is about a fourth of the overall Irish heat demand. It is assumed that the DH grid losses are 20% of the heat demand so the total DH demand is set to 8.9 TWh/year. Yet it should be acknowledged that in new DH systems in densely populated areas the heat losses are only 11 to 15%. It is moreover assumed that 10% of the DH demand is covered by NG boiler. For DH distribution is used the one for Denmark, which is defined in EnergyPLAN. It can be expected that the Danish DH demand is rather correct for the case of Ireland because of the climatic similarities between both countries discussed in (Connolly 2009). It is important to take in mind that for CEEP regulation it is chosen to replace heat generation from boiler with electrical heating in times of surplus wind generation. There is thermal storage of 20 GWh in the DH system. It is moreover assumed that the DH is replacing only NG individual boilers, as for an urban area such as Dublin it could be expected most of individual heat supply to come from NG.

5.1.5 *Scenario 4: Combi*

This scenario presents an optimized combination of all modification scenarios. Firstly, the coal and peat capacities are replaced by new CCGTs. Secondly, the HPES capacity is doubled (not tripled as in the storage scenario). Thirdly, district heating is included the way it is described above in the DH scenario.

5.1.6 *Summary scenarios*

To summarize, below are listed all five scenarios, which are studied in these analyses:

- The Reference 2020 = expected energy system in 2020 according to the current key energy policies;
- Scenario 1: NG = The Reference 2020, but without coal and peat capacities, which are replaced by new 800 MW of CCGTs;
- Scenario 2:storage = The Reference 2020, but with tripled HPES capacity;
- Scenario 3: DH = The Reference 2020, but includes DH supply;
- Scenario 4: Combi = optimal combination of scenarios 1, 2 and 3.

These scenarios are analyzed on technical level in the following subsection.

5.2 Technical analyses

This subsection presents to the reader the technical analyses performed in this study. Firstly are shown the analyses for all above described scenarios using EnergyPLAN for the Irish heat and power generation, amongst others: energy balances, CEEP study, fuel balances, CO_2 emissions, energy storage operation and power generation. Secondly, the results for the scenarios which include only the Irish power generation, namely Reference 2020, Scenarios 1 and 2, are compared to the ones which result from studying quarter-hourly series with the Excel dispatch model.

5.2.1 EnergyPLAN analyses of the Irish heat and power generation

All analyses in this subsection are performed with the energy modeling tool EnergyPLAN and include heat and power generation in Ireland for the studied scenarios of technical modifications.

5.2.1.1 Energy balance

Firstly, each scenario simulates a balanced energy system, with an insignificant surplus annual power production. Figure 5.1 below shows the annual power balances for all scenarios. All scenarios have a positive annual Excess Electricity Production (EEP) as it is nearly equal for all scenarios varying from about 1.45 TWh/year in the Reference 2020 and the NG scenario, down to 1.27 TWh/year in Scenario 2, because of the flexibility from tripled HPES capacity. The combination scenario is second lowest because of the doubled HPES capacity. The DH scenario has just slightly higher excess production than the Reference 2020 because of the increased share of CHP in the system. From these results it could be concluded that the EEP in all scenarios is similar, but the scenarios with increased HPES capacity decreases it. Yet there is almost no difference between tripled and doubled HPES capacity for the studied wind power capacities. Next, the figures for import are the same for all scenarios and are 0.01 TWh/year, which clearly is a very low amount and might be as result of peaking demand while not all PPs are available (note that the import distribution is historical for 2007). The exported amount of power is highest in the DH scenario amounting to 1.37 TWh/year, which is a result of cheaper power generation from CHP. For all other scenarios it is the same and is 1.25TWh. It should be mentioned that using historical time series for import/export is not correct, because since the marginal price of electricity drives the exchange of power, then with increasing the wind power capacity and hence decreasing the marginal power price it is expected more export to take place at times of high wind speeds. Therefore the historical import/export distribution is not accurate to use. Yet it is required in EnergyPLAN as well as external market definition in order to evaluate the expected amount of export. The figure for export in the DH scenario shows that it is simulated correct as more power is exported because of cheaper marginal price as a result from CHP production.

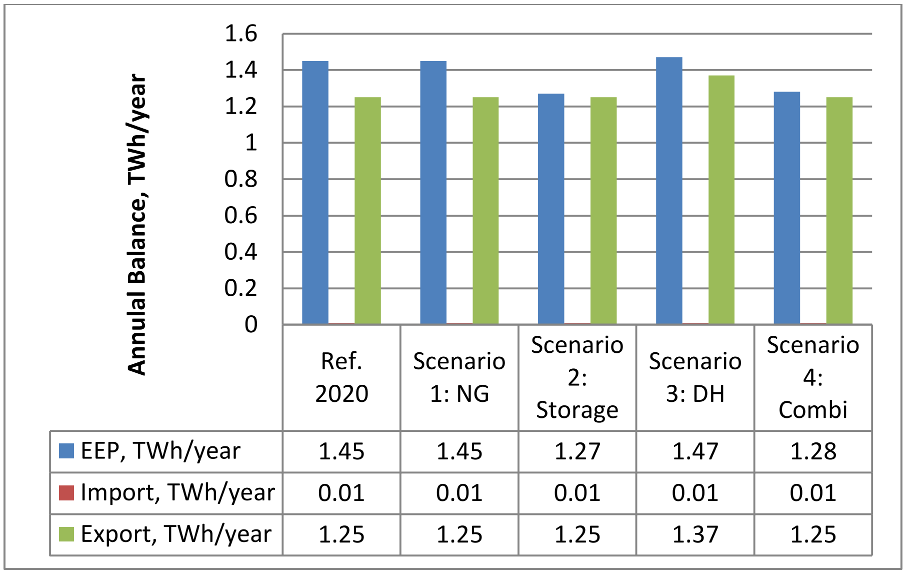


Figure 5.1 – Annual power balance all scenarios; Source: Modeled data

Next, Figure 5.2 illustrates the maximum rates of import and export of power. The results confirm the analyses from the previous figure and confirm that lowest excess production comes as result from increasing HPES capacity.

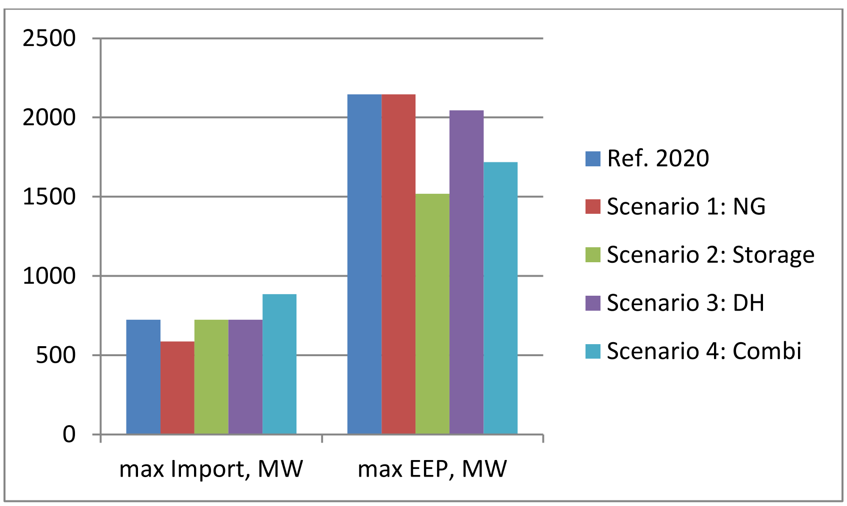


Figure 5.2 – Maximal import and export; Source: Modeled data.

Furthermore, figures 5.3 and 5.4 below present respectively the annual and the maximal CEEP for each scenario. It is clear that the Reference 2020 and Scenario 1: NG have highest CEEP. Including DH in Scenario 3 nearly halves the CEEP compared to the Reference 2020 and Scenario 1. The tripled energy storage decreases the CEEP by a factor of ten relative to the reference from 0.2 to 0.02 TWh/year. The combination scenario generated also CEEP as low as 0.03 TWh/year, which is almost seven times lower than in the Reference 2020. The results illustrate that the most effective technical modification in terms of decreasing the CEEP to neglectable levels is increasing the energy storage capacity. Next, DH also accounts for its decreasing and a combination of DH+doubled HPES in the combination scenario results in almost the same levels as tripled HPES. It should be mentioned that because of the chosen CEEP regulation, namely replace NG boilers with electrical ones, with increasing the levels of DH as well as inclusion of heat pumps it could be expected to decrease even more drastic.

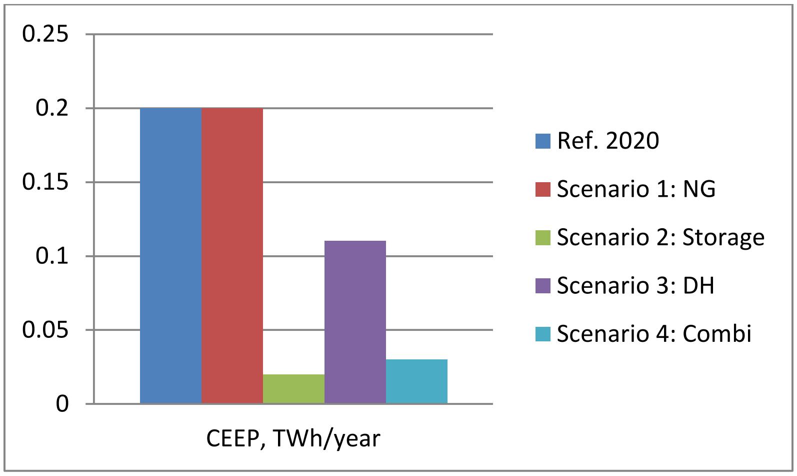


Figure 5.3 – Annual Critical Excess Electricity Production (CEEP) all scenarios; Source: Modeled data.

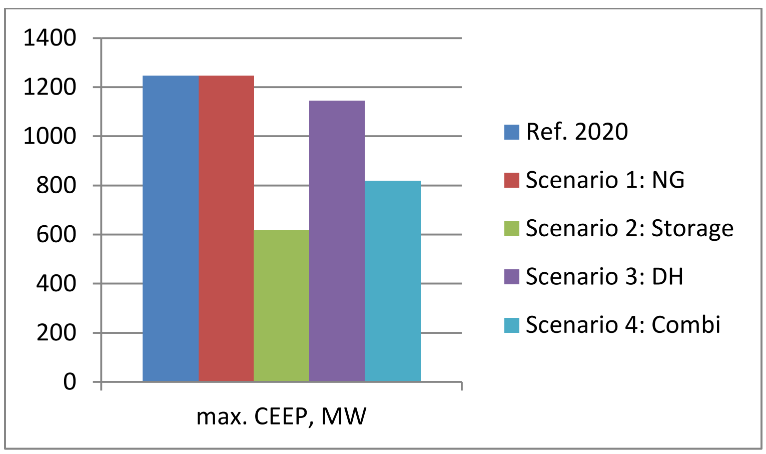
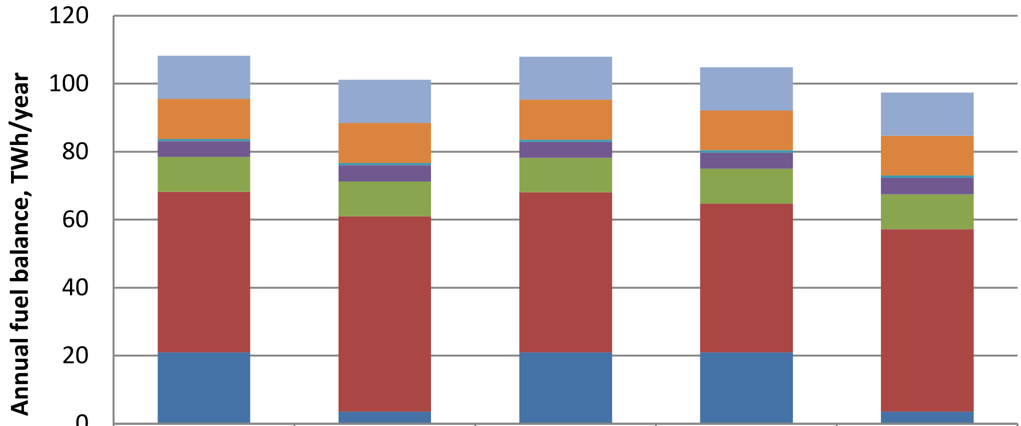


Figure 5.4 – Maximal Critical Excess Electricity Production (CEEP) all scenarios; Source: Modeled data.

To summary, from the performed power balance studies in this subsection, it is clear that in terms of excess production the Reference 2020 is the worst scenario, because of its inflexibility, which results in loss of useful fluctuating RE, which is utilized better in the other scenarios. Substituting peat and coal with NG does not affect excess power production in this model. Increasing the HPES capacity is evidently the most effective way to avoid excess production. The results show that a combination of DH and a double HPES in the combination scenario would give similar results as tripling the energy storage capacity in the high storage scenario.

5.2.1.2 Fuel balance

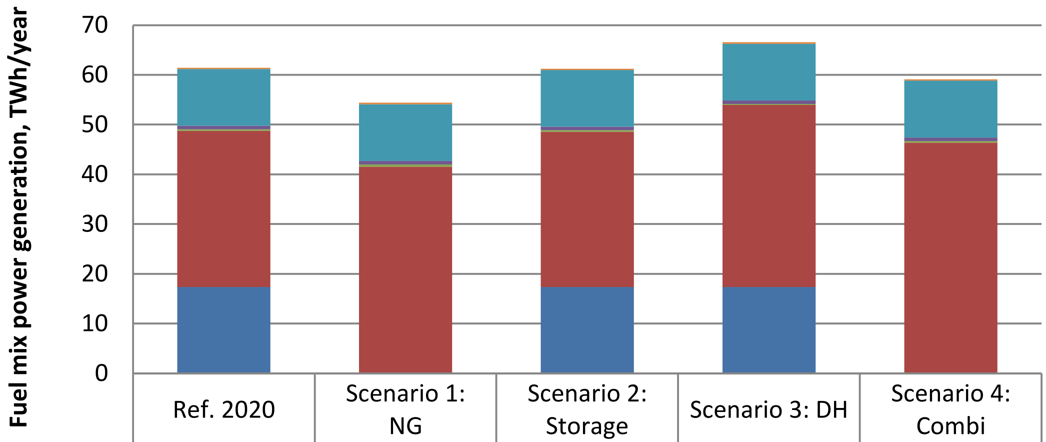
This subsection investigates the annual fuel balance from heat and power generation and the results are presented below in Figure 5.5. Clearly from the figures, the RE shares as well as oil products consumption is equal for each scenario. Biomass consumption varies in small limits as a result of different fuels for power generation, but still it does not have a significant role on the whole fuel consumption. Peat, coal and NG are the main fuels in heat and energy generation in Ireland. Evidently from the results the Reference 2020 is the worst scenario in terms of total fuel consumption as a result of its inflexibility. Single replacing of peat and coal capacities with CCGTs reduces the total fuel balance with some 6.5%, which is the most effective measure in decreasing the total consumption from all scenarios. Tripling the HPES capacity in Scenario 2 on the other hand gives only 0.18% reduction compared to the Reference 2020, which is insignificant. Introducing DH in Scenario 3 adds both flexibility and efficiency in the system as it could be seen from the figures for total annual fuel consumption in Figure 5.5 below. This results in about 3% decrease of the total fuel consumption compared to the Reference 2020. The combination scenario is the best scenario in terms of total fuel consumption as it consumes just 10% less fuel per year than the Reference 2020. It should be noted that this result is higher than all accumulated reductions from the other scenarios, which is 9.8% as even in the combination scenario the HPES capacity is with a third less than in Scenario 2. This illustrates the additional savings effect from combination of all modifications. Furthermore, it is clear that abolishment of coal and peat capacities is the most effective measure for decreasing the fuel consumption, because of its added flexibility. Including DH in the system also has a reducing effect on the system. Increasing the HPES capacity does nearly not affect the annual fuel consumption. Furthermore, in spite of the reductions in the total consumption compared to the Reference 2020 model, substituting peat and coal with NG driven CCGTs logically increases the consumption of NG. Scenario 1 has the highest NG consumption, which is higher than the Reference 2020 with a fifth. Tripling the HPES capacity decreases gas consumption with less than half percent, which is clearly insignificant change compared to the scale of increasing the energy storage capacity by a factor of three. Next, the DH scenario has the lowest NG consumption, which is with more than 7% lower than the reference. This is because of both replacing individual NG fired heat generation and increasing the efficiency by cogeneration of heat and power. The combination scenario has NG consumption higher than the Reference 2020 with some 13%, because it includes NG consumption for CHP. In general the results illustrate that only with abolishment of peat and coal the total fuel consumption reduces with more than 7%, but the NG consumption increases with more than 20%. In order to keep the total consumption lowest, but also minimize the NG dependency, DH is introduced to the system, which saves more than 7% of gas. So in the combination scenario the NG dependency is with 13% higher than the reference, but with increasing the wind power capacities as well as increasing the DH levels including el. DH boilers and heat pumps, together with including the transportation sector, as both will add further flexibility in the system, it could be expected the NG consumption to be decreased to the Reference 2020 levels or lower.



	Ref. 2020	Scenario 1: NG	Scenario 2: Storage	Scenario 3: DH	Scenario 4: Combi
Overall RE, TWh/year	12.7	12.7	12.7	12.7	12.7
Wind, TWh/year	11.7	11.7	11.7	11.7	11.7
Hydro, TWh/year	0.71	0.71	0.71	0.71	0.71
Biomass, TWh/year	4.63	4.76	4.63	4.7	4.82
Oil, TWh/year	10.24	10.24	10.24	10.24	10.24
NG, TWh/year	47.27	57.41	47.07	43.85	53.61
Coal/Peat, TWh/year	20.9	3.58	20.9	20.9	3.58

Figure 5.5 – Annual fuel balance heat and power generation all scenarios; Source: Modeled data.

Moreover, these results are furthermore confirmed by study of only the power generation sector in all scenarios. This study is provided below in Figure 5.6. Abolishing peat and coal capacities in Scenario 1 reduces the total fuel consumption in the power generation compared to the Reference 2020 with about 11.5%, but on the other hand increases NG consumption in electricity production. Tripling the HPES capacity does reduce the total consumption insignificantly with 0.33% compared to the reference. Including DH increases the fuel consumption because of increased gas fired CHP production, which is operating according to the heat demand. Overall in the combination scenario the total consumption in power generation is with nearly 4% lower compared to the Reference 2020 model. Yet this scenario has the highest NG consumption, as explained because of the CHP, which is with nearly 50% higher than in the Reference scenario. However this increase of NG in power generation is unimportant as it also accounts for heat, which was discussed in the previous graph.



	Ref. 2020	Scenario 1: NG	Scenario 2: Storage	Scenario 3: DH	Scenario 4: Combi
Other RE, TWh/year	0.28	0.28	0.28	0.28	0.28
Wind, TWh/year	11.4	11.4	11.4	11.4	11.4
Hydro, TWh/year	0.71	0.71	0.71	0.71	0.71
Biomass, TWh/year	0.31	0.44	0.31	0.2	0.33
NG, TWh/year	31.41	41.55	31.21	36.64	46.37
Coal/Peat, TWh/year	17.32	0	17.32	17.32	0

Figure 5.6 – Annual fuel balance power generation all scenarios; Source: Modeled data.

To summarize, the total annual fuel consumption in heat and power generation in Ireland is highest in the Reference 2020 model, as a result of running peat and coal power generation capacities and hence lack of flexibility and efficiency. With their abolishment the total fuel consumption is significantly lower and is further reduced with inclusion of DH systems. The RE generation is the same for all studied scenarios and the biomass consumption is nearly equal as well. Oil is used only for heat generation. NG consumption is lowest in the tripled storage scenario, but just with less than a half percent than the Reference 2020, because peat and coal and still generating power. With their abolishment the NG consumption is considerably increased, which cannot be reduced effectively with increasing the HPES capacity. However, with including DH systems on the NG consumption is being decreased considerably and could be expected to continue decreasing with utilization of more DH. The results illustrate that the Reference 2020 is the worst scenario in terms of total annual fuel consumption, but on the other hand the NG dependency is amongst the lowest. Yet including of DH system adds both flexibility and efficiency to the system and shows that this NG dependency could be decreased with increasing of DH as well as the total annual consumption of other fossil fuels used for individual heating, such as: oil, peat and coal.

5.2.1.3 Total annual CO_2 emissions

The amount of total annual carbon emissions for all scenarios is studied in this subsection. Figure 5.7 below illustrates the CO_2 emissions from heat and power generation in Ireland in all scenarios. The carbon emissions are clearly highest in the Reference 2020 scenario, again as a result from peat and coal power generation. With their abolishment and replacement with new CCGT capacities in Scenario 1, the annual CO_2 emissions are reduced with more than a fifth compared to the Reference 2020 model, which is explained by the specific carbon emissions: peat and coal are nearly twice more carbon intensive fuels than NG. Tripling the HPES in the storage scenario reduces the CO_2, but with only 0.20% compared to the Reference 2020 as a result that firstly HPES is not saving significant amounts of fuels and secondly, it reduces only the NG consumption, which is the least intensive carbon emitter. Yet with inclusion of DH in Scenario 3, the emitted carbon emissions are reduced with nearly some 3.5% compared to the reference model. This reduction is result of saving NG from individual heating and it could be expected that if the DH has highest share, it will also replace other carbon polluters, such as peat and coal, and hence greater carbon reductions will be achieved. The combination scenario is the best in terms of CO_2 emissions and as a result of the combination of optimizations it has almost 25% lower annual carbon emitted than the Reference 2020.

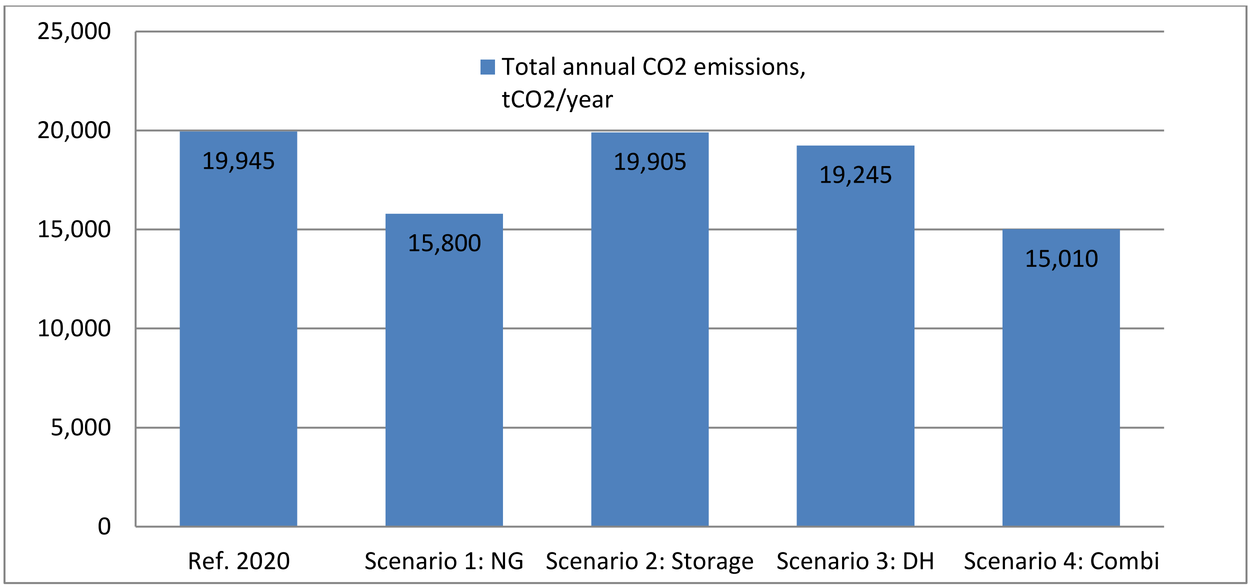


Figure 5.7 – Annual CO_2 emissions from heat and power generation all scenarios; Source: Modeled data.

For the summary, from environmental point of view, the Reference 2020 model is the worst, because of intensive carbon pollution from the largest CO_2 emitters peat and coal in the power generation. Only with their replacement with new CCGTs, the annual CO_2 emissions from power and heat generation in Ireland are cut by more than 20%. A further considerable carbon reduction is achieved by including DH, and moreover there are almost not further reductions from increasing the HPES capacity. The combination scenario is has the least carbon emissions which makes it best from environmental point of view also.

5.2.1.4 Hydro Pumped Energy Storage (HPES) operation

In order to analyze the effects from increasing the HPES capacity, its operation charging/discharging is studied in all scenarios. Figures 5.8 and 5.9 show the operation charge/discharge (pump/turbine operation) of the HPES in all scenarios, as respectively show the total annual HPES operation in TWh/year and the maximal HPES power input/output rate in MW. Evidently, from the diagrams, in each scenario both the annual and the maximum output of the HPES is lower than the respective one for charging the HPES in pump mode operation. A reason for this is the round-trip efficiency is about 63% and hence the annual output in each scenario is the input times the efficiency. Furthermore, in the low HPES scenarios the annual usage is the same, except for the DH scenario, where it operated slightly more in pump mode, probably as a result of using excess power from CHP. Furthermore, tripled capacity in Scenario 3 is only doubling the annual usage and yet the maximum output rate is far less than its maximal capacity, which means that the new capacities have a lower capacity credit than the existing one at Turlough Hill. This could be explained by different HPES system operation driven by the market. The combination scenario utilizes more its doubled HPES capacity than the storage scenario and has much higher capacity credit than it. Yet the maximal output rate is only 374 MW as the capacity is 600 MW.

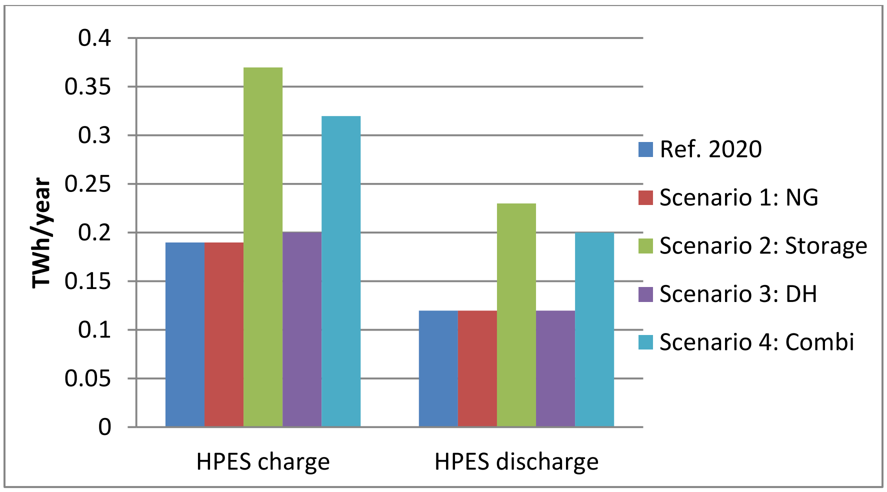


Figure 5.8 – Annual HPES operation all scenarios; Source: Modeled data.

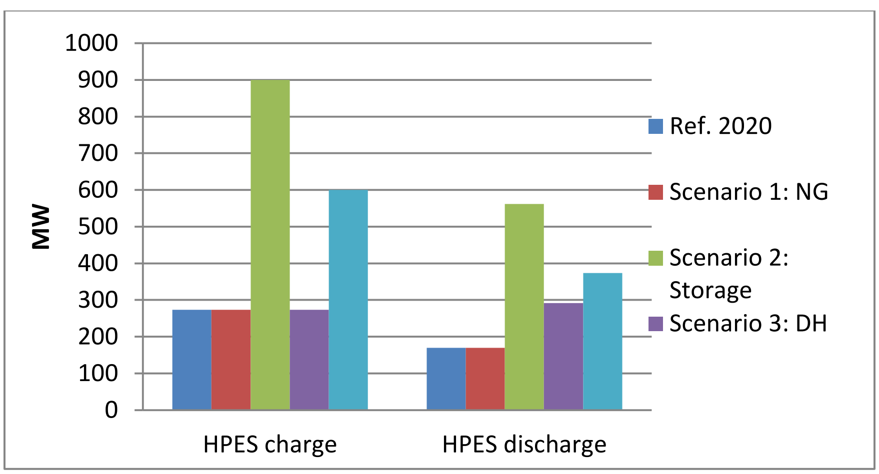


Figure 5.9 – Maximum HPES rates of operation all scenarios; Source: Modeled data.

To summarize, increasing the HPES capacity increases its operation on both annual and maximal hourly levels. However, the tripled capacity does result only in a doubled HPES operation, which means not all the newly installed HPES capacity could as much utilized as the presently existing one at Turlough Hill. From the figures, it could be concluded that the HPES in this simulation operates in charge mode at times of surplus production on its maximal capacity and discharges only in peak load hours with less than its maximum capacity. The results also suggest that with a further increase of the capacity, more power from fluctuating RE can be utilized, but not with the same capacity factor as with the present one at Turlough Hill.

5.2.1.5 Condensing Power Plants Operation

In this subsection it is presented the operation of power generation units for all scenarios. Table 5.1 below shows how the condensing power plants are operating on annual level for some of the scenarios. Unfortunately because of modeling the peat and coal generation as nuclear power (see Chapter 2: Methodology), it is not possible to distinguish the operation of the PPs in three out of five scenarios.

Table 5.1 Condensing Power Plants Operation; Source: Modeled data

	Annual el. From PPs, TWh/year	Average PPs, MW,	Minimum PPs, MW	Maximum PPs, MW
Ref. 2020	19.32	-	-	-
Scenario 1: NG	19.32	1723	639	4607
Scenario 2: Storage	19.2	-	-	-
Scenario 3: DH	14.51	-	-	-
Scenario 4: Combi	14.25	1623	600	3665

Clearly from the results, in the Reference 2020 model and Scenario 1 the produced power in condensing PPs is highest. The increased HPES capacity in Scenario 2 does have only a low impact on the PPs generation as it decreases it just slightly. Including DH in Scenaro 3 as well as in the combination scenario decreases the annual production from condensing PPs, which is replaced by CHP.. Unfortunately, because of modeling the peat and coal as nuclear power in EnergyPLAN (see Chapter 2: Methodology) it is not possible to analyze the annual average, minimal or maximal operation for the scenarios, which include peat and coal. The average and minimal outputs for all scenarios are similar. However, the maximum output from PPs in Scenario 4 is lower than in all others, which are clearly ramping up on the maximum capacity. These results suggest that including DH in Scenario 4 also decreases ramping of the PPs.

5.2.1.6 Summary on the EnergyPLAN technical analyses

To summarize, the analyses of the Irish heat and power generation systems studied for each of the scenarios defined in subsection 5.1 of this chapter on amongst others: energy balance, fuel balance, carbon emissions, HPES and condensing PPs operation, the following main trends could be suggested:

1) Firstly, the Reference 2020 scenario is the worst from energy balance point of view, as because of the inflexible peat and coal power generators operation, the system has a high surplus power production, which results in need for export and part of it results in CEEP, which should be regulated. Substituting peat and coal with NG does not affect excess power production in this model however it could be expected that switching to flexible CCGTs instead of peat and coal base load will play a very important role for future regulating power generation with increasing the wind power capacity. Increasing the HPES capacity is

evidently the most effective way to avoid excess production. The results show that a combination of DH and a double HPES would give as good results as tripling the energy storage capacity;

2) Secondly, the Reference 2020 is also worst in terms of annual fuel balance. Only shutting coal in peat would lead lead to a much lower total fuel consumption, but also to increased NG consumption. This cannot be significantly decreased with increasing the HPES. Yet the NG consumption could be significantly reduced if DH is introduced on higher levels, as it will save NG, as well as other fuels from individual heating as a result from adding both efficiency and flexibility to the system. It could be expected that increasing wind capacity together with DH could return the NG consumption to the previous levels in the Reference 2020 model;
3) Thirdly, the most important step in decreasing CO_2 emissions from heat and power generation should be abolishment of peat and coal capacities and replacing them with NG PPs. Increasing the installed HPES does not grant significant further decreasing. However, including DH supports achieving further considerable carbon reductions;
4) Study of the condensing PPs operation suggests that ramping of CCGT's is similar in all scenarios, but the DH ones, in particular the combination of DH, HPES and abolishment of base load peat and coal in Scenario 4 decreases the ramping of PPs in the system.

5.2.2 EnergyPLAN vs. Excel dispatch model of the Irish power generation system

This subsection compares the results of the analyses performed with EnergyPLAN to the ones, using the Excel dispatch model on quarter-hourly level. It is important to note that the DH scenarios 3 and 4 are not included in these analyses, because the dispatch model encompasses only power generation. The study includes, amongst others: energy balance, fuel and CO_2 balance studies for the Reference model and Scenarios 1 and 2. The EnergyPLAN results were already discussed in the previous subsection, so here are only discussed the results from the Excel dispatch model and compared to the EnergyPLAN's ones.

5.2.2.1 Energy balance

The energy balance is studied only on the basis of maximal CEEP, because the dispatch model ignores export and import. Figure 5.10 below illustrates the results of this study. Clearly from the results, the maximum CEEP in the dispatch model for all scenarios is much higher than the one in the EnergyPLAN model. This is a result of both ignoring the import/export of 900 MW in the dispatch model, and modeling peat and coal PPs as not dispatchable in the dispatch model, however in reality they still has small variations in its operation and can decrease its output with about 2% of their capacity per minute. According to the results in both models, shutting coal and peat decreases the maximum CEEP, yet while in the EnergyPLAN model it is decreased only with less than 1%, in the dispatch model it is reduced with about 20%. This could be explained firstly by the fact that EnergyPLAN uses a distribution for peat and coal based on 2009 figures, while they are modeled as constantly running with the same load in the dispatch model. Secondly, the EnergyPLAN hourly distribution derives from making averages for each quarter an hour (see Chapter 2: Methodology) and hence the distribution is more even, while in the dispatch model the time series are studied on quarter-hourly basis. Thirdly in the dispatch model there are uncertainties regarding the position of the HPES in the dispatch order and hence its operation is questionable and cannot shave the CEEP, as the EnergyPLAN simulation does. It could be expected that because of the same explanation, the maximal CEEP in Scenario 2 in the dispatch model is the same as in the previous scenario, while in EnrgyPLAN it about the half of the one in the Reference 2020.

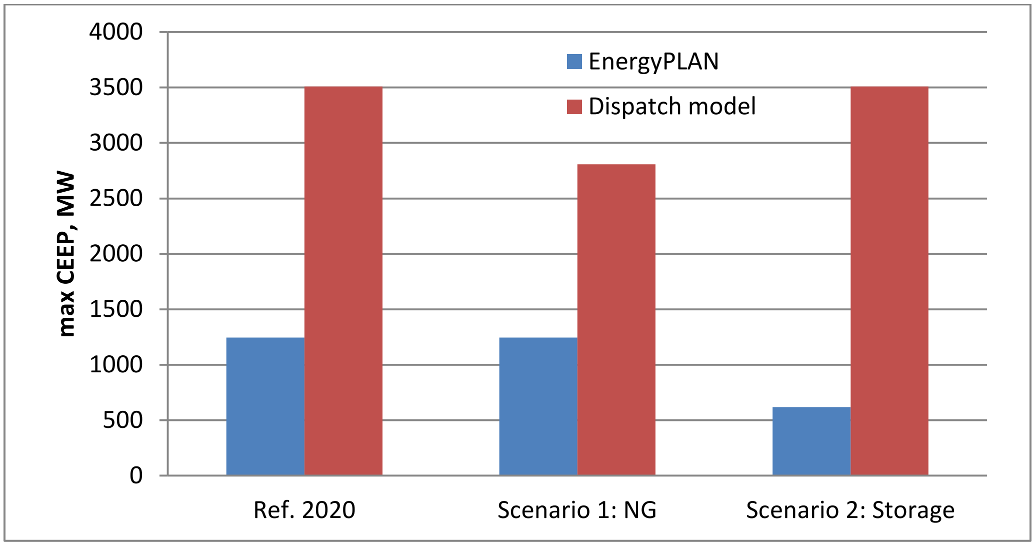
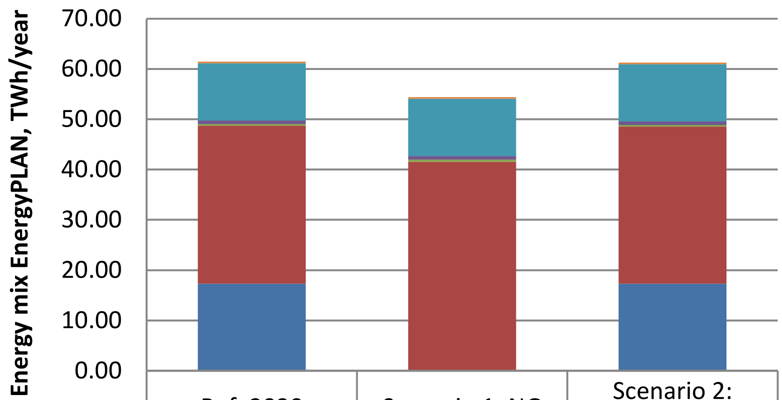


Figure 5.10 – Maximal CEEP in EnergyPLAN and the dispatch model; Source: Modeled data.

To summarize, despite the uncertainties in the models, they both confirm that the CEEP is reduced just replacing coal and peat with CCGTs.

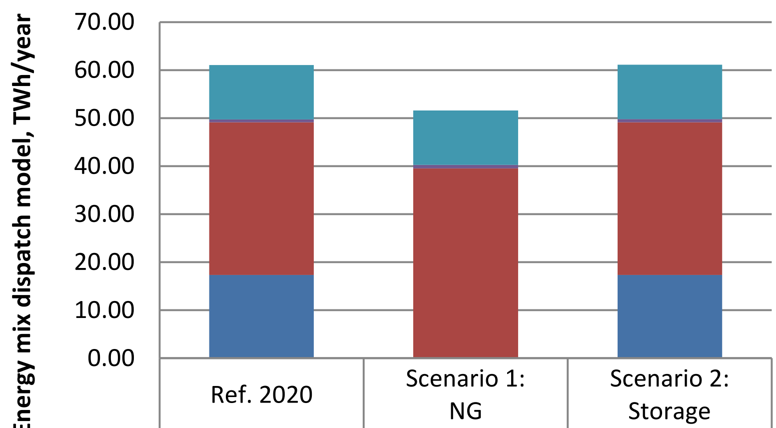
5.2.2.2 Fuel balance

In Figures 5.11 and 5.12 is presented the total annual fuel input for respectively the EnergyPLAN and the dispatch model of the Irish power generation systems. Clearly the results are very similar, with exception for the other RE and biomass, which are not included in the dispatch model. Nevertheless, the simulations from both the models give very close results for all other annual fuel inputs for the respective scenario. A rather small exception is that tripling the HPES capacity in Scenario 2 decreases slightly the NG consumption in the EnergyPLAN model, while it remains the same in the dispatch model for the same scenario. As discussed in the previous section this is a result of the uncertain place in the merit order in the dispatch model of the HPES, which results in a shortcoming from the storage in the model. Yet both models confirm that the total amount of fuels is significantly decreased only by abolishing peat and coal capacities in Scenario 1.



	Ref. 2020	Scenario 1: NG	Scenario 2: Storage
Other RE, TWh/year	0.28	0.28	0.28
Wind, TWh/year	11.40	11.40	11.40
Hydro, TWh/year	0.71	0.71	0.71
Biomass, TWh/year	0.31	0.44	0.31
NG, TWh/year	31.41	41.55	31.21
Coal/Peat, TWh/year	17.32	0.00	17.32

Figure 5.11 – Energy mix EnergyPLAN; Source: Modeled data.



	Ref. 2020	Scenario 1: NG	Scenario 2: Storage
Other RE, TWh/year	0.00	0.00	0.00
Wind, TWh/year	11.35	11.35	11.35
Hydro, TWh/year	0.59	0.75	0.65
Biomass, TWh/year	0.00	0.00	0.00
NG, TWh/year	31.82	39.50	31.82
Coal/Peat, TWh/year	17.31	0.00	17.31

Figure 5.12 – Energy mix dispatch model; Source: Modeled data.

To summarize, results from both models are very similar and hence it is confirmed by both EnergyPLAN and the dispatch model that replacing peat and coal generators in Scenario 1 grants a more flexible system, which results in both decrease in the total amount of fuel inputs for power generation and increases the NG consumption in power generation. Next, in both models tripling the HPES does not play a role in decreasing fuel consumption, as it replaces only an insignificant amount of NG from power generation. Unfortunately, the DH scenarios cannot be included in the dispatch model in order to verify the suggested by EnergyPLAN NG reduction in consumption, which was discussed previously.

5.2.2.3 CO_2 emissions from power generation

Below in Figure 5.13 are compared the annual carbon emissions from power generation from EnergyPLAN and dispatch model. The results are almost equal for each scenario, with small insignificant variations between the EnergyPLAN and the dispatch model. The results from both simulations are comparable between each other. Moreover, the results from the dispatch model further confirm the observations from the EnergyPLAN scenarios analyses, that in order to decrease the CO_2 emissions in the system, the most important step is to replace peat and coal capacities with CCGTs as according to both simulations, only with doing this, annual carbon emissions from power generation are reduced by a third. Both models confirm furthermore that tripling the HPES capacity in Scenario 2 does not grant almost any additional CO_2 savings as they are 0% and 0.3% respectively in the dispatch model and the EnergyPLAN model.

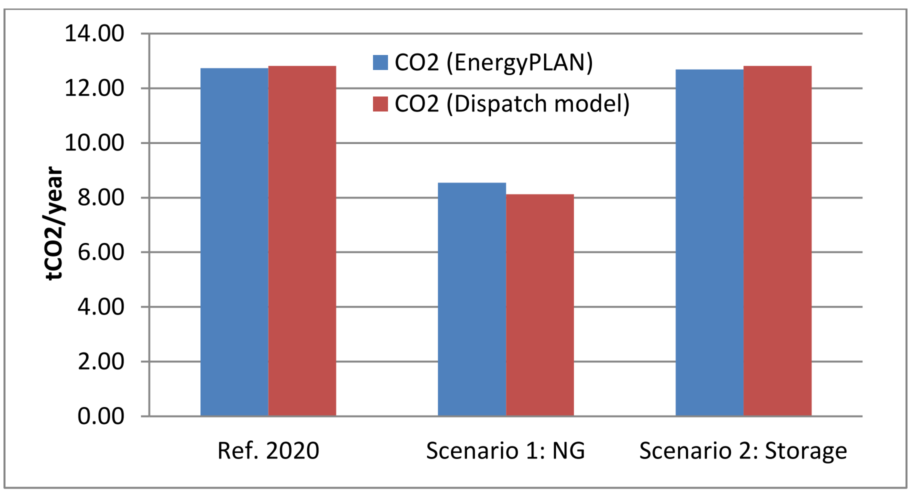


Figure 5.13 – Annual CO_2 emissions from power generation in EnergyPLAN and dispatch model; Source: Modeled data.

To summary, both models confirm that the most effective step in achieving carbon reductions in the power generation is abolishment of the coal and pear capacities. Increasing of HPES with the studied levels of installed wind power capacity do not offer almost any additional CO_2 savings.

5.2.2.4 Summary on analyses of both models

This subsection proved that both models describe the Irish power generation system accurately and the results from both simulations are comparable. Moreover, the results from the dispatch model confirm some of the previously discussed analyses, amongst others:

1) To begin with, replacing of coal and pear power generators with CCGTs decrease the surplus electricity production not significantly. Increasing the HPES capacity however

effectively reduces the excess production and hence the CEEP as a result of more flexible system;

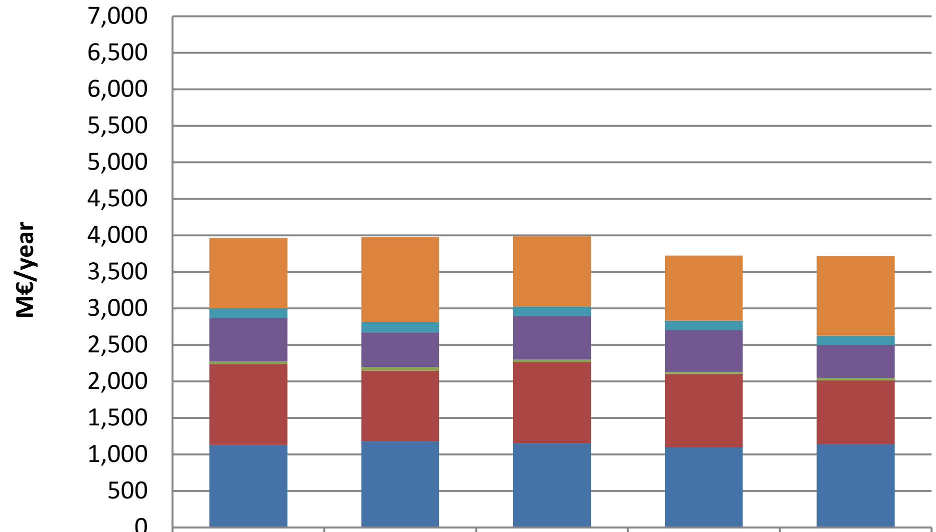
2) Secondly, abolishment of coal and peat capacity would decrease the total annual fuel consumption in power generation, but increase the NG dependency. Unfortunately, since the dispatch model simulates only the power generation, it could not analyze and confirm the EnergyPLAN result that including DH reduces the NG dependency as elaborates previously in this chapter;
3) Lastly, the dispatch model confirms that the most important step in achieving carbon reductions in the power generation is to replace coal and peat with CCGTs, which would reduce the carbon emissions by more than a third. At the studied in the scenarios levels of wind penetration, tripling the HPES capacity does not offer any additional carbon reductions.

5.3 COSTS

This subsection investigates the total annual costs for each scenario as it should be emphasized that the analysis is socio-economic, meaning that it includes external costs, such as CO_2. It is assumed that the price per tonne of carbon dioxide is €30 and is applied for the fuels used for power and heat generation in Ireland. It should be also taken into account that the all costs are used only for comparison between the scenarios and are only for orientation. The annual interest rate for investments is 6%. Next, there are no taxes on energy conversion used in the analyses as if they are included in policies, as for example carbon tax, it will have a strong impact on all scenarios, which include peat and coal. Last, but not least, it should be also taken into account that "sunk costs", such as closing generation capacities before the end of their lifetime, for instance: peat and coal power generators, individual boilers, etc., are not considered in this analyses.

Results from the performed costs analyses in this project are presented below in Figure 5.14, which encompasses the total annual socio-economic costs. From the results it is obvious that the system is most costly in the storage scenario, which amounts however to only 0.5% increase compared to the Reference 2020. This is a result from the highest capital cost due to tripled HPES capacity with almost none fuel or carbon reductions resulting from it. Second most expensive case, yet with only 0.3% higher than the Reference 2020, is in the NG scenario. This is a result the highest fuel costs including NG. The cheapest scenario is the combination one, which is with some 6.21% cheaper than the Reference 2020 model, followed by the DH scenario with about 6.04% cost reduction compared to the reference. Both are a result of saved fuels, CO_2 emissions and also re-investments in expensive coal PPs and individual NG boilers.

The results illustrate that the most important and costly part of the system are the fuels. Moreover, the high highest investment costs from HPES do not grant almost any fuel or CO_2 savings and hence the highest cost for the storage scenario. Furthermore, the annual fuel costs are lowest in the DH scenario with more than 8% than in the reference model, which is a result from decreased fossil fuels dependency. Next is the combi scenario, with 5.3% lower fuel costs than the reference model. The difference might become even higher with increasing of the prices of fossil fuels in future, as after a few decades it is expected the production to start decreasing and hence prices to rise. Furthermore, the total annual CO_2 costs are lowest in the combination scenario with about a quarter less than the reference model. Second lowest is the NG scenario with almost 21% lower CO_2 costs than the Reference 2020. Next, the fixed O&M costs are lowest in the DH scenario, followed by the combination one. Fixed O&M are highest in the NG. Lastly, the marginal operation costs aare lowest in the DH scenario, which are more than twice less costly than in the highest system model, namely the NG scenario. The other scenarios have almost equal marginal operation cost with insignificant differences.



	Ref. 2020	Scenario 1: NG	Scenario 2: Storage	Scenario 3: DH	Scenario 4: Combi
Total NG costs, M€/year	962	1,168	957	892	1,090
Fixed O&M, M€/year	132	138	134	125	130
Total annual CO2 costs, M€/year	598	474	597	577	450
Marginal operation costs, M€/year	35	49	35	23	36
Total fuel costs, M€/year	1,107	968	1,107	1,008	868
Annual investment costs, M€/year	1,128	1,179	1,153	1,097	1,142

Figure 5.14 – Annual total socio-economic costs; Source: Modeled data.

It is important to note the price of specific carbon reduction in M€/year/ΔtCO_2. This was calculated as the total annual costs were divided by the achieved carbon reductions for each scenario compared to the Reference 2020. The lowest specific carbon reduction has the combination scenario with 0.75 M€/year/ΔtCO_2, followed by the NG scenario wi th 0.96 M€/year/ΔtCO_2. The highest specific costs per a tonne of carbon reduction is in the storage scenario, amounting to almost 100 M€/year/ΔtCO_2, which is higher than the combination scenario by a factor of 133.

In summary to the performed costs analyses, it can be concluded that the NG sand storage scenarios have similar total annual costs as the Reference 2020 model, both within 0.5% higher. All these three system scenarios are higher than the DH and the combination scenarios, as the latter is the cheapest scenario from socio-economic perspective. The highest "heaviness" on the total costs have the fuel costs, as they are highest in the NG scenario and lowest in the combination scenario. CO_2

costs are lowest in the combination scenario. Lastly, no taxes on energy conversion were considered in the analyses (see explanation for socio-economic costs in Chapter 2: Methodology), but if taxes are introduced as result of policy, they will also have an impact on the results.

5.4 Sensitivity analyses

This subsection provides the results from all performed sensitivity analyses in this project, amongst others regarding: CEEP, fuel (excluding RES), CO_2 emissions and total costs. Sensitivities are made for each scenario as the mentioned energy system parameters are studied as a function of annual wind power production from 0 to 50 TWh. In 2020 it is expected that the annual wind power generation will amount to 11.7 MWh according to all scenarios.

5.4.1 CEEP sensitivity

Results from the performed sensitivity analysis for the annual CEEP in all scenarios as a function of the wind production are provided below in Figure 5.15. It is clear that in all cases the Reference 2020 and Scenario 1 have highest annual CEEP. On the other hand, the storage scenario together with the combination scenario have lowest CEEP, as the difference between them is insignificant. The results further show that up to wind penetrations of up to about 10 TWh/year the CEEP is constant is at fairly low levels from 0 to 0.02 TWh/year. For further penetrations of 10 to 15 TWh annually it steadily starts to increase as it could be distinguished in the different scenarios, and for wind power generation higher than 15 TWh per year, the CEEP increases very rapidly.

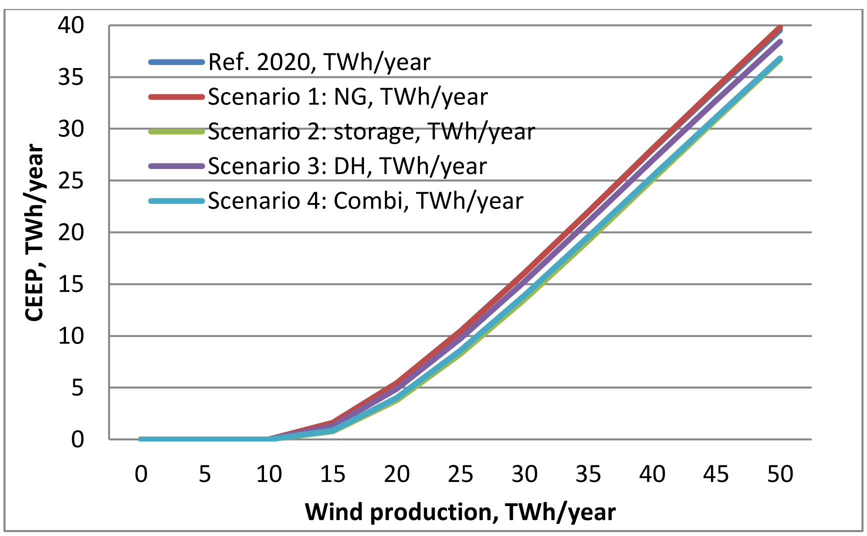


Figure 5.15 – Sensitivity analysis CEEP all scenarios; Source: Modeled data.

To summarize, the Reference 2020 has the worst CEEP performance from all studied scenarios. The storage scenario and the combination scenario have the lowest CEEP, which makes them best performing amongst the studied alternatives. The CEEP in all scenarios increases very rapidly for wind power penetrations above 15 and especially higher than 20 TWh/year. From power balance point of view, the optimal wind power penetration for Ireland is about 15 TWh annually and the best system scenario is the combination one. Yet it should be noted that with increasing the excess wind production, it could be expected that there will be more export, driven by the cheap marginal price, so the CEEP might decrease as a result.

5.4.2 Fuels consumption sensitivity

Next, sensitivity analysis for total annual fuel consumption, excluding energy from RES as it is the same for each scenario, are provided in Figure 5.16 below. From the results it could be considered that again the Reference 2020 is the worst scenario, with highest fuel consumption for all studied wind power penetration, followed by the storage scenario with a small difference. The combination scenario is clearly the best scenario in terms of annual fuel consumption as it has lowest levels amongst all studied scenarios. The study illustrates that for wind power production from 0 to about 10 TWh/year fuel consumption decreases steeply. Then for wind penetration between 10 and 15 TWh annually it still decreases, but with a lower rate. Furthermore, from about 15 to approximately 20 TWh of wind power per year the fuel consumption remains at rather constant levels for all scenarios, as it is interesting to be noted that for penetrations above 20 TWh the fuel consumption starts to grow again. This happens as a result of increased use of NG in the PPs after levels of annual wind production of above 20 TWh, because at so high levels of wind penetration it is a base load in the system, which results that CCGTs are used for regulation of the grid stability and therefore start consuming more NG at extremely high levels of wind power.

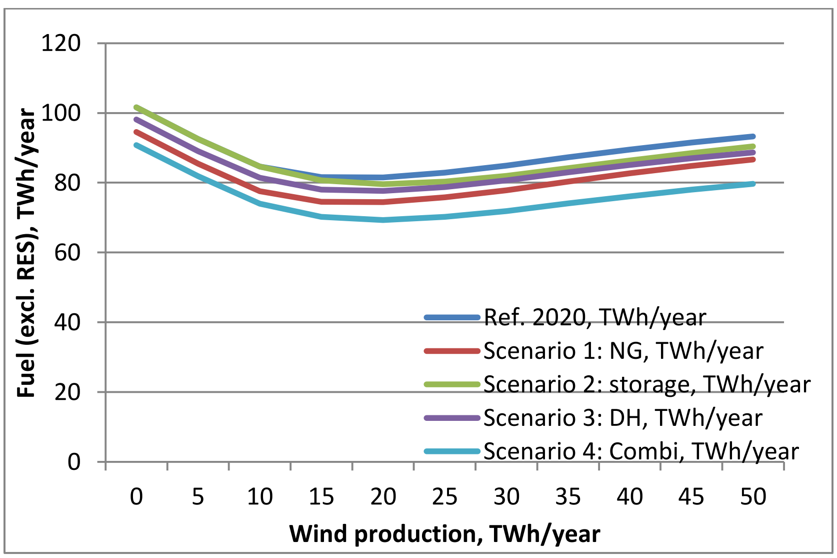


Figure 5.16 – Sensitivity analysis Fuel consumption all scenarios; Source: Modeled data.

In summary, sensitivity analysis for total annual fuel consumption for all scenarios as a function of the installed wind power capacity showed that the Reference 2020 is the worst scenario and the combination scenario has the best parameters. Results furthermore showed that the optimal levels of wind power for the studied systems from fuel balance point of view is about 15 TWh/year, which is equal to about 5,000 MW of onshore wind turbines capacity.

5.4.3 CO_2 emissions sensitivity

Furthermore, the annual carbon emissions development is also studied for all scenarios as a function of the wind power generation. The results are presented in Figure 5.17. Once again the

Reference 2020 is worst also from environmental point of view as in this case it is the highest carbon polluter, as a result of running peat and coal. On the contrary, it could be distinguished that the scenarios without peat and coal, namely the NG scenario and the combination one, have significantly lower CO_2 emissions than all other scenarios, which include peat and coal, as the combination scenario has the lowest carbon emissions per annum. Next, the trend of achieving carbon reductions is logically similar to the one of fuel consumption described in the previous subsection. The annual carbon emissions decrease rather steeply for wind penetrations from 0 to 10 TWh/year and then slightly less steep for the interval between 10 and 15 TWh. For penetrations from 15 to 20 TWh the CO_2 emissions remain at constant levels, as a result of no fuel savings with increasing the wind power. For penetrations of wind power higher than 20 TWh annually the CO_2 emissions start to increase again, as a result of increasing NG consumption because of the fact that at so high levels of wind energy, CCGTs operate more in order to grant grid stability, as explained in the previous section.

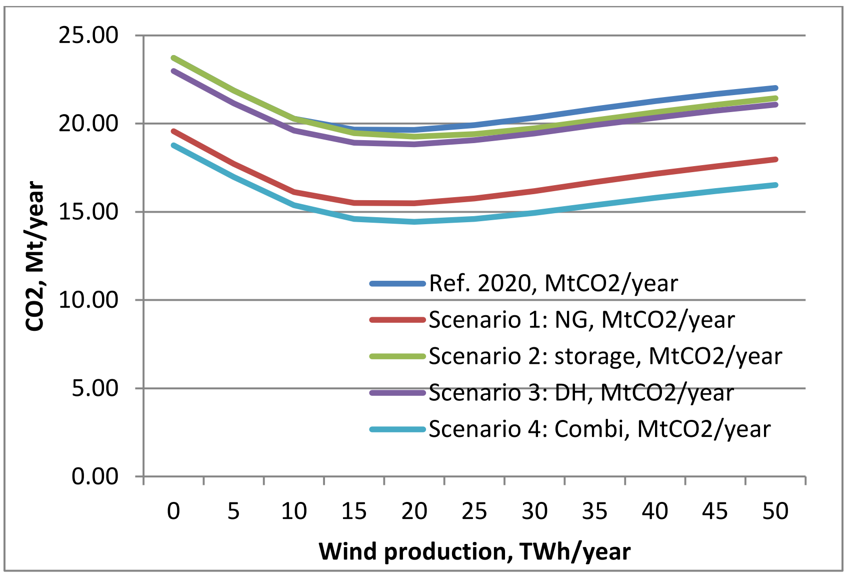


Figure 5.17 – Sensitivity analysis CO_2 emissions all scenarios; Source: Modeled data.

To summary, once again the Reference 2020 scenario is worst from environmental point of view, as the combination scenario is performing best with lowest carbon emissions. It could be distinguished that the most important measure to take in order to decrease carbon emissions is to abolish peat and coal capacities, as it is illustrated from the results the immediate and robust effect on the carbon reductions from this step. The optimal levels of wind penetration from this analysis also proves to be about 15 TWh, which is equal to about 5,000 MW of installed onshore wind power with wind power distribution of year 2011.

5.4.4 Total annual costs sensitivity

Moreover, sensitivity of the total annual system costs is studied also as a function of the wind power development in Ireland. The results are shown below in Figure 5.18. When looking at the results it should be considered that they are just for orientating and a small change in technology development and commercial availability, or in fuel prices, or taxation might seriously affect the total socio-economic costs presented in this study. Firstly, from the graph it is clear that the cheapest scenarios are DH and combination scenario as the differences between them are insignificant. The other scenarios are at a clearly higher levels with almost no changes. Next, from the results it could be seen that the total annual costs decrease with increasing the wind penetration from0 to around 10 TWh/year, the costs are decreasing, as a result from reduced fuels and CO_2 emissions. Then they have the same pattern as the fuels and the carbon emissions studies, namely: from 15 to 20 TWh of wind power production the costs are remaining at rather constant levels and for penetrations higher than 20 TWh per annum, the costs start to increase again for all scenarios. This is again a result from increasing both fuels used and emitted CO_2.

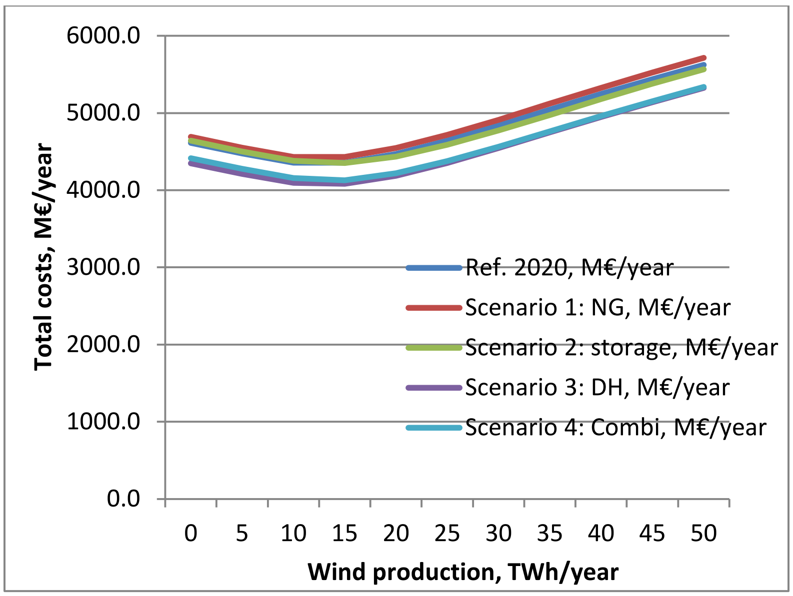


Figure 5.18 – Sensitivity analysis total annual socio-economic costs all scenarios; Source: Modeled data.

To summarize, from the total annual costs sensitivity analyses it could be concluded that the storage scenario has the highest annual total costs, as a result from large investments in HPES capacity without significant fuels savings as a result. The DH and combination scenarios have lowest costs, which makes them the best scenarios. From socio-economic point of view the optimal wind power penetration in Ireland is also around 15 TWh/year.

5.4.5 Summary on the sensitivity analyses

In summary of the sensitivity analyses in this study, several major points have to be remarked, as follows:

1) From power balance, fuel balance and environmental point of view, the worst scenario is the Reference 2020, while the best is the combination scenario;
2) From socio-economic cost point of view, taken in mind that cost for different technologies vary in time according to their maturity, as well as fuel prices according to the production on the international fuel market, it should be noted that the cheapest scenario is the combination scenario, with a small difference followed by the DH one. The high storage

scenario is clearly the most expensive one, while the Reference 2020 scenario has rather medium-high costs;

3) From all sensitivity analyses it could be concluded that the optimal wind penetration for Ireland is estimated to around 15 TWh/year, which could be produced by around 5,000 MW of onshore wind turbines capacity using the wind distribution of 2011. It should be however emphasized that this conclusion is for the specific assumptions for this study, which take into account electricity and heat sectors, but not the transportation sector. With inclusion of the transportation, the feasible wind penetration might be much higher, as result of the additional flexibility from electric vehicles or especially V2G, which is the case e. g. for Denmark.

5.5 Summary on all analyses in the project

In order to shortly summarize the results from the analyzes provided in this study, the main findings are listed as follows:

1) The Reference 2020 is the worst scenario from power balance, CEEP, fuel balance, CO_2 emissions and PP operation point of view. This is a result from ran as a base load peat and coal power generators;
2) Increasing the HPES is the most effective measure to cut the CEEP, but does not reduce fuel consumption and CO_2 emissions. This was verified by both EnergyPLAN and Excel based dispatch model. It is also the most costly scenario, due to the very large investment costs in HPES capacity. However, replacing peat and coal with CCGTs grants both fuels and carbon reductions. Introduction of DH in Dublin decreases furthermore fuels and emissions, as it adds flexibility and efficiency to the system;
3) The best technical scenario is combination of replacement of peat and coal capacities with new CCGTs, doubling the HPES and including DH, as this scenario does not only have the best technical parameters up for the reference year 2020, but also for future development of the wind power in Ireland. The combination scenario has also the lowest socio-economic costs.
4) The cheapest specific carbon reductions are achieved in the combination scenario at levels of 0.75 M€/year/ΔtCO_2; second is the NG scenario with some 0.96 M€/year/ΔtCO_2. The storage scenario is worst with almost 100 M€/year/ΔtCO_2.
5) From the sensitivity analyses it could be concluded that from both technical and socio-economic point of view, the optimal wind penetration in Ireland is about 15 TWh/year, which is expected to come as output from about 5,000 MW of onshore wind turbines capacity. Yet if the transportation sector is included it could be expected that the feasible wind penetration would increase, as a result of additional flexibility.

Based on these findings, the following Chapter 6 discusses the policies that should be implemented in order these improvements to be achieved.

CHAPTER 6: POLICY ANALYSES

The chapter tends to provide a discussion about the existing key energy policies in Ireland and their interaction with the results from technical and socio-economic analyses provided in the previous chapter.

Firstly, a rather general stakeholder analysis is made in this chapter in order to define the main stakeholders and their roles in the energy sector in Ireland. Secondly, preliminary policy proposes are made, which are based on the results of the analyses in this project and are not in the current key energy policies in Ireland, which were described in Chapter 1.

6.1 MAIN STAKEHOLDERS ANALYSIS

To begin with, the Irish Government is one of the major stakeholders in the energy system development. Moreover, most of the power plants in Ireland, including Moneypoint, the HPES at Turlough Hill and several CCGTs and open cycle GTs as well as two large peat PPs are state-owned through ESB. Documented by the discussed in Chapter 1 of this report policy measures taken from them in order to improve the system, it can be considered that the Government strives not only to meet its compulsory EU 20/20/20 targets (see Chapter 1) regarding carbon reductions, RE and EE improvements, but also has a long term vision for the development of green energy sector in Ireland. Their goals are to achieve high RE penetration, which is mostly focused on wind power as well as improve efficiency in heating, however at the lowest possible costs, which is also driven by the current global financial crisis. The Government furthermore strives to have a stable, least possible import dependent, diverse and secure energy supply, as well as jobs creation in the energy sector.

Secondly should be mentioned a number of non-governmental organizations, for instance Sustainable Ireland (Sustainable Ireland), Stop Climate Chaos (Stop Climate Chaos), etc., whose interests are to protect the environment and mitigate climate change, which amongst other means replacing fossil fuels energy generation with RE. They do not have decision taking power, but can lobby the formerly discussed stakeholder – the Government, to vote more climate friendly technologies.

On the other hand, business organizations, such as: Energia from the Viridian Group (Viridian Group), which own two new CCGTs as well as wind turbines though, Edenderry Power Limited (Edenderry Power Limited) owing a large peat PP, are another main stakeholder. Driven mainly by business interests, their main goal is to make maximal profit with minimal expenditures. Such organizations have historically the largest lobby in the Government, which in the neoclassical market economy is much higher than the new RE technologies lobbies (Hvelplund, Mendoca & Lacey 2009).

Last, but not least stakeholder in this analysis is the society, which also includes customers. Society's goals are normally secure and affordable energy supply, developed economy, secured jobs, clean climate, etc. Government is the stakeholder, who has to grant them their goals by implementing the correct policies.

Hvelplund in his work (Hvelplund, Mendoca & Lacey 2009) defines that for radical technological change, such as transition from fossils to RE the neoclassical market economy is not sufficient, but the market should be structured as institutional innovative democracy, which is presented below in Figure 6.1. The figure clearly describes how the main stakeholders interact between each other in order to achieve the goals of society. It is apparent that the political unit should consist not only from old technologies lobbies, but also from new technologies and NGOs. Also there should be a transparency in the processes, driven by a public debate. Very often it had been the case that because of lack of transparency in the public discussion, not all possible options for energy supply are presented in public. On the contrary, it had been shown to society that only fossil fuel decisions are available or are the only economic, which years after proved not to be the case. All options should be presented and evaluated from socio-economic perspective, but not business economic. (Lund 2009) This is also the case for the public debate in Ireland now as for example in all plans and official documents there is not analyzed and showed in public alternatives to the coal and peat generation such as DH and CHP for example, which proved to be the most effective optimizations of the Irish energy system in this project.

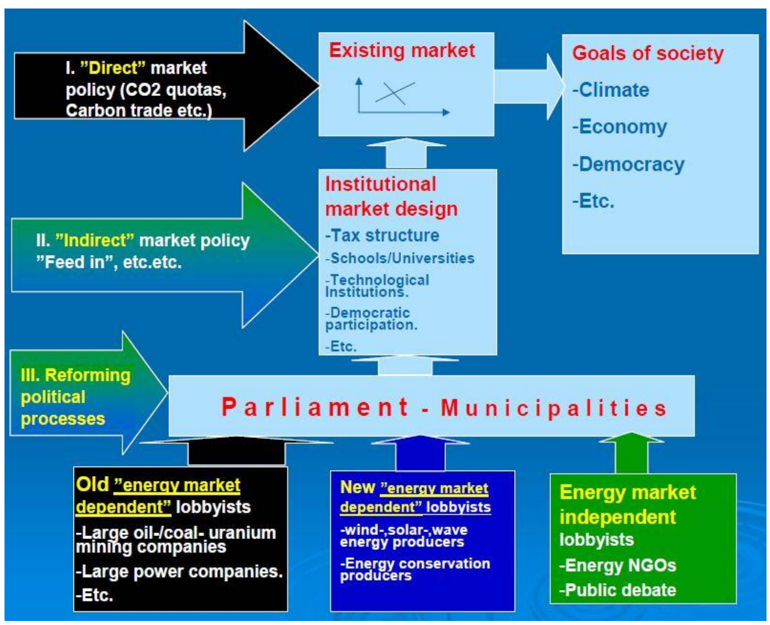


Figure 6.1 – Innovative democracy structure; Source: (Hvelplund, Mendoca & Lacey 2009)

To summarize, this subsection presented the main stakeholders in a broad perspective. It moreover discussed what should the market structure be in order to achieve the goals of society and presented the Innovative democracy structure as well as lack of public awareness regarding alternatives for energy generation.

6.2 POLICY PRELIMINARY SUGGESTIONS

First and foremost these policy suggestions are only preliminary and very general. They should be considered only as a first step in a new direction for the Irish energy system.

From the proposed optimizations of the heat and power energy sectors in Ireland, it is apparent that not only each scenario is better than the Reference 2020 model and also that the combination scenario is best in all technical and socio-economic aspects, with certain considerations regarding the costs. Moreover, all proposed changes contribute to system optimizations and there is synergy between them. In order to achieve combination of all technical modifications it does not matter the order in which they should be performed. Yet it really matters the time each of them take in order to be effectively implemented. Below is presented a possible order, in which the proposed changes can take place. <u>It should be noted that achieving these measures is possible to come as a result from direct and indirect market policies</u> (see the figure above).

- <u>Replace coal and peat generators with new CCGTs</u>

Substituting the coal and peat power generators with new capacity of about 800 MW CCGTs should be the first step. Clearly from the analyses they are the worst carbon polluter, they are inefficient and inflexible and hence hinder wind power development. It could be considered that without much effort, they could shut down in one to two years after taking the decision. Building the new CCGT capacity should also not take more than two-three years, but it should be noted that there is overcapacity, which means that the power demand could be met even with the available generators, without peat and coal. It should be mentioned that this measure will be opposed not only from the old technology lobbies, but also from others, as for example there will be sunk costs including the recent Government investment of €368 to retrofit the coal PP Moneypoint.

- <u>Introduce district heating in Dublin</u>

Introduction of DH in Ireland is a rather drastic change, as there has not been used before in the country. Therefore if could be expected to take a longer period of time for the whole project 5 to 10 years. Yet it could be separated into few steps, say two times by five years. It requires building of heat generation facilities, which could happen without many efforts, rather cheaply and quick by retrofitting of an existing gas turbine plants into CHPs and building a DH boiler. However, DH grid should also be built, which is the most expensive and time consuming element of the system. In the buildings already exists central heating systems with the whole inner heating circle, so only the DH substations should be mounted, which consist of heat exchangers from both space heating and DHW, shutting and measurement valves, strainers, etc. It should not be underestimated that this is a very new system for Ireland, and it could be expected to have difficulties in implementation on all levels, also from the society, as it could be even considered cultural change. Therefore DH should be promoted on all through both direct and indirect market policies. Denmark is an excellent example of how DH could be implemented cheaply and effectively, even on much less energy dense areas than Dublin. It should be mentioned that the new EU Directive 2012/27/EU on energy efficiency (European Commission 2012) requires utilization of DH and CHP in the member states. DH systems are currently developing in other countries, e.g. the UK as in the city of London there are already plans and financial support for development of DH (London.Gov.UK 2013). Moreover, in the

Netherlands there are also successful ongoing as well as already completed DH projects, such as geothermal DH installation in Hague (Geoenergy 2012).

- Increase the HPES capacity (optional)

Illustrated from the technical analyses HPES does not provide neither substantial fuel savings, nor carbon reductions. Yet it offers excess production reduction and further added flexibility. It was investigated only HPES in this report, but also other storage technologies can be developed over a broader time horizon, which could be also used, such as batteries, etc. However, it is considered optional as the two further measures bring much more flexibility as well as efficiency to the system. Building new HPES could be also expected to be done within a rather long time frame over e.g. 10 years, as there are difficulties from geographical location and public acceptance point of views

To summary, this subsection discussed the proposed technical improvements in the system, which have to be achieved by both direct and indirect market policies. It is considered that it the first two measures are the most important to be taken in order the previously described goals of society to be achieved.

6.3 Business perspective

The investments, as well as studies and design of both policies and technical system design, as well as building and implementing the facilities require investments. It should be studied in details the concrete structure of the market in Ireland as well as a detailed business plan should be prepared. This section only discusses very broadly the roles of the main stakeholders in the implementation plan.

Firstly, for abolishing peat and coal capacities, the owner of almost all three out of four of these plants (ESB Ireland 2012) is state-owned, these plants could be left as a strategic reserve and no money will be paid to private companies for their decommissioning them. Moreover, if the money which is required to invest in the new CCGTs could be lent from the Government with a very low interest e.g. 3%, then private companies will have the option to build the new PPs affordably. Furthermore, the Danish example for DH should be taken into account when implementing DH in Ireland. In Denmark all the DH companies are publicly owned by the municipalities and are non-profit organizations and therefore it is cheap to build DH in Denmark as they can lease money at very low interest rates. In order to attract financing also from the business, different schemes for subsidizing CHP production can be also combined with low interest rates loans for building the plants. In this way, both public investments for building and maintaining the DH grid will be involved, as well as private investments for building and operating the CHPs will be attracted.

In summary, this chapter provided only preliminary policy proposals very broadly discussed from the perspectives of different stakeholders, which should be further studied and also compared to other measures, which could provide the required results in order the goals of society to be achieved.

The next chapter concludes on the whole project and answers the research question.

CHAPTER 7: CONCLUSIONS AND FUTURE WORK

This chapter summarizes on the entire project and answers the research question through the provided analyses. It presents how the problems defining the research questions are addressed in the project and how they could be solved. In the second subsection of the chapter it is reflected upon the project delimitations and discussed the consequences to which they led in the analyses. Lastly, it is discussed what could be considered as future work on the topic.

7.1 CONCLUSION ON THE ANALYSES

It was outlined in Chapter 1 that the project strives to study how the goals of Government regarding both EU 20/20/20 goals and national targets from socio-economic point of view can be met, which amongst others are: carbon reductions, increasing RE share (mostly wind power), reducing fuel consumption, limiting import fuels dependency, etc., with a "check-point" year 2020, but also investigate the future development of the energy sector. A main issue was defined the fluctuating character of wind and its integration in the power system. The **first problem** was defined of the currently limited flexibility of power generation system and consequently more troubled power balancing with high wind penetrations. Furthermore, wind power practically replaces NG power generation, and therefore carbon reductions are not effectively achieved in the present Irish power generation system, which is the definition of the **second problem**. Lastly, this report is inspired also by the **third problem**: extensive use of natural gas as a partner for wind energy increases natural gas consumption and import dependency.

In order to solve the above described problems, it was defined the research question of this study:

- *How can the Irish energy system be designed in order wind energy to both reduce CO_2 emissions and minimize natural gas imports?*

In order to achieve a general understanding, two models were used. Firstly, an Excel based dispatch model for year 2011 was created with quarter hourly data from Eirgrid, which includes only the power generation. Secondly, the EnergyPLAN energy analyzing tool was used to simulate the operation of the Irish heat and power sectors for the same year on an hourly resolution. Then the results for the power sector were compared and verified. Furthermore, overall five different scenarios (see section 5.1 of Chapter 5) of technical modifications of the Irish heat and power system in year 2020 were investigated on their technical characteristics, amongst others: excess power generation, CEEP, fuel balance, CO_2 emissions, energy storage operation. Moreover, they were also compared through their annual total socio-economic costs, which include: investments, total fuel costs, marginal operation costs, fixed and variable O&M costs, CO_2 costs. Finally, sensitivity analyses were performed in order to study the already described power system parameters as a function of installed wind power capacity.

Consequently several conclusions derive from the results of the analyses. Firstly, the Reference 2020 system is the worst in all terms of technical operation compared to the proposed modifications as it is the most inflexible and the most inefficient. From socio-economic point of view it is in the middle as it is more expensive than the DH scenarios. These observations are also confirmed by the sensitivity analyses. Secondly, the best system in terms of both technical operation and socio-economic costs is the combination scenario. It is as a result of synergy between all proposed technical modifications and mostly because of the added flexibility and efficiency from including DH and abolishment of peat and coal generation. The second cheapest scenario is the DH one. Thirdly, looking at the CO_2 emissions, there can be sharply distinguished the scenarios, where peat and coal generators are substitute with NG ones, which means that the only effective way of achieving carbon reductions is to abolish the peat and coal PPs. Furthermore, the purely energy storage scenario proved to be not only the most expensive in socio-economic terms, but also the most inefficient in achieving CO_2 reductions. On the contrary, including DH rapidly decrease the CO_2 emissions as a result of higher efficiency in energy generation. Next, the optimal wind power penetration according to the results of this study is about 15 TWh/year, which is estimated to come from about 5,100 MW of installed onshore wind power. Lastly, as discussed in the previous chapter for policy analyses, there currently do not exist neither policies, nor incentives in Ireland to support the proven in this analysis most effective way to decrease carbon emissions as well as fuel consumption, namely building CHP and DH as well as substitution of peat and coal generators abolishment. Such were proposed as well as crude stakeholders and implementations analysis was also proposed in the chapter.

To answer the research question, the performed technical and socio-economic pre-analyses showed that the optimal system modification is in Scenario 4: Combi. The system design in the combination of all proposed measures both reduces CO_2 emissions from power generation most effectively, but it also minimizes the NG consumption. The two main pillars of this system are substitution of coal and peat generators with CCGTs and including DH and CHP for the feasible part of Dublin. The third element, namely doubled HPES, only is utilized for short periods for grid stabilization and its increasing does not meaningfully affect fuel balance and CO_2 emissions and is hence considered optional. On the other hand, including DH is a key element for such a system and should be considered a key technology for utilizing more wind power, together with flexible PPs. The report concludes that for optimal harvesting of wind power, it is important to have a flexible coherent energy system instead of adding flexibility to a currently inflexible one with increasing the HPES capacity. The main findings from this report could be also generalized through the proportions of the key new technologies in the combination scenario as follows: for each TWh of annual wind power production, there should be about 0.77 TWh/year of DH demand and about 19 MW of installed HPES in order optimal results from the implementation of wind power in Ireland to be achieved.

7.2 FUTURE WORK

There are two main consequences from the project's assumptions, which were made because of the short project period. Firstly, the study investigates only the heat and power sector, but not the coherent energy system, which also includes transportation. For future work transportation should also be studied with the different types of smart el. vehicles, especially V2G technology and hybrid cars, which will grant further flexibility into the system, which means that more wind power can be utilized than the suggested by this study 15 TWh/year. Secondly, using historical time series for electricity trade is incorrect, because they change in time. For instance in this study were used time series from 2009, when the installed wind power was about 1.3 GW, but in the reference year 2020 is expected to be tripled, which will result in cheaper marginal price of the electricity and hence more higher export through the interconnectors. Another element which was not studied is also the power market, in particular the local energy systems in UK close to the interconnectors to Ireland, in order to achieve general understanding from where and on what cost they supply power the el. demand. The last two points drive the export of power from excess capacity in Ireland to the UK and from them depends the annual amount of exported wind power.

For future work it should be considered to include the above mentioned two main points in the study as it could be anticipated that it will increase the validity of the report as well as improve the studied system flexibility and give more realistic figures regarding the system operation as a function of increased wind penetration.

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APPENDIX

Please note that the appendixes can be also downloaded from:

https://drive.google.com/folderview?id=0BwqOj-RJtGz3MmF5a212Q3hEajA&usp=sharing