An Investigation into how Renewable Energy can be Successfully Integrated into the Irish Electrical Transmission System

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DECLARATION OF ORIGINALITY

September, 2011.

The substance of this thesis is the original work of the author and due reference and acknowledgement has been made, when necessary, to the work of others. No part of this thesis has been accepted for any degree and is not concurrently submitted for any other award. I declare that this thesis is my original work except where otherwise stated.

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ABSTRACT

Policy makers worldwide are currently promoting the use of renewable energy sources as concerns over global climate change continues to grow. These resources are substantial, and in particular wind energy, which could in theory supply all of the electricity demand of the US and northern Europe, whilst also acting as a means of meeting emissions reduction targets. However, these resources are by no means perfect as their intermittent character presents formidable barriers to their utilisation on the scale required by a modern industrial economy.

The integration of increasing levels of renewable power, mainly wind, combined with the deregulation of electricity markets have resulted in some unconventional operation of base load units. These units have been designed to operate continuously and are therefore not suitable for flexible or cycling operation which results in a physical degradation of the unit's components and increased costs for the plants operators.

In contrast, the combination of a wind energy generator and energy storage possess the potential to produce a source of electricity that is functionally equivalent to a base load coal or combined cycle gas turbine power plant without the aforementioned increased operational and maintenance costs.

In this paper a model was developed to assess the impact of combining wind generation and dedicated large scale energy storage to form a base load wind energy system capable of providing the base load required by Ireland. In order to complete such as assessment, the impact of the proposed system on the conventional thermal plant mix, demand profile and net load of a power system are presented. Additionally, the benefits and savings of such a system including the fuel savings and emissions benefits are highlighted.

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LIST OF ACRONYMS

Symbol	**Description**
AC	Alternating Current
BESS	Battery Energy Storage System
BEV	Battery Electric-Vehicles
CAES	Compressed Air Energy Storage
CCC	Capacitor Commutated Converters
CCGT	Combined Cycle Gas Turbine
CDM	Clean Development Mechanism
CER	Commission for Energy Regulation
CO_2	Carbon Dioxide
Cp	Coefficient of Power
DC	Direct Current
DG	Distributed Generation
DSM	Demand Side Management
DSO	Distribution System Operator
EES	Electric Energy Storage
EPRI	Electric Power Research Institute
ERSI	Economic and Social Research Institute
ESB	Electricity Supply Board
ETS	Emissions Trading Scheme
EU-MENA	European Union – Middle East North Africa
EV	Electric Vehicle
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GJ	Gigajoule
GRPS	General Packet Radio Services

GW	Gigawatt
HTLS	High Temperature Low Sag
HVDC	High Voltage Direct Current
IAMU	Iowa Association of Municipal Utilities
ICT	Information and Communications Technologies
IEEE	Institute of Electrical and Electronic Engineers
IHD	In home display
LAN	Local Area Network
MJ	Mega joule
MW	Megawatt
MWh	Megawatt-hour
NREAP	National Renewable Energy Action Plan
OCGT	Open Cycle Gas Turbine
PCGS	Personal Consumption of Goods and Services
PHS	Pumped Hydro Storage
PLC	Power Line Carrier
PSO	Public Service Obligation
RF	Radio Frequency
SEV	Smart Electric-Vehicle
SEM	Single Electricity Market
SMES	Superconducting Magnetic Energy Storage
TER	Total Electricity Requirement
ToU	Time of Use
TSO	Transmission System Operator
UNFCCC	United Nations Framework Convention on Climate Change
VAR	Volt Ampere Reactive
VPP	Virtual Power Plants
V2G	Vehicle to Grid

CHAPTER 1

INTRODUCTION

1.1 Thesis Statement

This thesis is entitled, "An investigation into how renewable energy can be successfully integrated into the Irish electrical transmission system".

Electricity networks are vital national infrastructure in terms of supporting economic development (Shine, 2009). They are also increasingly crucial to the delivery of EU and national sustainability targets. For example, the Irish government has set a target of meeting at least 33% of electricity demand from renewable generation by 2020 (DCMNR, 2007). In order to achieve the aforementioned targets radical change is needed in the design, operation and embedded intelligence of electricity networks. Networks of the future will have to be smarter, more accessible and more efficient (Shine, 2009). These networks must be capable of accepting large amounts of new renewable and conventional generation. Developing and deploying these networks can help Ireland realise the great promise of renewable energy sources while also helping to meet our ever-increasing energy appetite (GE Energy, 2010).

1.2 Background

There is now consensus among governments worldwide that there is a need to urgently address the threat of climate change from carbon dioxide (CO_2) and other greenhouse gases and hence develop a more sustainable relationship with the planet. Electricity generation has been identified as a key area under which this can be achieved as it is one of the largest sources of CO_2 production (Shine, 2009).

Ireland has set a target of 40% of electricity to be generated from renewable sources by 2020 (DCMNR, 2007). This will require over 6,000 MW of renewable generation connected to the electricity networks (Shine, 2009). The increasing production of renewable electricity and the geographical restructuring of the conventional power generation combined with the expected increase in electricity demand, has led to a situation where the current transmission grid will not suffice in satisfying future electricity needs (Haas et al., 2009). Ireland's electrical transmission system has little capacity for further growth because since the mid-1980s the power network has changed little while demand in the same period has grown by over 150% (EirGrid, 2008). In some parts of Ireland overburdened power lines make it difficult to move electricity from wind farms into the grid for public consumption. Attempting to squeeze more power through the lines than is possible results in grid congestion and the loss of potential power (GE Energy, 2010).

Ireland's network of the future will need to have bidirectional power flows at different voltage levels and thousands of generators at customer sites exporting energy onto the system. Resolving these challenges in ways that are economically viable and also enhance the security of supply are critical elements of the smart networks journey (Shine, 2009).

1.3 Hypothesis

If the current Irish electrical transmission system was upgraded it would have the following benefits (EirGrid, 2008):

- Ireland's natural renewable sources of energy (primarily wind & wave) would be fully exploited;
- By transmitting renewable energy in line with Government Policy, Ireland's carbon emissions would be greatly reduced;
- Ireland's connectivity to the European grid would be increased, which would in turn allow for both bulk exports of electricity and imports of electricity when appropriate.

1.4 Thesis Goal and Significance of Thesis

The purpose of this research was to evaluate the various different approaches and techniques available to integrate renewable energy sources into modern power systems. Such methods must be capable of transmitting renewably generated electricity from a variety of small and large generation sites scattered over wide areas with the ability to manage both fluctuating supply and loads.

The author examined the feasibility of investing in a base load wind energy system to be integrated into the Irish Transmission System. This system will seek to provide the base load requirement for Ireland through a combination of generated wind energy and energy storage technologies. The environmental and energy benefits will also be examined.

If significant investment in the transmission system does not take place the consequences of non-action are (EirGrid, 2008):

- The drive to reduce Ireland's CO_2 emissions and meet its targets for the use of renewable energy in compliance with legislation will be seriously undermined;
- Within the next five to ten years vital parts of the current grid will have reached capacity and will hence be in danger of overloading. This may result in loss of supply to customers;
- High-tech industry that requires secure, high quality energy supplies will be limited to locations with strong grid infrastructure;
- The power system will not be able to guarantee security of supply;
- Ireland will not be strongly connected to the European Grid and will be unable to participate fully in a pan-European electricity market.

1.5 Research Overview

This thesis is primarily a research thesis with the bulk of the effort focussed on the possible design of a sustainable generation and transmission system for Ireland that will in part help to combat the climate change concerns and secure its electricity supply.

The author's initial research into this area revealed that the topic of integration of renewable energy sources into electrical transmission networks is a worldwide issue. Research is being completed into Supergrids with the DESERTEC concept of the Club of Rome the leading vision to-date (Haas et al., 2009).

The largest technically accessible source of energy on the planet is located around the equatorial regions of earth (DESERTEC, 2009). The DERERTEC concept is designed to bring desserts and existing technology into service to improve global security of energy, water and the climate. The concept proposes that Europe, the Middle East and North Africa (EU-MENA) begin to cooperate in the production of electricity and desalinated water using concentrated solar thermal power and wind turbines in the MENA deserts (DESERTEC, 2009).

The first part of the research entailed a review of the studies and theories that support and oppose the integration of renewable energy sources into electrical transmission networks. The initial research completed suggested that while the sheer magnitude of the investment will be great and technologically challenging it is however an achievable feat.

1.6 Approach/Methods

Two different research methods were utilised in this research project, qualitative and quantitative. The qualitative research method is typically utilised during earlier phases of research projects where the researcher may only have an idea of what he/she is looking for. The aim of this type of research method is to complete a rather detailed description of a chosen topic or area (Miles & Huberman, 1994). As the researcher gathers data a clear design emerges. This method of research is quite subjective and the individual's interpretation of events is important (Miles & Huberman, 1994).

On the other hand, the quantitative research method is often utilised in the latter phases of research to firstly classify features, then count them and construct statistical models in an effort to clearly illustrate what is observed (Miles & Huberman, 1994). In contrast to the qualitative method, the researcher in this case knows exactly in advance what he/she is looking for and uses questionnaires or equipment to collect numerical data. The objective is to present precise measurements to test the particular hypothesis while the researcher generally tends to remain objectively separated from the subject matter (Miles & Huberman, 1994).

The vast majority of material presented in this thesis was done so using the quantitative research method. For example, this type of research method was utilised during the author's examination of the existing electrical transmission system in Ireland including its weaknesses and its environmental impacts. This type of research method was also used during the exploration of the possible renewable sources available in Ireland to replace those currently in use.

The quantitative research method was also used in the latter stages of this thesis during which an analysis of the possible introduction of a base load wind energy system for Ireland was proposed to enable the optimisation and use of high percentages of wind power to ultimately improve our energy security.

In this thesis data was retrieved from bodies such as the Commission for Energy Regulation (CER), the Sustainable Energy Authority of Ireland (SEAI), the Electricity Supply Board (ESB) and EirGrid. This data was then used to examine the current generation sources and the present demand on the system. The data was also used to find weaknesses in the current system and reveal what the future demands are likely to be.

An examination of both the conventional methods and possible putative renewable sources of electricity generation was compiled by the author to point out the effects of conventional methods on resource depletion and the obvious benefits of adapting to renewable energy sources.

Based on a collation and analysis of the literature review, the author will make a proposal for a future sustainable electricity supply system with the possible introduction of smart grids and Irelands integration onto a European Supergrid.

1.7 Thesis Structure

This thesis consists of five chapters covering different aspects relating to how renewable energy can be successfully integrated into the Irish transmission system. An appendix is also included to support the information presented in the main thesis body.

Chapter 2 gives a review of the literature that has been completed in the field of integration of renewable energy. This includes details in relation to the drivers behind the promotion of renewable energy sources and energy management. An overview of the Irish transmission system is detailed also in this chapter through the examination of the national grid, its limitations and future strategies to develop it. The remaining sections of chapter 2 discuss the methods by which renewable energy can be integrated onto the grid. These include distributed generation, energy storage, demand side management and the development of future power grids.

Chapter 3 presents the base load wind energy system concept made in this thesis and the model used to highlight its potential if it were to be adapted. Ireland was chosen as the case study to run the model on. The wind farm data generated using the model is discussed and the importance of the Weibull distribution statistical tool is highlighted in detail in this chapter.

Chapter 4 details the results of the model developed in the previous chapter. These results include the emissions and fuel savings benefits of a base load wind energy system. Additionally, the impacts of such a system on the demand profile and net load are provided along with a look at the cost of future options to meet demand.

Chapter 5 presents a discussion of the issues raised in this thesis and considers the impact of future penetration levels of renewable sources. The main conclusions of the thesis are presented and some directions for possible future research are provided.

CHAPTER 2

LITERATURE REVIEW

2.1 Drivers for Energy Management

2.2 Introduction

Energy is the life blood of modern society. The well-being of our people, industry and economy depends on safe, secure, sustainable and affordable energy (COM 639, 2010). The worrying fact is, European energy requirements are primarily provided by the combustion of fossil fuels. The consequence of this heavy dependence on fossil fuels is becoming increasingly concerning. Fossil fuels have limited potential, and at the current rate of exploitation, it is expected that these resources will deplete within the coming decades.

However, the security of supply issues is not the only concerning factor from an over-reliance on fossil fuels to meet energy demand. The resulting CO_2 released into the earth's atmosphere from the burning of fossil fuels restricts the earth from radiating the heat from the sun back into space, resulting in the rise in global temperature. This global issue known as the greenhouse effect causes dramatic climate change.

As an alternative, renewable energy resources offer clean alternatives to fossil fuels. In effect they produce little or no pollution or greenhouse gases. They are widely available within Europe and will never run out. It is of no surprise therefore that one of the key objectives of

European energy policy is a substantial increase in the use of renewable energy sources, coupled with a massive increase in energy efficiency.

Energy is an essential component for economic development for any nation. Despite this fact however, Europe continues to waste at least 20% of its energy due to inefficiency. The direct cost of these actions amounts to more than €100 billion annually (COM 545, 2006). If Europe is to lead the way in reducing energy inefficiency, all available policy tools must be introduced at all different levels of government and society.

Energy efficiency is by far the most effective manner in which a greater level of security of supply can be achieved, a reduction in carbon emissions and the fostering of competitiveness. It can also stimulate the development of a market for energy-efficient technologies and products. Even when the initial investment costs are taken into account, this statement remains equally true.

The European Commission has introduced a strengthened policy which is aimed at more energy efficient consumption and production patterns to collaborate with the energy saving target of 20% by 2020. In order for this saving to be realised a significant shift in our approach to energy consumption will have to occur. The behavioural patterns of our societies must change to the degree that we use less energy while still enjoying the same quality of life. Encouragement must be firstly given to producers to develop more energy-efficient technologies and products and secondly stronger incentives must be given to consumers to purchase such products and use them rationally.

The following sections will examine the drivers for energy management such as climate change, security of energy supply and economic drivers. Particular attention is given to both the national and European drivers including the relevant policies, standards, legislation and initiatives that are driving energy management.

2.2.1 Kyoto Protocol

The Kyoto Protocol was agreed upon on in December 1997 in the city of Kyoto Japan to combat global warming. The treaty was introduced as a means of implementing both the objectives and principles agreed in the previous UN Framework Convention on Climate Change (UNFCCC) of 1992 (Grubb and Hite, 2008). The central theme upon which the treaty was based is that the stabilisation of the atmosphere can only be achieved through an agreement whereby governments must quantify limits on their greenhouse gas emissions. This will involve sequential rounds of negotiations for successive commitment periods. The treaty came into force on the 16th of February 2005 and by July of 2010 a total of 191 states had signed and ratified the protocol. These states are illustrated in green in Figure 2.1. The countries highlighted in red have signed the agreement but have been refused ratification while the countries in grey have not taken a position on the protocol.

Figure 2.1 World's countries position about Kyoto Protocol (Utopia, 2011)

All member countries have given general commitments under the protocol. However, Annex I countries (37 countries), under the protocol committed themselves to achieving a noted reduction in greenhouse gases (GHG) including carbon dioxide, methane, nitrous oxide and sulphur hexafluoride. In complying with the terms of the protocol, these countries agreed to reduce their collective greenhouse gas emissions to the degree of 5.2% from the level of them in 1990.

In order to help Annex I countries to achieve these ambitious targets the protocol allowed for several what are known as 'flexible mechanisms'. These mechanisms include Emissions trading, Clean Development Mechanism (CDM) and Joint Implementation.

In terms of emissions trading, Europe has developed the most advanced system. Within its first two years of operation the EU emissions trading system (ETS), it was estimated that there was a 2.5 - 5% emission cut achieved. This cut was unexpected as there was an increase of 1-2% forecast.

2.2.2 Climate Change & Ireland

The National Climate Change Strategy 2007-2012 was published by the Department of the Environment, Heritage and Local Government on the 2nd of October 2007. It set out measures by which Ireland could meet its Kyoto Protocol 2008-2012 commitments and measures for when the protocol expires in 2012. Due to the fact that the target of 15% renewable electricity by 2010 was achieved the report estimated that this will result in an annual emissions reduction of 1.47 million tons of CO_2. Furthermore, the report also estimates an annual emissions reduction of 3.26 million tons if the target of 33% renewable electricity by 2020 is achieved (DOEHLG, 2007).

2.2.3 EU Directive (2009/28/EC)

The European Commission published the EU Directive (2009/28/EC) in June 2009. The directive established a common framework for both the production and promotion of the use of energy from renewable sources. The introduction of this directive repealed previous directives (2001/77/EC) and (2003/30/EC) which provided the framework for the integration of renewable electricity sources into the electricity grid and the promotion of biofuels and renewables in transport energy respectively (SEAI, 2010a).

The plans laid down by the Directive include the following (SEAI, 2010a):

- The establishment of mandatory national targets to be consistent with a 20% share of energy from renewable sources in Community energy consumption by 2020;

- The aforementioned targets for each member state should be calculated based on the share of renewable in gross final consumption;
- A national renewable energy action plan (NREAP) be submitted by each member state no later than June 2010;
- The establishment of a mandatory national target to be consistent with a 10% share of energy from renewable sources in transport in Community energy consumption by 2020.
- A statistical transfer can be used as a tool to exchange an amount of energy from renewable sources between member states.

The Directive forms part of a package of energy and climate change legislation. This package provides a legislative framework for Community targets for greenhouse gas emission savings (Europa, 2011). Ireland has been set an overall target of 16% of gross final energy consumption from renewable sources by 2020 (SEAI, 2010a).

2.2.4 Energy 2020 (COM/2010/639)

As previously stated the EU is committed to cut its greenhouse gas emissions in order to combat climate change. A new energy system must therefore be developed that is low-carbon. A shift must be created towards a lower dependency on imports of oil and gas by saving energy and locating new energy alternatives. This will in turn ensure citizens and businesses of access to affordable energy.

With the above issues in mind the European Commission adopted the Communication "Energy 2020 – A strategy for competitive, sustainable and secure energy" on the 10th of November 2010. The energy priorities are defined for the next 10 years within the communication as well as actions to tackle the challenges of saving energy, achieving a market with competitive prizes and secure supplies, boosting technological leadership and effectively negotiate with the EU's national partners. The new energy strategies five main priorities are (European Commission, 2010):

- To achieve an energy-efficient Europe;

- To build a truly pan-European integrated energy market;
- To empower consumers and to achieve the highest level of safety and security;
- To extend Europe's leadership in energy technology and innovation;
- To strengthen the external dimension of the EU energy market.

It is hoped that within the next 15 months concrete legislative initiatives and proposals will be introduced on the basis of the priorities and the action presented in the communication.

2.2.4.1 Energy Savings

Transport and buildings have been identified by the commission as the two sectors with the biggest energy saving potential. Investment incentives and innovative financial instruments will be proposed by the commission by June 2011 to help home owners and local entities to finance renovation and energy saving measures. In relation to the public sector the commission has suggested consideration should be given to energy efficiency when purchasing works, services and products.

2.2.4.2 Pan-European Integrated Energy Market

One of the main priorities of the strategy is to complete the internal energy market to the effect that by 2015 no member state will be isolated. It is estimated that an overall energy infrastructure investment of €1 trillion will be required to achieve this in the EU so the commission has proposed the establishment of a "one-stop shop" to coordinate all the permit requests needed to realise a project.

2.2.4.3 Maintaining Europe as a leader in energy technology and innovation

The commission has identified the following three major projects as key areas for Europe's competitiveness to be launched upon:

- The establishment of new technologies for intelligent networks and electricity storage;
- Ongoing research into second-generation biofuels;

- The promotion of the 'smart cities' partnership to promote energy savings in urban areas.

2.2.5 Energy Green Paper

On the 1st of October 2006 the Irish Government's Energy Green Paper "Towards a Sustainable Energy Future for Ireland" was published. The paper set out the policy proposals up until the year 2020 in the hope of transforming Ireland's energy landscape. The paper was based on the identification of the three pillars that Energy Policy must be built upon. These are security of supply, environmental sustainability and economic competitiveness.

In relation to renewable energy in Ireland, the paper set an ambitious target of 33% of electricity consumed to be generated from renewable sources by 2020. However, the paper's key policy target is to achieve a 20% increase in energy efficiency by 2020. This target was proposed to be ascertained through the National Energy Efficiency Campaign, the Greener homes scheme and the National Action plan for Energy Efficiency along with energy efficiency programmes integrated in to the National Development Plan.

2.2.6 Energy White Paper

Building on the energy "Green Paper", the related consultation process during 2006 and in a response to the joint international challenges of energy security and climate change the Irish government released the Energy White Paper entitled "Delivering a Sustainable Energy Future for Ireland" on the 12th of March 2007. The paper sets out the necessary actions and targets for the energy policy framework to 2020 in order to promote economic growth and to meet the needs of all consumers. The aim of the paper was to formulate a clear path through which the Governments goals of promoting a sustainable energy future, ensuring safe and secure energy supplies and supporting competitiveness, could be achieved (DCMNR, 2007). In total the paper outlines 22 strategic energy policy goals with many more related actions. However, these goals are primarily concerned with following main areas:

- Ensure security of supply;

- Promote the sustainability of energy supply and use;
- Enhance competitiveness of energy supply;
- Integrated approach to delivery.

2.2.6.1 Security of Supply

The government has identified security of supply as a crucial element for both the national economy and also for today's society. In order to ensure security of supply, reliable access to oil and coal supplies need to be established along with the necessary infrastructure to import, distribute and store the supplies. Consistent supply to all consumers will have to be achieved through the upgrade of the existing network and improvements in electricity generating capacity. Sections 3.2 to 3.7 of the White Paper detail the range of actions underway and planned to ensure security of supply. However the underpinning strategic goals are (DCMNR, 2007):

- Ensuring the physical security and reliability of gas supplies to Ireland;
- Ensuring that electricity supply consistently meets demand;
- Being prepared for energy supply disruptions.

The government is also seeking to enhance the diversity of fuels used for power generation. Due to this fact, it has set a goal of achieving 33% of electricity consumption from renewable sources by 2020. The government has also set about encouraging biomass in power generation with its support for biomass technology transfer. Significant investment has also been made in specific biomass research and development and confronting supply side problems.

2.2.6.2 Sustainability of energy supply and use

One of the biggest challenges faced by the Irish government was to complete a document that would help to create a sustainable energy future for Ireland. It is of no surprise then that sustainability lies at the very heart of the Government's energy policy objectives. Particular emphasis has been made on the promoting in growth of renewable energy sources with the following actions outlined in the paper (DCMNR, 2007):

- The production of at least 500MW of installed ocean energy capacity by 2020;
- A biofuels penetration target of at least 10% by 2020;
- Optimising deployment of solar energy in electricity and heating by 2020;
- Supporting second generation biofuels.

The paper also details actions to address climate change and how we must reduce energy related greenhouse gas emissions along with the promotion of the sustainable use of energy in transport and the maximisation of energy efficiency and energy savings across the economy.

2.2.6.3 Competitiveness of Energy Supply

In order to ensure national competitiveness and to support economic growth, competition in energy markets along with a reliable and competitively priced energy supply is a key concern. The energy white paper points towards the direction of structural change in the energy market as the path to take to enable competition and to deliver consumer choice. The goal is to provide the consumer with a greater level of choice and to promote innovation in a less regulated environment and to deliver a responsive and stable energy market. The primary strategic goals set by the government in the paper include the following (DCMNR, 2007):

- The availability of affordable energy for all consumers;
- The creation of jobs, growth and innovation in the energy sector;
- The establishment of the All-Island Energy Market Framework;
- To deliver both competition and consumer choice in the energy market.

2.2.6.4 Integrated approach to delivery

In the final section of the energy white paper, the government outlines its plan to collaborate with all stakeholders to achieve one common goal, namely a sustainable energy future for

Ireland. The following are the strategic goals set out in the paper for integrated delivery of energy policy objectives (DCMNR, 2007):

- Ensuring a whole of government approach to energy policy;
- Strengthening Ireland's national capabilities in the energy policy field;
- An integrated approach with stakeholders in implementing the strategic goals for energy.

This section also details the fact that interim reviews of the energy policy framework will be carried out by the government every two years which will provide reports on progress. The necessary adjustments can then be made to the targets set and policy actions outlined. A fundamental review will then be carried out every five years which will be informed by the public and stakeholder consultation.

2.3 Overview of Irish Transmission System

2.3.1 The Irish Electricity Market

The Irish electricity market can be divided up into three distinct sectors: generation, transmission / distribution and supply (DETI, 2005). Large utility companies like the ESB and Veridian are vertically integrated and play a pivotal role in both electricity generation and supply. Other non-integrated generators and suppliers include Synergen, Airtricity and Bord Gais. However, the ESB is still the dominant player in all three of the aforementioned sectors as it owns the transmission and distribution assets. The company is responsible for the operation and development of the distribution system in Ireland which consists of systems operating at 230 V, 400 V, 10 kV, 20 kV, 38 kV, and part of the 110 kV network. ESB Networks is known as the Distribution System Operator (DSO) in Ireland (SEI, 2008).

2.3.2 National Grid

EirGrid is responsible for operating and developing the transmission system or national grid and is known as the Transmission System Operator (TSO). The national grid is used to transport power from the electricity generators to the demand centres. This is achieved through the utilisation of a system compromising of 400 kV, 220 kV and 110 kV networks. As can be seen from Figure 2.2 the grid is not a standalone grid as it is electrically connected to the transmission system of Northern Ireland through a 275 kV double connection at Louth. Two additional 110 kV connections have been established at Letterkenny in Co. Donegal and Corraclassy in Co. Cavan (EirGrid, 2006).

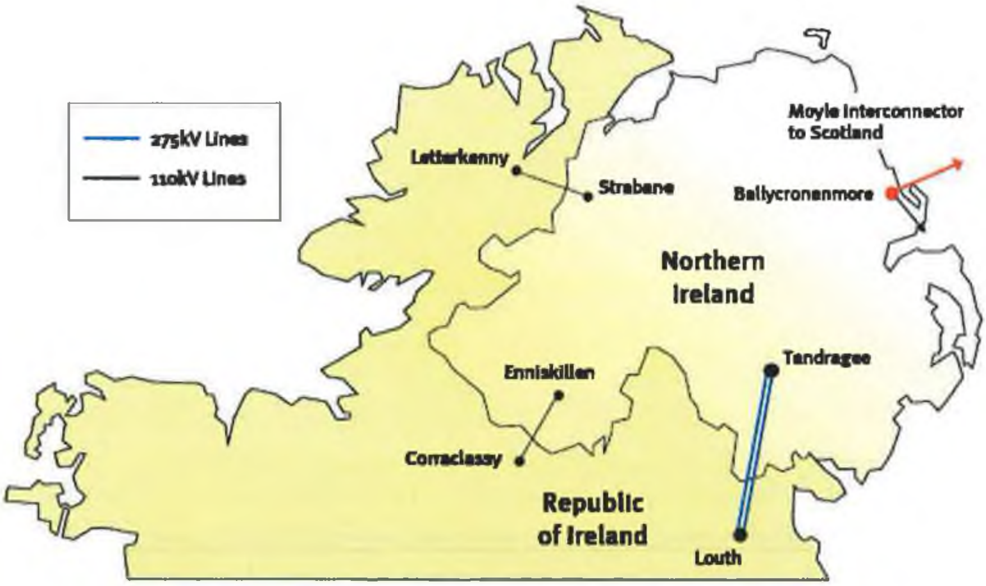


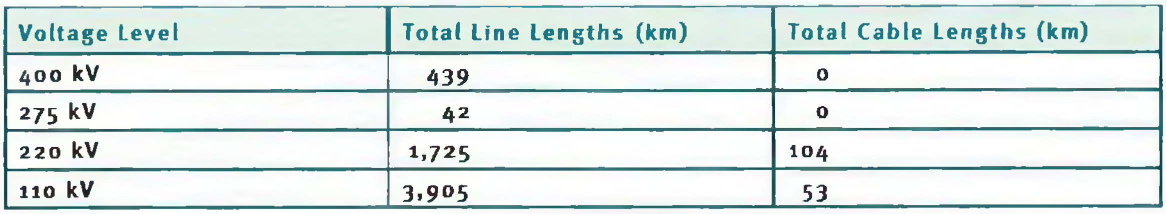
Figure 2.2 Cross Border Connections (EirGrid, 2006)

The 400 kV and 220 kV networks are critical to the system as they form the backbone of the grid. In comparison to the 110 kV network, they have much higher capacities and experience lower losses. The Moneypoint generation station in Co. Clare is linked to Galway on the west coast and Dublin on the east by means of the 440 kV network. On the other hand, the 220 kV network consists of a number of single circuit loops spread throughout the country. Generations stations of greater than 100 MW are typically connected to either the 440 kV or 220 kV networks (EirGrid, 2006).

Prior to the 1960s, the entire transmission system in Ireland comprised of 110 kV lines. Today, these lines provide parallel paths to the 220 kV system. They form the most extensive element of the national grid as they are located in every county in the Republic of Ireland (EirGrid, 2006).

The vast majority of the transmission system comprises of overhead power lines. However, in areas such as city centres like Dublin and Cork, circumstances may not allow the installation of such lines and therefore underground lines have been put in place. Table 2.1 details the total line and cable lengths for each of the voltage levels while Table 2.2 provides the relevant details for the transmission system infrastructure for both 2009 and 2010.

Table 2.1 Total Length of Existing Grid Circuits as of July 2009 (EirGrid, 2006)



Voltage Level	Total Line Lengths (km)	Total Cable Lengths (km)
400 kV	439	0
275 kV	42	0
220 kV	1,725	104
110 kV	3,905	53

2.3.3 Limits of Existing Grid

Similar to most of the grids in Europe the Irish national grid is to a large extent some 50 years old. Its design is solely based on a hierarchical, top-down flow and distribution of power (Haas et al., 2009). It was built in the 1970s and 1980s to connect lower voltage networks while also serving as a reserve system to cover for any potential breakdowns of power plants. Since that time the number of customers has increased substantially, as has their needs, with the demand increasing by over 150% (EirGrid, 2008). Yet the methods of operating the grid have not changed and the infrastructure has little capacity for further growth. If the anticipated increase in power flows occur between now and 2025, the capacity of the bulk transmission system will need to be doubled (EirGrid, 2008). This growth will occur primarily due to the increase in the renewable generation capacity levels.

Table 2.2 Transmission System Infrastructure 2009 & 2010 (EirGrid, 2011)

Plant Type	2009		2010	
	No. of Items	Circuit Length [km]	No. of Items	Circuit Length [km]
110 kV Circuits	183	4,087	187	4,115
220 kV Circuits	53	1,835	55	1,850
275 kV Tie-lines[6]	2	97	2	97
400 kV Circuits	3	439	3	439
Circuit Total	**241**	**6,458**	**247**	**6,501**
Plant Type	**No. of Items**	**Transformer Capacity [MVA]**	**No. of Items**	**Transformer Capacity [MVA]**
220/110 kV Transformers	39	7,064	39	7,064
275/220 kV Transformers	3	1,200	3	1,200
400/220 kV Transformers	5	2,500	5	2,500
Transformer Total	**47**	**10,764**	**47**	**10,764**
Total No. of sub-stations	**152**		**156**	

2.3.4 Grid 25

On the 8th of October 2008 EirGrid released its plan for the upgrade of the Irish national grid in its publication “Grid 25”. The plan outlines the measures to double the capacity of the transmission system by 2025 with an investment up to €4 billion. The objective of the strategy is to facilitate the target of 40% of electricity generation from renewable generation by 2020, to support regional development and to also create jobs.

With the projected increased demand levels and significantly higher renewable generation capacity levels, EirGrid has identified the need to invest in the national grid. In order to strengthen the grid, EirGrid will put in place an additional 1,150 km of new circuits comprising of 800 km at 220 kV level with the remaining 350 km at 100 kV level.

Additionally 2,300 km of the existing transmission network will be upgraded to provide greater capacity.

For the purposes of their strategy, EirGrid divided the network up into seven regions. The proposed expenditure by region in illustrated in Figure 2.3. The largest expenditure is set to occur in the South East region with an investment of €830 M to upgrade approximately 490 km of the existing network and to build new infrastructure to cater for the expected increase of 45% in electricity demand by 2025 (EirGrid, 2008). If the investments were not to take place as outlined in Figure 2.3, EirGrid predict that within the next five to ten years there will be no capacity in the network for new customers or for further renewable generation to be connected.

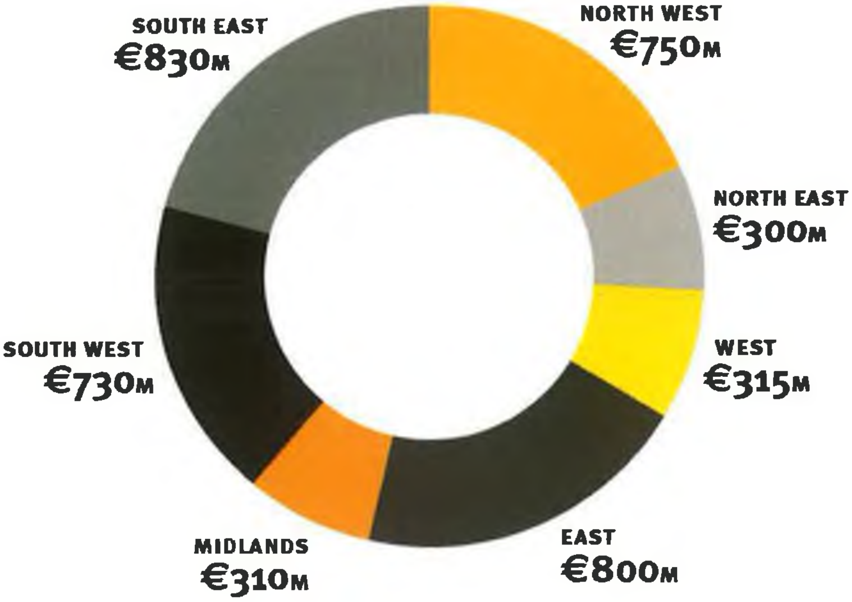


Figure 2.3 Proposed Expenditure by Region (EirGrid, 2008)

To-date major progress has been made by EirGrid in terms of both the construction of new transmission circuits and on uprating circuits. In 2010, approximately 300 km of existing transmission circuits were up-rated during the year, which represents about 5% of the total transmission circuit length in the country. The 220 kV transmission line from Killonan to Knockraha in Cork was the first to be up-rated using the new High Temperature Low Sag

(HTLS) conductor (EirGrid, 2011). The use of this type of conductor allows utilities to push more power through them due to the reduction in sag.

2.3.5 East-West Interconnector

The East-West interconnector is currently under construction by EirGrid. The electricity link will provide a 500 MW interconnection between the grids of Ireland and Britain. The connection is being built between Rush North Beach, Co. Dublin in Ireland and Barkby Beach, North Wales in Britain.

The transmission system currently being installed is a HVDC Light. This system has the added environmental benefits of neutral electromagnetic fields, oil free cables, low electrical losses and compact converter stations (ABB, 2009).

Figure 2.4 East West Interconnector (ABB, 2009)

2.3.6 Electricity Generation

The total operational generation capacity on the Irish transmission and distribution system is 8,504 MW. Generation can be fully-dispatchable, partially-dispatchable or non-dispatchable.

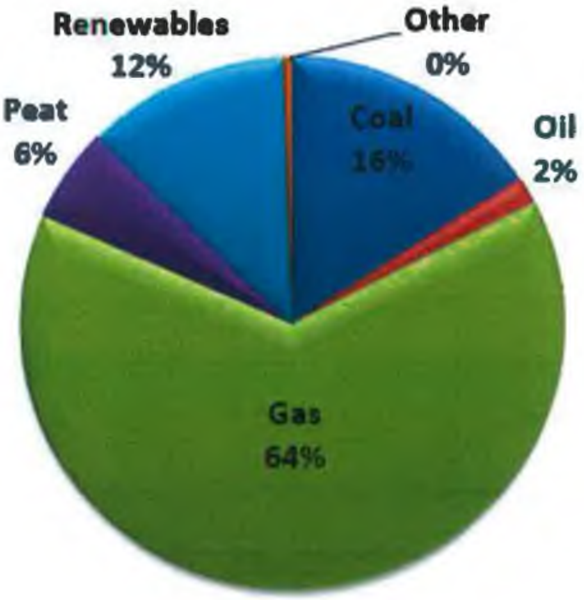


Figure 2.5 All-Island Fuel-Mix 2010 (CER, 2011e)

Figure 2.6 illustrates the fuel-mix comparison from 2008-2010. It can be clearly seen that the contribution of gas has been steadily growing since 2008. In contrast, the contribution of Oil to the overall fuel-mix has decreased from 4% in 2008 to a mere 2% in 2010. Renewables impact to the fuel mix reached a peak of 14% in 2009 (CER, 2011e).

Although still in its infancy, renewable energy is making an ever increasing contribution to the generation plant mix. The predominant renewable technologies are wind and hydro generation. Figure 2.7 illustrates the total connected renewable generation capacity (MW) for 2010. Total connected Renewable Generation Capacity equates to a total of 1,700 MW with wind accounting for 84% at 1428 MW and Hydro at 14% at 242 MW.

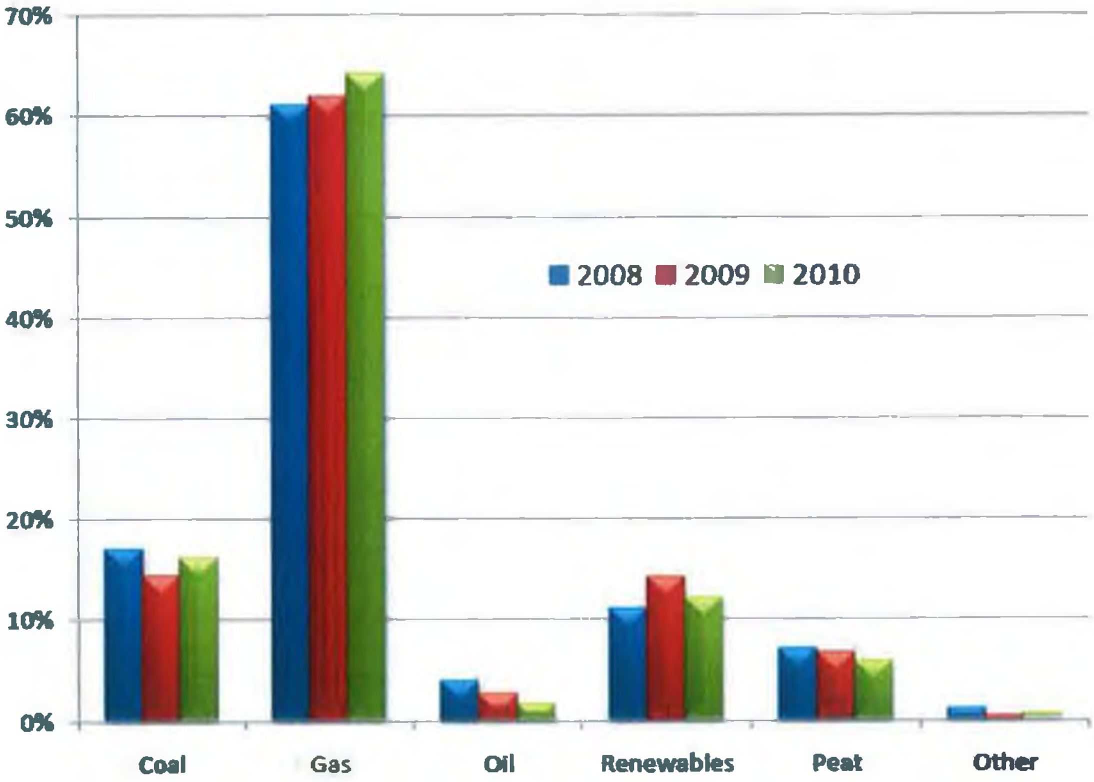


Figure 2.6 Fuel Mix Comparison 2008-2010 (CER, 2011e)

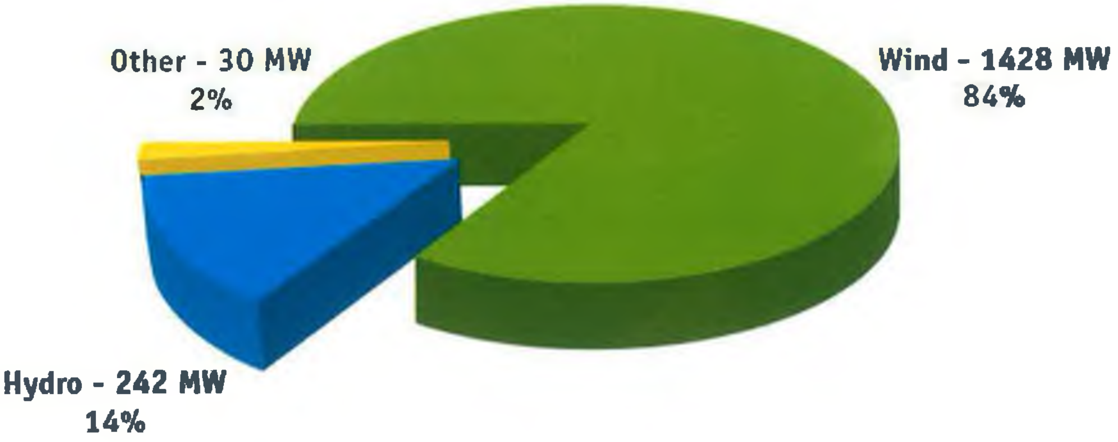


Figure 2.7 Total Connected Renewable Generation Capacity 2010 (EirGrid, 2011)

2.4 Distributed Generation

Distributed generation has been defined by the Institute of Electrical and Electronics Engineers (IEEE) as the generation of electricity by facilities that are sufficiently smaller than central generating plants so as to allow interconnection at nearly any point in a power system (Dondi et al., 2002). While the concept may be fairly new in the economics literature about electricity, the idea was actually developed in the early days of electricity generation. The original power plants were designed to supply electricity to customers in the close neighbourhood of the generation plant only (Belmans et al., 2005). The grids used to transport the power were direct current (DC) based. The supply voltage was therefore limited and there were further limitations on the distance between the generator and the consumer. Local storage, in the form of batteries, were used to balance demand and supply. However, the emergence of AC grids and other technological evolutions meant that distributed generation became out-dated as electricity could now be transported over longer distance with a substantial increase in the power output of the generation units.

However in more recent times, innovations in technology along with a changing economic and regulatory environment have resulted in the re-emergence of the concept of distributed generation (Belmans et al., 2005). The distributed generation system is not centrally planned and is operated by independent power producers or consumers. The power generated is not centrally dispatched and the generators are typically smaller than 50 MW. The concept is based on the direct connection to the electricity distribution network (CDA, 2006) or on the customer side of the meter (Belmans et al., 2005). The distribution networks will thus change from being passive to active systems. The idea of virtual power plants (VPP) as shown in Figure 2.8 will become a reality under which a number of dispersed and renewable generation units along with storage units and controllable loads will be clustered. The system will be managed in such a manner that power exchange can be scheduled and dispatched with a greater higher level of accuracy (Hammons, 2008).

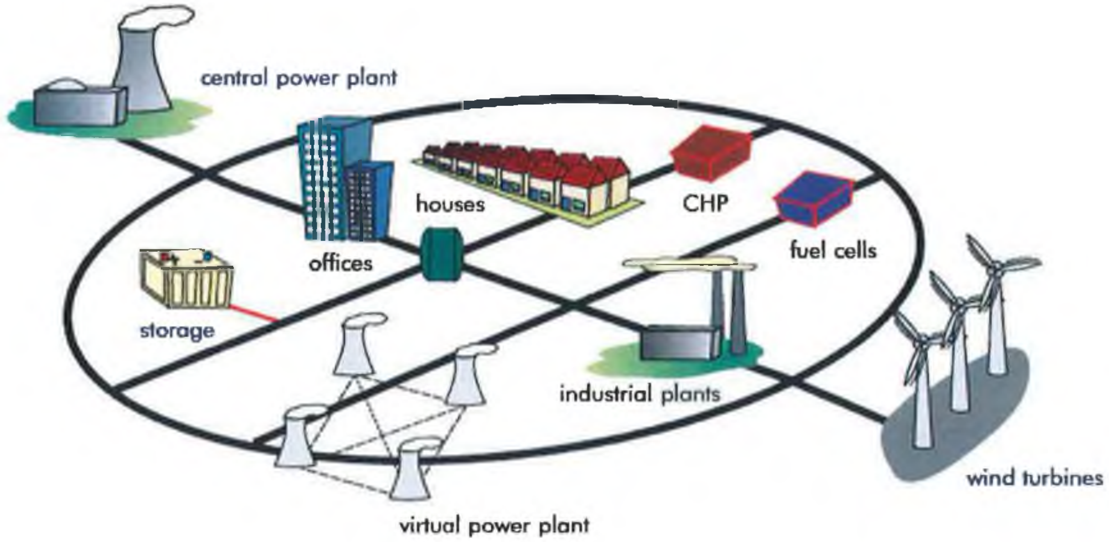


Figure 2.8 Electricity network of the future (CDA, 2007)

2.4.1 Driving forces behind Distributed Generation

According to (Belmans et al., 2005) the two main driving forces behind the renewed interest in distributed generation are firstly the electricity market liberalisation and secondly environmental concerns. Electricity suppliers have shown a great level of interest in distributed generation as it will allow them to respond in a flexible way to changing market conditions (Belmans et al., 2005). Distributed generation can provide this flexibility due to the size of the technologies and time to construct in comparison to conventional larger power plants.

The major driving force behind the demand for distributed generation in Europe stems from environmental policies and concerns as the implementation of regulations has forced the hand of the players in the electricity market to look for cleaner energy and cost effective solutions (Belmans et al., 2005) . The combination of distributed generation and renewable energy sources is seen across Europe as critical to achieving the following two goals (CDA, 2006):

- Reducing the dependency on imported fossil fuels and thus increasing the security of energy supplies in Europe;

- Reducing the emission of greenhouse gases from the burning of fossil fuels (in particular carbon dioxide).

2.4.2 Benefits of Distributed Generation

Distributed energy generation is intended to provide small-scale power close to users using a broad range of renewable technologies (Bogdan et al., 2007). Today's electricity production is dominated by central, rather than distributed, electricity generation. The main reasons for this are the economy of scale, efficiency, fuel capability and lifetime. (Willis and Scott, 2000 cited in CDA, 2006). By increasing the size of a production unit, the efficiency will in turn be increased along with a decrease in the cost per MW.

Up until now the small-scale generation technologies were not capable of pushing the "economy of scale" out of the system (Belmans et al., 2005). However, the once significant advantage of economy of scale is becoming less of an issue as smaller units are reaping the rewards of technological developments (CDA, 2006). An effective distributed generation system can ensure that electricity is generated and delivered to consumers in a fair, reliable and environmentally sustainable manner. It can address the much publicised issues of security of supply, efficiency and environmental concern (Nair and Zhang, 2009). The following benefits of distributed generation have been highlighted by Nair and Zhang (2009) and Belmans et al. (2005):

- Improve security of power supply;
- Reduced losses and deferred future network investment;
- Make power supply more diverse and geographically dispersed.

However, the actual viability of distributed generation and renewable energy sources depends largely on regulatory and stimulus measures which are a matter of EU and national political decisions (CDA, 2006). The current change of the electricity supply structure towards more decentralised power generation will essentially require changes to current safety, control and communication technologies. This will ensure the realisation and the benefits of the concept of distributed generation to be made a reality (Hammons, 2008).

2.5 Energy Storage

The increased level of penetration of renewable generation onto the grid has resulted in it experiencing a shift from steady generation to intermittent generation (Chris, 2011). The occurrence of this adds uncertainly and volatility to the grid. Due to the fact that the generation from renewable sources are unpredictable, difficulties have arose in relation to the scheduling and managing of traditional generator assets to compensate (Chris, 2011). Transmission constraints are another issue to be faced with renewable generation as the sources tend to be geographically concentrated and isolated. Energy storage can however help facilitate the increased penetration of renewable energy sources to the grid as they can enable for example wind and solar to overcome their intermittency.

Both energy storage and power management are becoming increasingly important with many countries policies directed towards a greater emphasis on electrical production from renewable source (Hall and Bain, 2008). Electric energy storage (EES) can be defined as the capability of storing either electricity or energy to produce electricity and then releasing it for use during other periods when the use or cost is more beneficial (Apt et al., 2006). Although storage does not play a huge role in the effectiveness of the present-day grid, cost effective ways of storing electrical energy can make the grid more efficient and reliable (Yousefi et al., 2009). Present energy storage technologies include the following:

- Pumped Hydro Storage (PHS);
- Compressed Air Energy Storage (CAES);
- Batteries;
- Flywheels;
- Superconducting Magnetic Energy Storage (SMES);
- Electrochemical Capacitors;
- Electric Vehicles (EVs).

Hydroelectric and CAES are geographically restrained, while battery and flywheel technologies can be used in various locations (Apt et al., 2006). Other storage technologies exist such as the electrolysis of water combined with a hydrogen fuel cell. The efficiency of electrolysis is approximately 70% and 50% for commercial fuel cells (APS, 2007). The cycle efficiency therefore stands at best at 35%, which does not compare favourably with the aforementioned energy storage technologies and for this reason it has not been considered in this thesis.

2.5.1 Pumped Hydro Storage (PHS)

The only energy storage technology deployed on a gigawatt (GW) scale worldwide is pumped hydro (NREL, 2010) with some 90 GW of capacity installed (Baker, 2008). In this system, water is recycled between upper and lower reservoirs. The plants typically have a 50 year life time with the largest issue in the construction of them being the lack of suitable sites and the environmental impacts of them. If a vertically integrated power system is in place, the plant can adopt a hydro-thermal unit coordination to reduce the fuel cost by letting the pumped-storage plant serve the peak load and then pump the water back into the upper reservoir at times of light-load (Yousefi et al., 2009).

Due to the sheer size of the installation of a pumped hydro storage plant and the cost associated with them they are most suited to utility scale storage applications rather than for small-scale renewable energy systems (Nair and Garimella, 2010). Pumped hydro is ideally suited to situations where a fast supply of power is needed, for meeting sudden peaks in demand, frequency regulation and voltage control (APS, 2007).

2.5.1.1 Turlough Hill

Ireland's only pumped-storage hydroelectricity plant is located in Turlough Hill in the Wicklow Mountains. It was built between 1968 and 1974 for the ESB at a cost of £20 million at the time. The hill has four motor/generators units installed on it. It is capable of generating 292 MW for five hours when operating as electrical generators. On the other hand when operating as motors driving pumps they use 272 MW. The site consisting of 2 connected reservoirs is shown in Figure 2.9. The electricity is generated by releasing water from the upper reservoir, passing it through turbines connected to generators. The impressive feature of the plant is that once the order is given, electricity can be made available within approximately a minute of startup. This compares favourably to that of conventional sources such as coal, oil and gas.

Figure 2.9 Turlough Hill (ESB, 2011)

2.5.2 Compressed Air Energy Storage (CAES)

This energy storage system centers around a high-pressure compressed air which is stored in a suitable underground cavern and is used by expanding through a turbo-alternator set (Baker, 2008). The configuration of a typical compressed air energy storage facility is illustrated in Figure 2.10. The CAES system is constrained by the fact that it needs an underground cavern and its reliance on fossil fuel. However, research is currently underway regarding alternative configurations using manufactured above-ground vessels along with designs that re-use the heat of compression to avoid the use of fuel totally (NREL, 2010). This system is known as adiabatic CAES where the heat given off during the compression process is stored and used during the expansion process. Adiabatic CAES systems are capable of 70% thermo efficiency (Gaelectric, 2010).

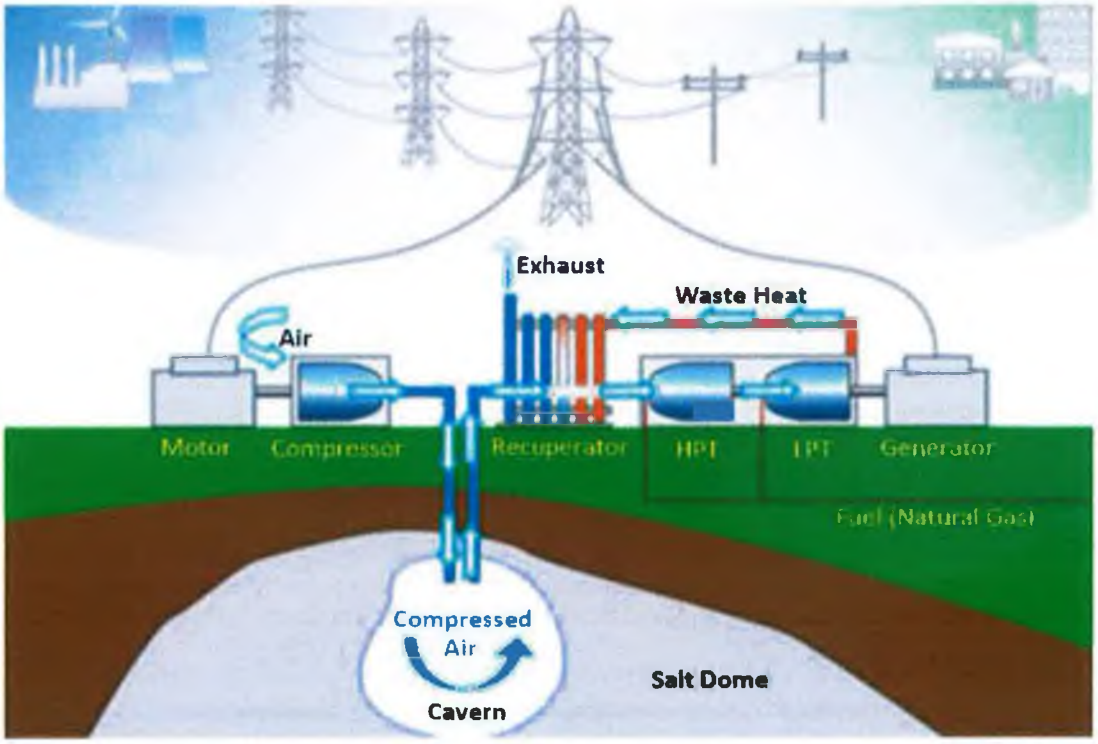


Figure 2.10 Compressed Air Energy Storage Facility (Renewable Energy Info, 2011)

The number of CAES plants worldwide is quite small but it is generally believed to be commercially viable (Chi-Jen and Williams, 2009). The Huntorf Plant was the world's first compressed air power station. The 290 MW CAES plant has been in operation in Bremen, Germany since 1978. The plant provides peak shaving, spinning reserves and VAR support. Two underground salt caverns at depths of 640-790m below ground level with a storage capacity of 311, 485m^3 are utlised to store the compressed air at pressures up to 1000 psi or 69 bar. The recharge of the plant requires 12 hours of off-peak power. The full output of 290 MW can then be utilised for four hours (Gardner and Haynes, 2007).

The only other fully operational CAES plant is the McIntosh plant, built in 1991 in Alabama, USA. The Alabama Electric Company runs the 110 MW plant to store off-peak power, provide spinning reserve and to generate peak power. The plant has the capability of providing 26 hours full power output from the 538,020 m^3 of compressed air at 1080 psi or 75 bar pressure at a depth of 762 metres. The advantage of this plant is the system recovers the waste heat during the combustion process which in turn reduced fuel consumption by approximately 25% (compared to the aforementioned Huntorf Plant) (Gardner and Haynes, 2007).

In the US, CAES is being considered presently in the context of buffering the output of large-scale wind farm developments, thus enhancing their financial viability (Baker, 2008). Through the partnership of the Iowa Association of Municipal Utilities (IAMU) and the Department of Energy the concept of the Iowa Stored Energy Park has been developed. The project is the first of its kind as it will use an aquifer CAES system in Dallas Centre, Iowa that will be directly coupled to a wind farm. The CAES storage facility will occupy 40 acres and utilize a 915m deep anticline in a porous sandstone formation to store the energy generated by the wind farm as far as 100 to 200 miles from the site. The wind farm is planned to have a power output of between 75 to 150 MW (Succar and Williams, 2008). Once completed in 2015, the project will provide invaluable information about these systems and in particular the feasibility of utilising aquifers for air storage and the coupling of CAES to wind.

Figure 2.11 The Wind/CAES Iowa Stored Energy Park (Succar and Williams, 2008)

While Ireland may not have the suitable natural landscape for additional pumped hydro storage, it is currently being explored for CAES opportunities. An Irish company called Gaelectric Energy Storage has completed site investigations in Larne, Co. Antrim that has revealed the potential of the underlying geology to support a CAES facility. The company believes that the large salt deposits in the rock could be leeched out to create appropriate caverns for the compressed air to be stored in. Drilling of salt was due to commence in the first quarter of 2011. The company hopes to construct a 150 MW facility that will provide Ireland with an opportunity to develop a flagship demonstration project with the following benefits (Gaelectric, 2010):

- €6-7 M reduced system costs;
- Up to 50,000 tonnes CO_2 reduced emissions annually;
- Reduce the need to curtail wind and manage congestion.

Additional opportunities for CAES in Ireland are being explored in the gas fields of the Celtic Sea. Once the gas reserves have been fully exhausted, sites such as Kinsale Head could have CAES potential. Any potential developments would be greatly simplified due to the existing knowledge and infrastructure at such sites (EirGrid, 2009a). However, in comparison to methane, air has both different physical and chemical properties that could pose challenges for air storage in sites previously used for gas storage (Succar and Williams, 2008). Gaelectric Energy Storage are currently exploring the possibility of developing a demonstration project in Montana USA in a depleted gas field that would be a world first and could possibly be transformational for bulk energy storage (Gaelectric, 2010).

Another interesting design involving wind and compressed air is being investigated by Seamus Garvey of Nottingham University. Garvey's proposal is to use CAES with floating wind turbines in deep water at sea. The turbine blades are used to compress the air directly rather than producing electricity first. The pressurised air is then passed down to a large polythene bag type structure which is anchored to the sea floor. The heat produced during the compression process is stored and then later utilised to warm the expanding air. Similar to that of the conventional CAES facility, the expanding air would be connected to a generator to produce electricity. Costs for such a system are estimated at €12,000 / MWh. Garvey states that to deliver 2000 MW for four days would require 7 million cubic meters of air storage, equating to 1750 bags with coverage of approximately 1 sq. km (Douthwaite, 2010).

2.5.3 Batteries

The technologies involved with battery energy storage are at a mature stage. Batteries have high energy densities and can be easily used. The type of batteries used for energy storage operates in a similar manner to traditional batteries except on a much larger scale. Basically two electrodes are immersed in an electrolyte, the result of which allows a chemical reaction to take place in order for the current to be produced when required. The three main types of battery energy storage technologies include the following:

- **Lead-acid**: is the oldest and most mature technology used for electrical energy storage. They had a US rechargeable market share of 79% in 2008. The batteries shown in Figure 2.12 can be discharged repeatedly by as much as 80% of their capacity (Nair and Garimella, 2010). The drawbacks of this technology are their limited cycle life and their environmentally unfriendly lead content along with the acid electrolyte which result in a somewhat large eco-footprint.

- **Nickel cadmium (NiCd)**: are a competitive replacement for lead-acid batteries due to their ability to supply continuous power for long durations along with the fact that they can be used in applications which require instantaneous power (Nair and Garimella, 2010). They are robust and rank alongside the lead-acid batteries in terms of their maturity and reliability (Baker, 2008).

- **Sodium Sulphur (NaS)**: this type of technology involves very high temperatures, operating at 300°C (Baker, 2008). They have excellent cycle life and have been installed in over 55 locations worldwide for peak shaving and load leveling at the distribution level (Apt et al., 2006).

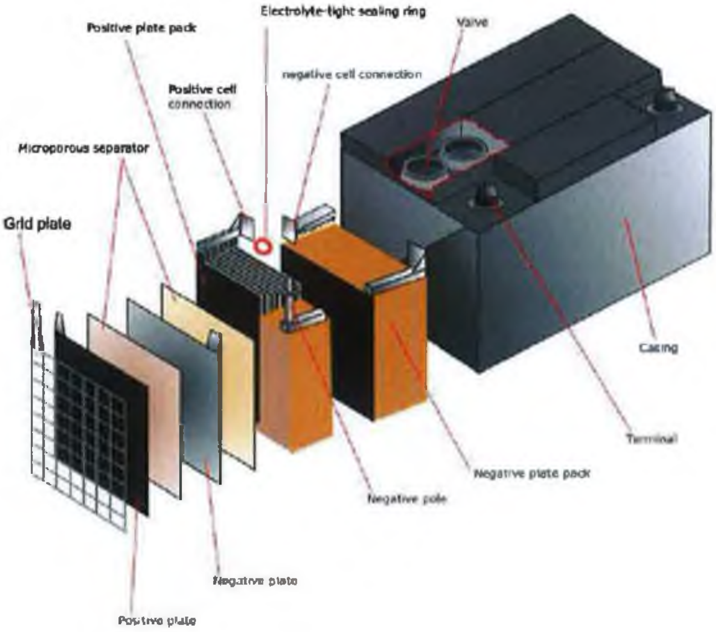


Figure 2.12 Lead Acid Battery (University of Cambridge, 2011)

The battery energy storage system (BESS) is the world's most powerful single storage battery and was built for Alaska's Golden Electric Association in November 2003 to ensure continuous power supplies to Alaska. The 1,500 ton BESS cost in the region of $35 million. The system protects 90,000 residents in the Fairbanks region from the effect of power cuts. It is designed to provide 27 MW of back-up for 15 minutes (Lee, 2004).

Figure 2.13 BESS at Golden Valley Alaska (Baker, 2008)

Battery energy storage technologies have also been used in bridging power applications including the provision of contingency reserves, load following and additional reserves to cater with issues such as forecast uncertainty and unit commitment errors. As batteries have rapid responses they are ideally suited for such applications (NREL, 2010).

2.5.4 Flywheels

Flywheels utilise the angular momentum of a spinning mass to store energy. During the charging process, the flywheel is spun up by a motor with the input of electrical energy (Figure 2.14). On the other hand, during discharge, the same aforementioned motor acts as a generator which produces electricity from the rotational energy of the actual flywheel (Apt et al., 2006). They possess the potential to simultaneously be both high-energy and power-density devices (Hall and Bain, 2008) and are ideally for frequency regulation (NREL, 2010). A typical flywheel is capable of several hundred thousand full charge-discharge cycles but have relatively poor energy density and also possess large standby losses (Apt et al., 2006). The technology is still at demonstration stage with no commercial applications to-date with the main limitation to the more widespread use being the high cost due to the precision engineering needed (Hall and Bain, 2008).

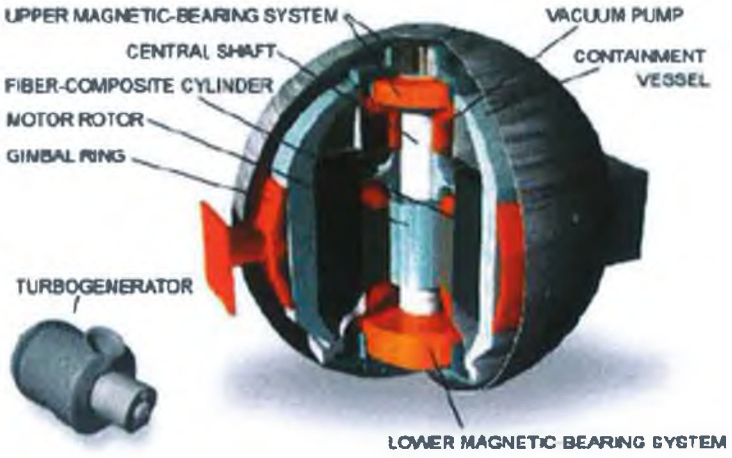


Figure 2.14 Flywheel Energy Storage Device (Sheppard, n.d.)

However, a 20 MW flywheel energy storage facility is being constructed by Beacon Power in Stephentown, New York. The facility has been designed to provide Regulation Service to the electric grid (NYISO, 2010). The system is comprised of 10 individual 25kWh/100kW flywheels integrated into a plant to provide the rated output of 20 MW. Once completed, the project is expected to store and return energy to the grid to serve approximately 10% of the New York's overall frequency regulation needs (Gaelectric, 2011).

2.5.5 Superconducting Magnetic Energy Storage (SMES)

The design basis for SMES technologies is the storage of energy in the magnetic field of a direct current (DC) current flowing in a superconductor (Hall and Bain, 2008). The main parts of the system are motionless resulting in high reliability and low maintenance. In order for the system to function effectively the superconducting coil must be cryogenically cooled below its superconducting critical temperature (Chi-Jen and Williams, 2009). They are similar to capacitors as they possess the ability to respond extremely fast, but are yet limited by the total energy capacity. These limitations have meant that SMES technologies are mainly utilised in power application with extremely short discharge times (NREL, 2010). High capital costs have hindered the commercialisation of large SMES (Chi-Jen and Williams, 2009) although several demonstration projects have been deployed.

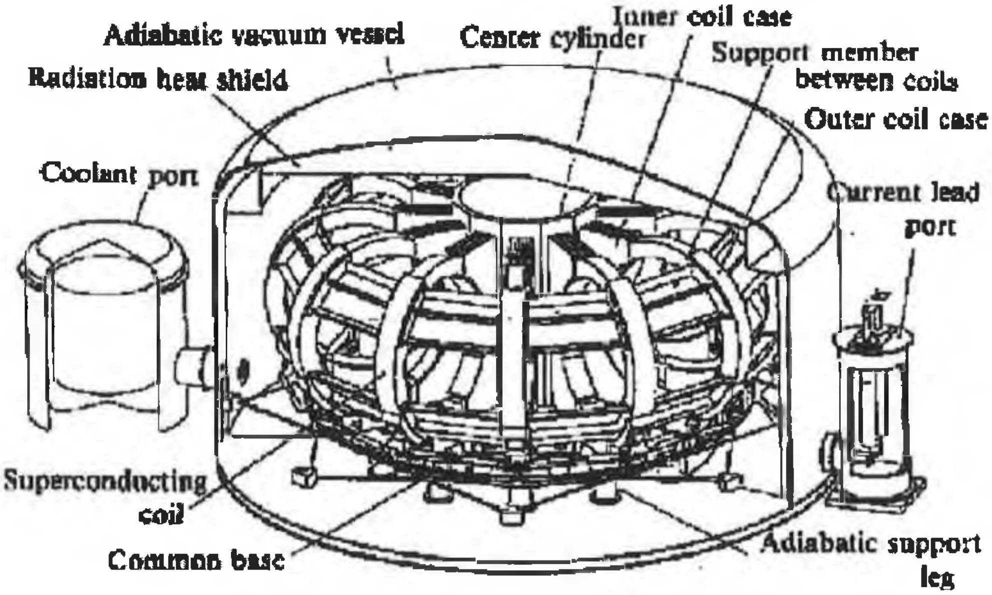


Figure 2.15 Superconducting Magnetic Energy Storage (Gonzalez et al., 2004)

2.5.6 Electrochemical Capacitors

An electrochemical capacitor stores energy in electrostatic charges on opposite surface of the electric double layer (Baxter, 2006 cited in Chi-Jen and Williams, 2009). They can provide high power density and they live through charge/discharge cycles with extremely low maintenance. This particular type of capacitor does not depend on temperature and have projected lifetimes up to 20 years (NREL, 2010). The round trip efficiency is about 80-95% and they are capable of fast response (Chi-Jen and Williams, 2009). The technology has been tested to provide bridging power by the Electric Power Research Institute (EPRI) Power Electronics Application Centre in 2003 but many experts believe that this particular technology is only in its infancy and will require additional fundamental research before its ready for large scale testing (NREL, 2010).

2.5.7 Electric Vehicles (EVs)

The final type of energy storage method to be discussed in this paper is that of Electric Vehicles. They can be used to both increase the flexibility of the power system and facilitate greater penetrations of renewable resources. As can be seen from Figure 2.16, electric vehicles can be recharged directly from the grid or at individual homes or specific recharging stations while stationary. The introduction of such devices makes large-scale battery energy storage economical whilst also reducing the transports sector dependency on oil (Lund & Kempton, 2008). Furthermore, electric vehicles offer a means of integrating previously isolated existing energy-systems more effectively.

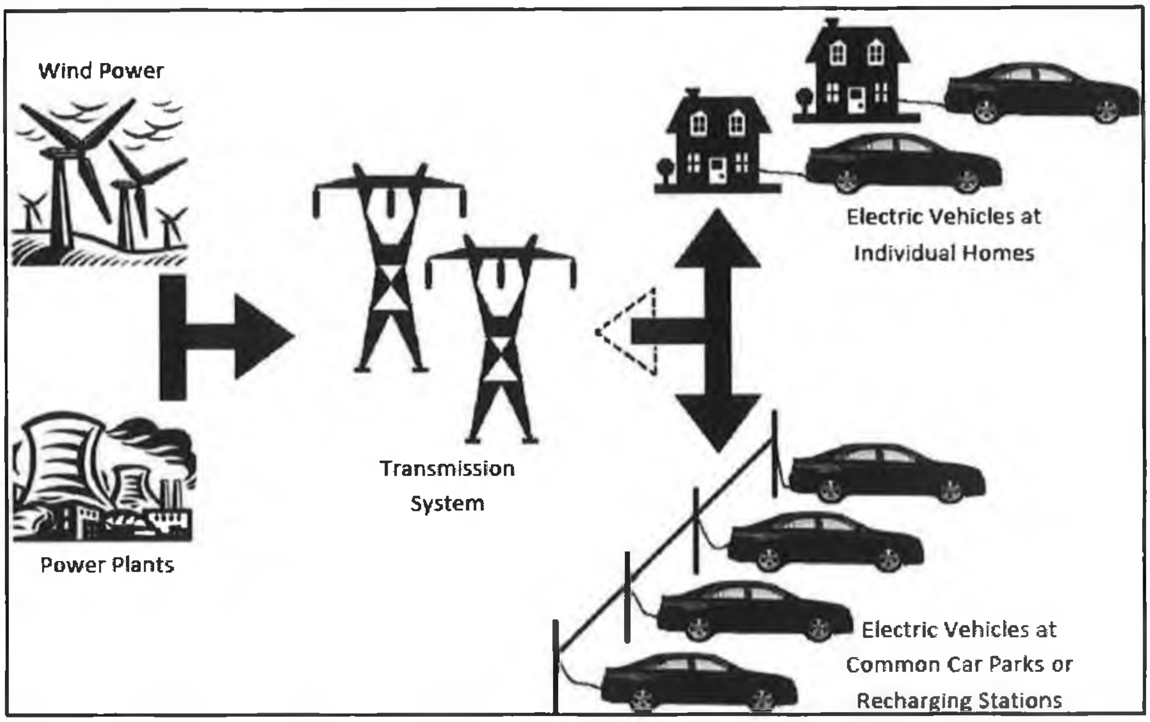


Figure 2.16 Schematic of electric vehicles and electric power grid (Connolly, 2009)

The three primary categories of electric vehicle are as follows:

- Battery Electric-Vehicles (BEV);
- Smart Electric-Vehicle (SEV);
- Vehicle to Grid (V2G).

BEV's can offer a means of reducing emissions from the transport sector but act as additional load as they are plugged directly into the grid. SEV's on the other hand, have the potential to communicate with the grid and can therefore be charged at off peak periods to prevent ramping up on the power system due to excessive loads during peak periods and can also be controlled to extract the full potential at periods of greatest variable generation (NREL, 2010). V2G are quite similar to SEV's but they also have the added benefit of being able to supply power back to the grid and thus represent a means of increasing the flexibility within the power system (Connolly, 2009). If electric vehicles can succeed in achieving significant market growth in the coming decades, these devices have the capability of discharging back to the grid to improve grid utilization, level the demand profile and increase the reliability of the power system (APS, 2010).

Similar to the aforementioned energy storage technologies, electric vehicles face barriers to reaching large scale deployment. The biggest barrier faced by these devices is the significant initial investment to establish the infrastructure required to accommodate electric vehicles. The upgrade of the infrastructure would include the uprating of transmission lines to facilitate the charging and in the case of V2G's receiving power back, numerous charging stations and maintenance stations to facilitate the transfer from traditional internal combustion engines to electric motors. Other barriers faced by electric vehicles include the driving range that can be obtained and attempting to change the driving styles and travelling habits of consumers to combat the limitations of electric vehicles (Connolly, 2009).

Fortunately EirGrid is currently upgrading the transmission system in Ireland and on the 12th of April 2010 a support programme was launched for electric vehicles in Ireland by the Irish Government. The programme is administered by the SEAI and provides financial support to consumers buying qualified models of electric vehicles. It is hoped that the programme will incentivise the purchase of up to 6,000 electric vehicles onto the Irish market during 2011 (SEAI, 2011). Charging of the cars will take place primarily at home as there are only four public charging points available in Dublin at the moment but there are plans to install further charge points in Cork, Galway, Limerick, Waterford and Portlaois. By the end of 2011 there will be 1,500 on-street charge points throughout Ireland. The aforementioned programme will attempt to begin to meet the following ambitious targets set by the Irish Government in relation to the introduction of electric vehicles in the coming years (DCMNR, 2007):

- 10% of all vehicles to be electric by 2020;
- 2000 EVs by end of 2011;
- 6,000 EVs by end of 2012.

A project is currently under way on the Aran Islands where electric vehicles are being trialed to store high amounts of wind or ocean energy to achieve the maximum utilsation of renewable resources available. This future energy system could reduce the importation of energy onto the island and more importantly act as a blueprint for a similar system that could serve the island of Ireland. Over a three year period a total of 24 Mega ECity cars will be operating on the island to tes the concept.

2.6 Demand Side Management (DSM)

Distributed generation, based on the integration and use of renewable energy sources, is set to play a pivotal role in the establishment of a future sustainable electricity supply. As many renewable energy sources like wind and solar energy are by their very nature intermittent, the balancing problem between energy supply and energy consumption will increase (Stadler and Bukvic-Schäfer, 2003). In the preceding section the integration of energy storage into the electricity sector was discussed as a possible solution to the balancing problem. Another possibility to solve the aforementioned problem exists in the form of demand side or load management. According to de Almeida and Moura (2010) demand side management can provide a means to compensate the effects of the variability and randomness of the wind, solar and hydro power availability.

Instead of attempting to match power generation to consumer demand, the philosophy of load management takes action to vary the load to match the power available (de Almeida and Moura, 2010). In order to achieve this there has been considerable developments of customer-side energy management systems to provide new services to customers. The key technical feature is to provide the real-time energy prices and network status information to customers (Nair and Zhang, 2009). Freris & Infield (2008) stated that exploiting the deferability of loads is a useful tactic in any power system; it is especially valuable in systems relying on variable renewable energy sources, and can be far cheaper than employing energy storage.

Getting consumers to deal with the surplus power generated by renewable resources at times of low demand is possibly the best solution to counteract the variable nature of the resource. This is mainly due to the fact that it is much cheaper for consumers to soak up the surplus by increasing their demand rather than storing it or exporting it via an interconnector. This can only take place if the consumer has a financial incentive to do so and a system must be put in place to make consumers aware of when the electricity rates are cheap.

Looking forward, the presence of ageing assets, the growth in renewable and other low-carbon generation technologies and advances in information and communication technologies have all been are identified as major additional drivers that could lead to wider applications of DSM in the medium term. A key element of such applications will be the introduction of smart meters onto the electricity power system.

2.6.1 Smart Meters and Smart Metering Trials

A smart meter is an intelligent metering system that is capable of measuring the consumption of energy whilst also providing additional information to that of a conventional meter. These types of meters can transmit data using a form of electronic communications. One of the key features of these devices is its ability to provide bi-directional communication between the consumer and the supplier/operator (CER, 2011a).

The Commission for Energy Regulation (CER) began the smart metering project in March 2007 with the release of a paper entitled 'Demand Side Management and Smart Metering Consultation Paper'. In this paper the CER made a case for providing smart meters and time of use electricity prices for domestic and small business customers. Following on from this the Smart Metering Project Phase 1 commenced on the 1st of January 2010 with the monitoring of the following installations (CER, 2011c):

- 5,800 single phase and 500 three phase meters with GRPS communications throughout the country;
- 1,100 single phase meters with PLC communications for customers in Limerick and Ennis;
- 1591 metering systems with 2.4 GHz Wireless mesh in Cork City and County.

A number of information papers were published by the CER on the 16th of May 2011 outlining the findings from the electricity smart metering technology trials which were conducted by the ESB as part of the CER Smart Metering Project. The documents will be used to inform future decisions regarding electricity smart metering for both residential consumers and small to medium enterprises (SME's) in Ireland (CER, 2011a).

2.6.1.1 Customer behaviour trials findings

At the core of the smart metering project was the question of how the introduction of smart metering in Ireland could impact energy consumers. To achieve this, a number of different smart metering enabling energy efficiency measures were trialed to measure their impact on customer consumption. These measures included time of use tariffs (ToU) along with a number of demand side management informational stimuli such as detailed billing on a bi-monthly and monthly frequency, in-home displays (IHD), an overall load reduction (OLR) incentive and Web access (CER, 2011b).

A representative sample of 5,000 residential consumers took part in the trials. The key findings of the residential customer behaviour trials in terms of the response to ToU tariffs and DSM stimuli and demographic, behavioural and experiential conclusions were as follows (CER, 2011b):

- Overall electricity usage was found to be reduced by 2.5% and peak usage by 8.8% with the deployment of the ToU tariffs and DSM stimuli;
- A specific trial DSM stimulus conducted which combined bi-monthly bill, energy usage statement and electricity monitor was found to be more effective than other DSM stimuli in reducing peak usage with a peak shift of 11.3%;
- A clear shifting of load from peak to the post-peak period and in general to night usage from peak.
- 82% of participants made some change to the way they use electricity with 74% stating major changes were made within the household;
- Safety and convenience was seen as the largest barrier to shifting to night usage.

650 businesses throughout Ireland participated in the electricity customer behaviour trial. The key findings of the SME trials were as follows (CER, 2011b):

- Overall electricity usage was only reduced by 0.3% and peak usage by 2.2% with the deployment of the ToU tariffs and DSM stimuli;
- 41% of participants believed that they reduced overall usage with 59% stating they reduced peak usage. The tariffs, in particular the peak cost was cited as the driving force behind these reductions;
- The electricity monitor was deemed as being effective with 93% of those reducing overall usage stating it was a key element in achieving the reduction.

2.6.1.2 Technology trials findings

The trials examined a range of smart metering functionality and communications technology options. The trials were used as a method to assess the performance of such devices and to enable both learning and a better understanding of the risks involved with a potential national electricity smart metering rollout to both residential and small business customers in Ireland (CER, 2011c).

Three key communication technologies were selected for the purpose of the trial: power-line carrier (PLC), wireless LAN (2.4 GHz wireless mesh) and point-to-point (GPRS). All three systems were assessed based on their ability to deliver a core set of smart metering functions which all require reliable communications.

The key findings of the technology trials were as follows (CER, 2011d):

- While the PLC system was capable of reliably delivering monthly readings, it had serious issues with delivering daily collection of profile data from every meter and performing on-demand tasks;
- Despite the fact that the GPRS system worked well with good availability the trials unearthed concerns regarding the wide scale adoption of this system and its longevity in terms of a technology in a large number of meters. The GPRS system would however be considered as an appropriate solution if required to roll out a limited number of meters on a priority and dispersed basis;

- In terms of the 2.4 GHz mesh the trials revealed that this system worked well in urban areas where meters were relative close to each other. On the other hand, this system proved less effective in rural areas where wireless is most needed.

2.6.1.3 Cost-benefit analysis

In order to deliver an economic assessment of all the long-term costs and benefits to both the market and individual consumer of a national electricity smart metering rollout a thorough cost-benefit analysis was carried out based on a methodology developed by the Economic and Social Research Institute (ESRI). 12 main national electricity smart metering rollout options were analysed as detailed in Table 2.4

Table 2.4 Rollout Options (CER, 2011d)

Option	Billing baseline	Billing Scenario	Comm's	IHD
Option 1	Bi-monthly	Bi-monthly	PLC-RF	N
Option 2	Bi-monthly	Bi-monthly	PLC-RF	Y
Option 3	Bi-monthly	Monthly	PLC-RF	N
Option 4	Bi-monthly	Bi-monthly	PLC-GPRS	N
Option 5	Bi-monthly	Bi-monthly	PLC- GPRS	Y
Option 6	Bi-monthly	Monthly	PLC- GPRS	N
Option 7	Bi-monthly	Bi-monthly	GPRS	N
Option 8	Bi-monthly	Bi-monthly	GPRS	Y
Option 9	Bi-monthly	Monthly	GPRS	N
Option 10	Monthly	Monthly	PLC-RF	N
Option 11	Monthly	Monthly	PLC- GPRS	N
Option 12	Monthly	Monthly	GPRS	N

The key findings from the cost-benefit analysis of the 12 main national electricity smart metering rollout options analysed were as follows (CER, 2011d):

- The estimated total net present values (NPV's) of the options analysed were generally positive and remained so under a range of sensitivity analyses carried out and if an actual deployment took place would bring about substantial net benefits for Ireland in comparison to the existing scenario;
- In comparison to other technologies examined, Power line carrier (PLC) / Radio Frequency (RF) communications showed higher net benefits from a communication technology perspective.
- In terms of the information stimuli bi-monthly billing with no in-home display consistently exhibited the highest total NPV;
- The cost-benefit analysis estimated that the CO_2 emissions to be at 100,000-110,000 Tonnes below the baseline scenario each year (Figure 2.17) and an annual SO_2 emission reduction of 117-129 Tonnes, which equates to a considerable societal benefit.

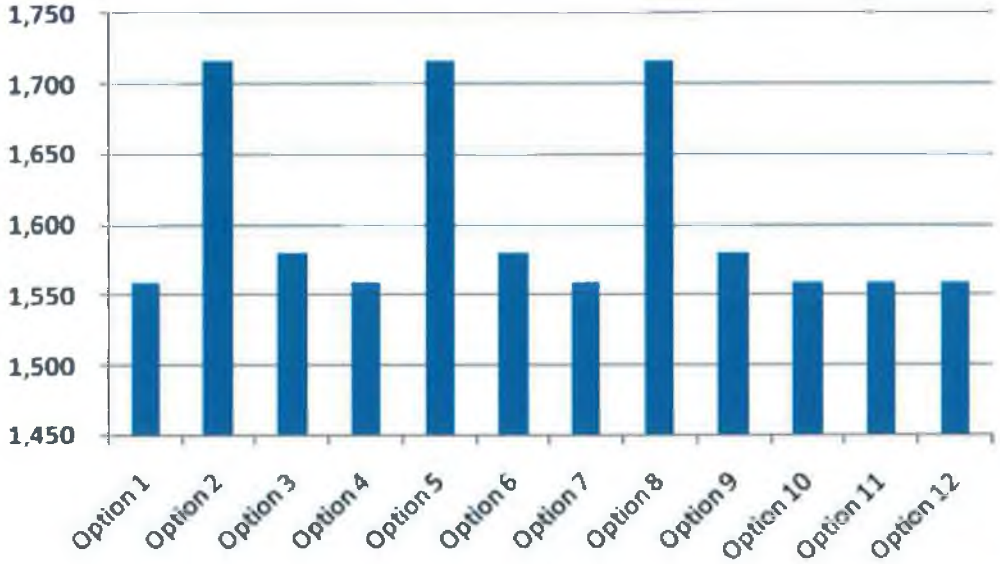


Figure 2.17 Total CO_2 emissions reduction (000 Tonnes) (CER, 2011d)

2.7 Demand Forecasting

Forecasts of how much electricity will be needed to satisfy future societies' requirements are critical for determining generation adequacy. Models based on economic forecasts and historical trends are used by EirGrid and SONI to predict future electricity demands including future peaks in demand. Initially the forecasts for Ireland and Northern Ireland are treated separately as both jurisdictions possess economies and drivers for economic growth that vary considerably. These forecasts are then combined to produce an all-island energy and peak demand forecast. The forecasted demand figures are expressed in terms of Total Electricity Requirement (TER) and are used in the all-island adequacy studies (EirGrid and SONI, 2010).

2.7.1 Ireland's Annual Electricity Demand Forecast Model

The current energy forecast model for Ireland consists of a multiple linear regression model. The model is capable of predicting electricity sales on the basis of 'Gross Domestic Product' (GDP) and 'Personal Consumption of Goods and Services' (PCGS). High, median and low demand forecasts are produced by the model for Ireland over the period of the next 10 years. The median demand scenario was built first and then the growth rates for each year were shifted by -0.5% and +0.5% to create the remaining low and high demand forecasts respectively.

The model also takes into account the losses experienced through the transportation of electricity from the supplier to the consumer. It is estimated, based on findings completed by ESB, that 8.3% of power produced is lost as it passes through the electricity transmission and distribution systems (EirGrid and SONI, 2010).

At the core of the model lie historical economic data sets supplied by the Economic and Social Research Institute (ERSI) along with demand data sets by the DSO. In the latest forecasts made by EirGrid & SONI, presented in the publication "All-island Generation Capacity Statement 2011-2020" in December 2010, the ERSI's expertise in modeling the Irish economy was utilized as regular consultation took place during the modeling process.

2.7.2 Results of Annual Electricity Demand Forecast

The aforementioned publication detailing the forecast of the TER for Ireland over the next 10 years revealed a relatively slow recovery in comparison to the previous two decades with the model predicting a return to 2007 levels by 2013, as illustrated in Figure 2.18.

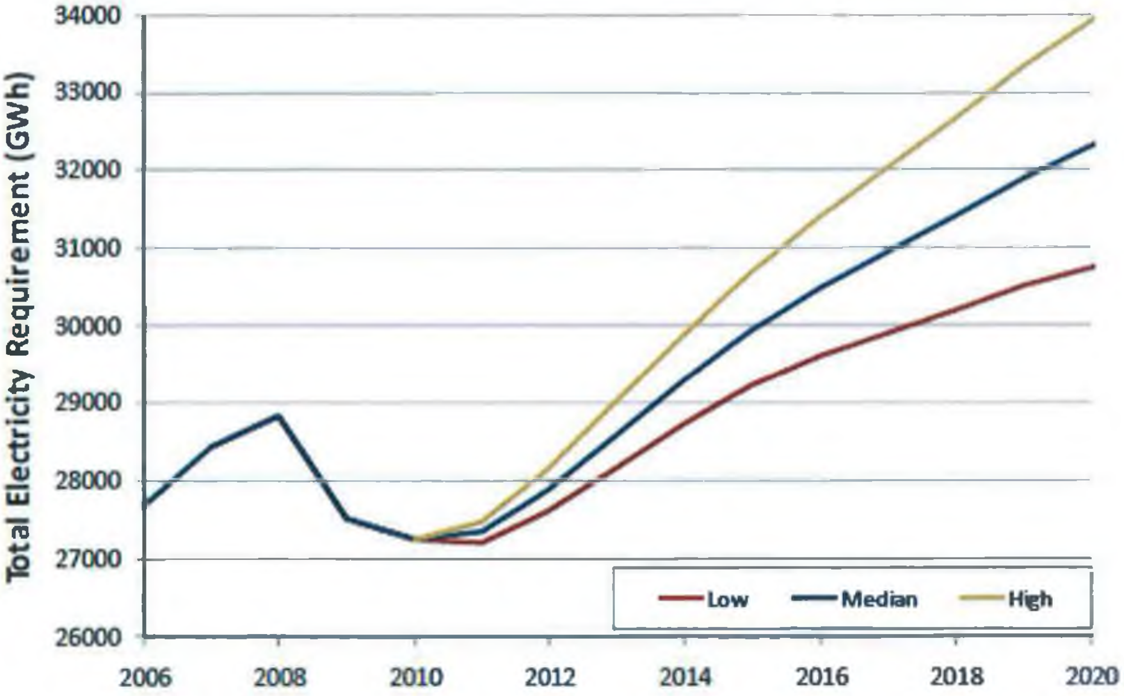


Figure 2.18 TER forecasts for Ireland (EirGrid & SONI, 2010)

In terms of forecasts of transmission peaks, Table 2.5 presents the forecasts of transmission demand for a seven year period form 2011-2017. The winter peak, the summer peak and the summer valley is presented for each year. The winter peaks refer to the expected annual peak demand to occur between the winter months of October to February. There will be an expected increase of 12% in the winter peak over the seven year period analysed.

On the other hand, the summer peak figures represent the average value between March and September. These figures are typically 20% lower than that of the winter peak (EirGrid, 2011). The forecasts reveal an expected increase of 12%, from 3,779 MW to 4,234 MW.

Finally, the annual minimum or base load is referred to as the summer valley. Typical figures of summer valley equate to approximately 36% of the annual maximum demand. This is consistent with historical summer valley demand data (EirGrid, 2011)

Table 2.5 Transmission Demand Forecast, MW (EirGrid, 2011)

Year	Summer Peak	Summer Valley	Winter Peak
2011	3,779	1,701	4,724
2012	3,850	1,733	4,813
2013	3,942	1,774	4,927
2014	4,037	1,817	5,046
2015	4,135	1,861	5,169
2016	4,184	1,883	5,230
2017	4,234	1,905	5,292

2.7.3 Demand Profiles

It is possible to identify patterns in electricity usage. Typically, annual peak demand occurs between the hours of 17:00 and 19:00 on winter weekday evenings. In contrast, minimum usage is typically encountered during the summer weekend night-time hours. Figure 2.19 illustrates the profile for the weekly peaks across the year for 2010.

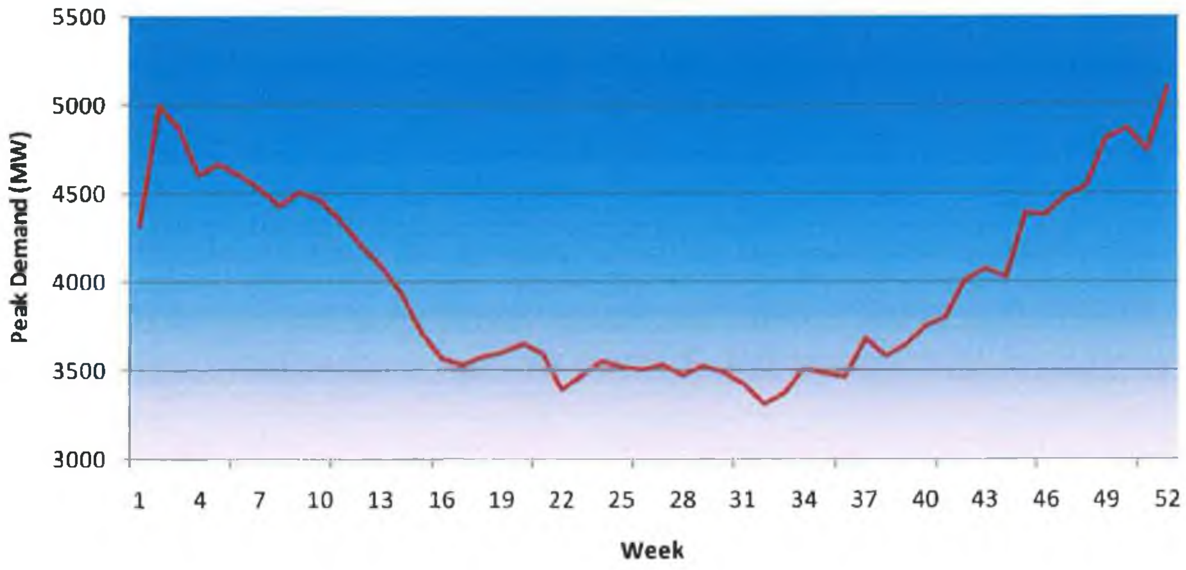


Figure 2.19 Weekly Peak Values for 2010

Figure 2.20 illustrates three daily demand profiles along with the maximum wind generated. The daily demand profiles clearly indicate how electricity usage varies through the day. They consist of the winter peak, the summer minimum which represent the base load. The demand levels range from 1,579 MW which occurred on Sunday the 4th of July to a demand of 5,090 MW which occurred on Tuesday the 21st of December 2010. These demand figures indicates that the power system deals with a wide variation in demand throughout the year. The maximum wind output for 2010 was 1,228 MW which occurred on Sunday the 26th of December.

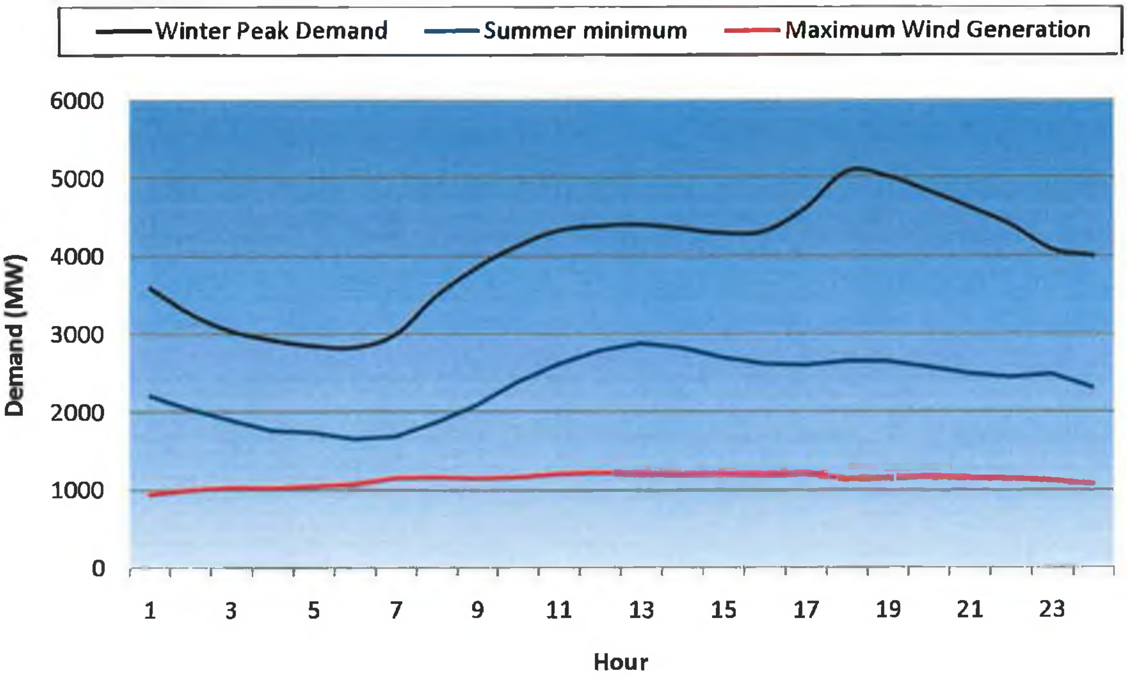


Figure 2.20 Daily Demand Profiles for 2010

2.8 The Future Grid

The decisions made today in terms of the structure of the grid infrastructure of the future can play a pivotal role in solving both the climate change and security of electricity supply problems facing modern society. One such future system is that of the development of an interconnected 'Supergrid'. However, this idea is not new. As early as the 1970s, Buckminster Fuller envisioned an interconnected global grid linked to renewable resources (Higgins, 2008).

2.8.1 Supergrids

The term 'Supergrid' refers to the concept of large-scale transmission of renewable electricity over long distances (Haas et al., 2009). The potential of the available resources in Europe are enormous. So much so that one day the electricity supply could be generated exclusively from renewable sources. However, if this is to materialise, the problems presented by the geographical dispersion of these sources will have to be overcome.

2.8.1.1 High Voltage Direct Current (HVDC) Transmission

An electricity system based wholly on renewable sources would require the development of an efficient, long-distance transmission grid in a wide-area supply system (Haas et al., 2009). This system would allow the transmission of renewably generated electricity from sites of favorable conditions to the load centers, with distances no longer a limiting factor. Fortunately, the technology required exists in the form of high voltage direct current (HVDC) systems. This system offers the ability to transmit electrical power as direct current at a high voltage (Reynolds et al., 2010). The introduction of such a system can overcome the stability issues often associated with connecting both onshore and offshore devices to the grid and it has become an economic alternative to high voltage alternating current for transmitting electrical power over large distances (Ereño et al., 2008). A typical HVDC system consists of the following (Reynolds et al., 2010):

- Transformers;
- AC to DC converters;
- DC current filtering reactance;
- DC cable;
- DC to AC converters.

The first commercial HVDC transmission line was constructed in Gotland in Sweden in 1954 (Rudervall et al., 2000). Since then a large amount of HVDC has been installed around the world, about 70,000 MW HVDC capacities in more than 90 projects (Ragheb, 2009). These various installations are highlighted in Figure 2.21. In a HVDC system, electrical current is converted from AC to DC (rectifier) at the transmitting end and from DC to AC (inverter) at the receiving end. This can be achieved through any one of the following methods (Rudervall et al., 2000):

- Natural Commutated Converters;
- Capacitor Commutated Converters (CCC);
- Forced Commutated Converters.

The cost of constructing a HVDC transmission system is dependent on a number of factors including the power capacity to be transmitted, the type of transmission medium, the presence or not of any environmental conditions along with other safety and regulatory requirements. Rudervall et al. (2000) estimates the costs for HVDC lines at $250/ kV km and $250 M for converter stations.

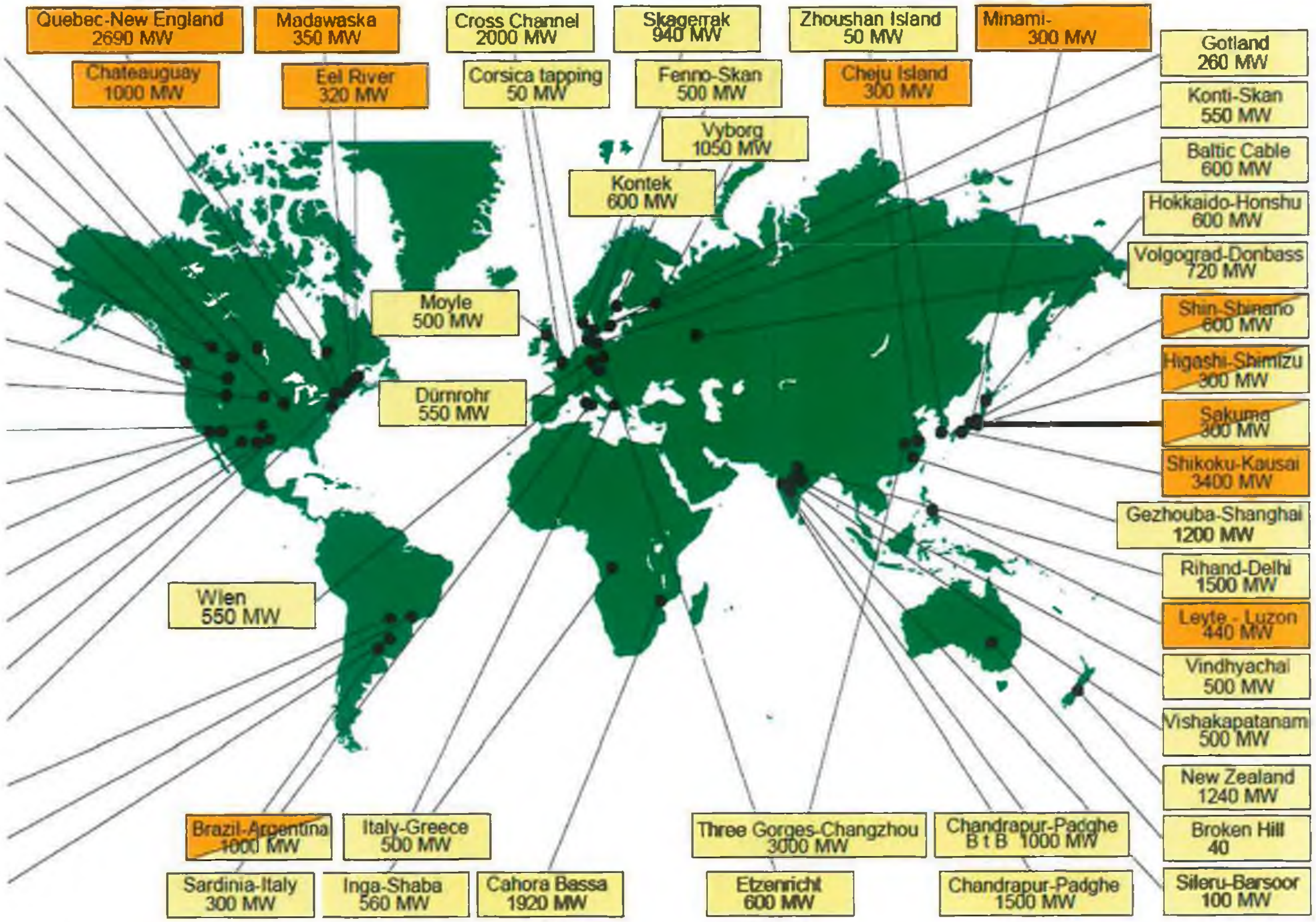


Figure 2.21 HVDC Transmissions around the world (Gross, 2011)

A typical cost comparison curve between AC and DC transmission is shown in Figure 2.22. The curve is based on the following considerations:

- AC vs. DC capitalized value of losses;
- AC vs. DC line cost;
- AC vs. DC station terminal costs.

It can be clearly seen from the figure that the DC curve is not as steep as the AC curve. This is due to the fact that DC transmissions have much lower line costs per kilometer. The breakeven distance is approximately 500-800km (Siemens, 2001). This is dependent on a number of factors such as interest rates for project financing, cost of right of way and country specific cost elements (Siemens, 2011).

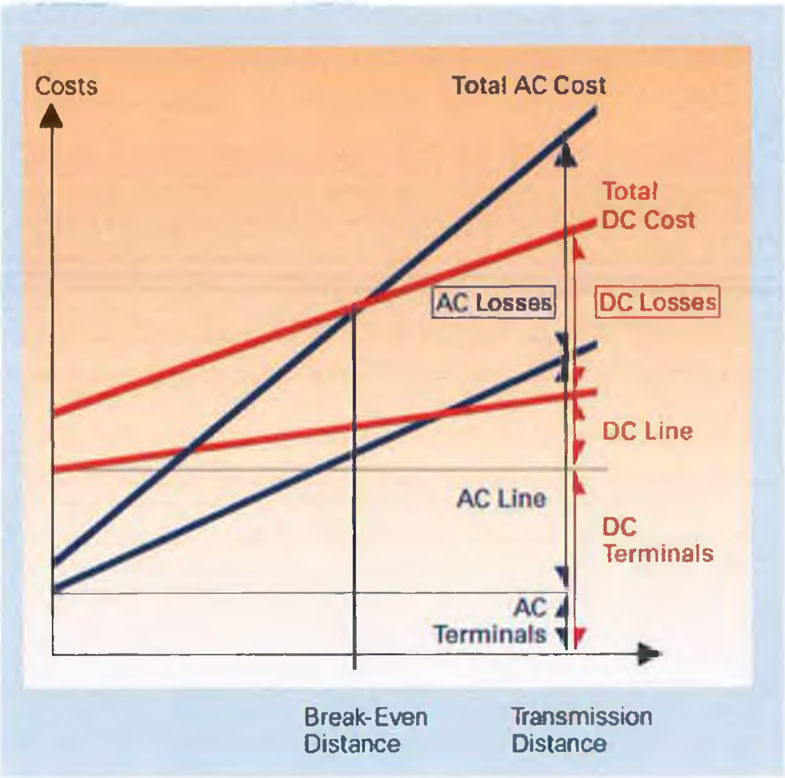


Figure 2.22 Total Cost/Distance (Gross, 2011)

The advantages of HVDC transmission include the following (Ragheb, 2009):

- Lower investment costs – the cost of an HVDC transmission line is less than that of an AC line for the same transmission capacity;
- Long distance water crossing – an HVDV transmission cable has no technical limits;
- Lower losses – HVDC losses are much lower than that of AC losses in the vast majority of cases;
- Environmental benefits – HVDC systems reduces the need for additional power stations. The right of way for a DC line can be reduced to that of half that needed for an AC line as it requires less space and has less of a visual impact.

2.8.1.2 Moyle Interconnector

The electricity grids of Northern Ireland and Scotland in Great Britain are connected via the Moyle Interconnector. This high voltage direct current transmission line has a capacity of 500 MW and went into service in 2001 after a construction period of 27 months. Northern Ireland Energy holdings owns and operates the interconnector that is capable of importing 450 MW in winter and 400 MW in summer from Scotland (EirGrid, 2009). A contractual arrangement has restricted the export capacity to Scotland of 80 MW. This arrangement is currently under review (EirGrid, 2009).

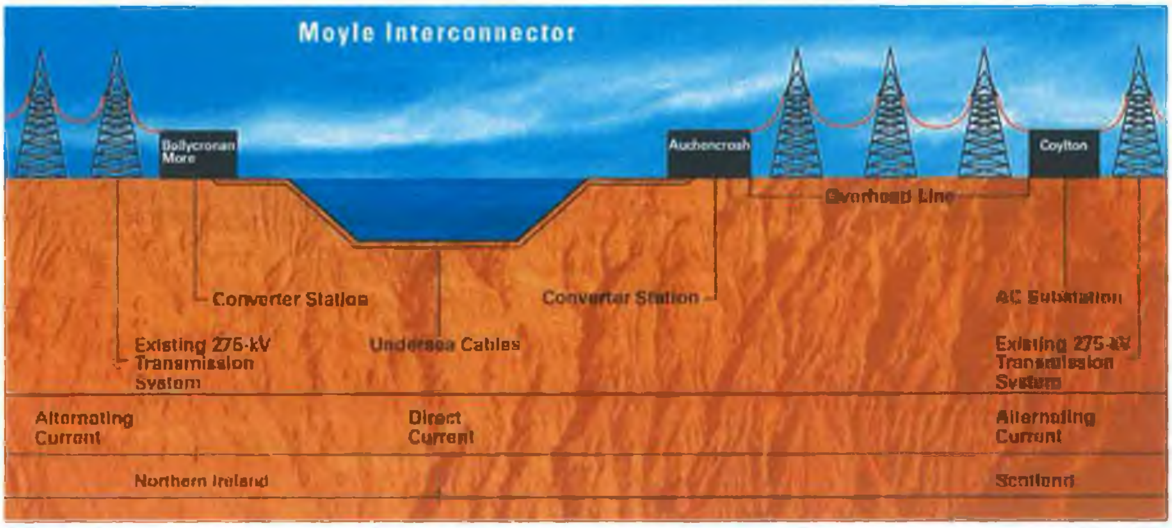


Figure 2.23 Moyle Interconnector (Gross, 2011)

The project reflects the principle arrangement of an HVDC transmission project with the following highlights (Siemens, 2011):

- Unmanned stations, fully automatic remote operation with an automatic load schedule operation;
- Triple tuned AC filter in both stations with hybrid optical ohmic shunt for DC current measuring unit;
- The stations have been designed for DC sea/land cable with an integrated return conductor fibre optic cable for the purposes of better control and communication.

2.8.1.3 Borwin Wind Farm

The world's largest offshore wind farm is located in the North Sea, 81 miles off Germany's coast near Borkum. It was commissioned in September 2009 and is connected to the European grid using advanced HVDC light underground and submarine technology (Steinhusen, 2009). The HVDC cables have been installed both underwater and underground. This has greatly reduced the project's environmental impact and helped overcome any regulatory issues that may have otherwise delayed the project (Gross, 2011).

The BorWin 1 facility is a prime example of how effective HVDC lines can be to gather power generated in remote locations and successfully transmit to place of high demand (Gross, 2011). The wind park consists of 80 wind turbines, each with a capacity of 5MW.

Figure 2.24 Offshore Windpark – Cluster Borkum (Gross, 2011)

2.8.1.4 Xiangjiaba to Shangai UHVDC Link

Unlike in the United States and Europe, there is no state or national obstacles to be faced with in China. Therefore China continues to be a significant player in the advancement of transmission technologies capable of extracting the power from renewable energy sources. It is of no great surprise then that the world's longest and most powerful transmission link is under construction in China from Xiangjiaba to Shanghai (Gross, 2011). This transmission link represents a major breakthrough in the technology of electric power transmission.

The link will have a voltage of 800kV and a power rating of 6,400 MW, which is more than double the power rating of the most powerful transmission in operation today. When the link is complete it will have an overhead line link of 2,071 km with expected losses of 7%. The 800 kV voltage will be formed with the combination of two 400 kV series connected 12-pulse converters (ABB, 2009b).

Figure 2.25 Xiangjiaba to Shangai UHVDC Link (Gross, 2011)

2.8.2 Smart Grids

One vision of the future electrical networks is one where the user has the ability to play an active role in the supply chain. This is in much contrast to today's system where users are on-demand receivers of electricity. No further participation is played by the user in the operational management of the network as each user node is quite simply a sink for electricity usage (Hammons, 2008). However, the power grids of the future will be based on an increasing level of intelligence augmented with an integration of Information and Communication Technologies (ICT) (Nair and Zhang, 2009).

2.8.2.1 European Vision

The SmartGrid infrastructure design was originally developed as part of the European Strategic Energy Technology Plan (SET-Plan) introduced by the European Commission in 2007. The transition of the European energy infrastructure networks was identified as a key method under which Europe's energy targets could be achieved. The main objectives of this transition are to integrate the somewhat segmented energy systems across Europe in the hope of establishing flexible, accessible, reliable and sustainable electricity networks in the future (Nair and Zhang, 2009). The SmartGrid concept in Europe has evolved due to the concern over the wide range and degree to which the grids across Europe have progressed (Lightner et al., 2007). In terms of generation sources, there has been a focus placed upon distributed generation with a high penetration of renewable energy sources (Nair and Zhang, 2009).

2.8.2.2 GridWise

A similar project has been developed in the US, known as GridWise. This concept is largely based on the idea of large power stations based on clean coal technologies to form a new power system infrastructure. A high integration of demand response technologies will also be used (Nair and Zhang, 2009). In this case however, distributed generation is used only as a means of improving the security of the system and is not seen as a main part of the solution (Lightner et al., 2007).

2.8.3 Irelands Smartgrid Opportunity

Energy systems of the future will strive to be sustainable, efficient and secure. Electricity will play a pivotal role in these systems. The introduction of a Smart Grid in Ireland will result in a different approach to how we generate, distribute and use electricity. There will be a paradigm shift from the traditional planned and centralised generation and distributions system to a more responsive and dynamic one where consumers manage their electricity consumption and costs. All this can be achieved while being much less carbon intensive (SEAI, 2010b).

Figure 2.26 illustrates the various Smart Grid activities taking place in Ireland at this present time. In terms of research, Ireland has already a smart academic research infrastructure in place. This includes the Electricity Research Centre, which is a collaboration of academia and major Irish and international electricity partners. The research underway in such centres is being monitored closely by Smart Grid Ireland, an industry-led group which was established in the hope of exploiting the benefits and opportunities in the Smart Grid Sector.

The first steps towards a future Smart Grid for Ireland were taken with the conducting of an aforementioned national trial for Smart Meters in 2009 by the Commission for Energy Regulation (CER).

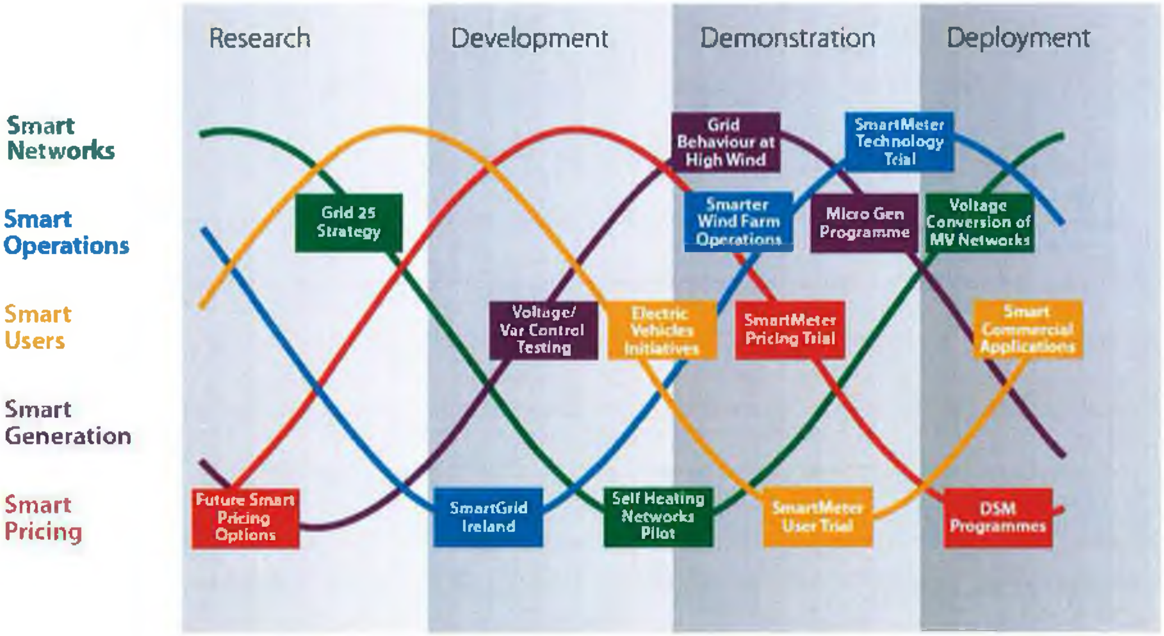


Figure 2.26 Smart Grid Activities in Ireland (SEAI, 2010b)

CHAPTER 3

METHODS AND MODELS

3.1 Introduction

As the expansion of wind power in the electricity sector continues to grow so do the questions about how this intermittent resource might affect the capacity factor of wind farms at high levels of penetration. Electricity storage technologies have the capability to shift wind energy from periods of low demand to peak times as well as smoothing out any fluctuations in output. Therefore, these storage technologies will play a vital role in bolstering the value of wind power at the levels of penetration set in the policies of governments worldwide (NREL, 2008).

Power companies are continuously monitoring data to determine the capacity value of operating wind farms. What this essentially means is the amount of conventional capacity a given amount of wind capacity can replace. Although the accuracy of wind forecasting has improved greatly in recent times, the resource by its very nature is intermittent and will therefore not allow operators to dispatch wind power to meet load similar to what can be achieved with a conventional plant. The use of storage technologies to provide synergies with wind power may result in a decrease in the cyclical operation of conventional units as system operators are no longer attempting to coordinate the following of the fluctuating demand throughout the day and the variable output of wind power generation. As the levels of penetration of wind energy onto the power system rise, the more valuable storage becomes (NREL, 2008). If the necessary investment were to take place in a base load wind energy system (a system combining wind energy and energy storage), the generation capacity would be greatly increased along with a reduction in harmful emissions with the displaced output from thermal units. Furthermore, a fuel cost saving can be achieved due to the reduction in the operation of the thermal units who's fuel costs are quite excessive when compared to a base load wind energy system (Denny, 2009).

The author will, through the creation of an appropriate model, seek to quantify the value storage can add to wind by introducing a base load wind energy system and identifying the main potential costs and benefits of incorporating a base load wind energy system onto an electricity system. These costs and benefits will then be used to highlight the obvious potential of a base load wind energy system in a case study on a real electricity system. The approach adopted attempts to maximise social welfare. Due to this fact, both direct and indirect costs and benefits are included.

3.2 Base load Wind Energy Systems

Base load power plants are capable of generating electricity at nearly constant power as well as providing a high capacity factor, output stability and reliability (Denholm et al, 2005). In Ireland, these base load plants are responsible for providing a large proportion of the electricity generated to meet the annual electricity demand of approximately 27 TWh per annum (EirGrid, 2008). Large combined cycle gas turbine (CCGT) plants such as the Aghada plant and coal fired conventional steam stations such as Moneypoint in County Clare are utilised in Ireland to provide the base load. In the combined cycle plants both gas and steam turbines are used to generate power. Gas is first burnt in a gas turbine and a heat recovery boiler is then fed with the hot exhaust gases to produce steam. A steam turbine then uses this steam in conjunction with a generator to produce electricity. The combination of the two turbines has proven to work very well with efficiency levels of 58% recorded (SOI, 2011). Despite this fact however, plants powered by natural gas still produce harmful air emissions and draw on finite natural gas resources (Denholm et al, 2005).

Large coal fired single cycle steam stations such as Moneypoint in Co. Clare typically only convert 38% of the energy in the fuel into electricity, deplete fossil fuel resources whilst also producing greenhouse gases in the form of sulphur dioxide and nitrogen oxides (SOI, 2011). These plants do however produce cheap electricity as coal is frequently less expensive than natural gas or oil. Figure 3.1 illustrates the existed and planned fully dispatchable power generators in Ireland for 2013.

Due to the obvious environmental concerns surrounding current electricity generation methods there has been much research conducted exploring alternative power sources that can match the capacity factor, output stability and reliability of conventional base load plants.

Wind energy on its own cannot possibly act as a viable alternative. However, when it is combined with energy storage it offers a functional equivalent to a conventional base load plant. As previously stated, Ireland has set a target of 40% of electricity consumed to come from renewable sources by 2020, which will equate to approximately 4,350 MW of wind capacity using EirGrid's median demand forecast (EirGrid & SONI, 2010). With the creation of a base load wind system, these levels can be greatly increased in the future. Additionally, the cost of wind energy has declined in recent years making a base load wind energy systems economically feasible.

In order to realistically assess a base load wind system, an economically viable energy system must be included along with the additional transmission requirements of the proposed system. Consequently, the author has prepared a base load wind model using a wind turbine, storage, and transmission technologies that are considered economically viable in Ireland when deployed on a large scale. The energy storage system can be used to increase the capacity factors of a typical wind farm in Ireland. The capacity factor is defined as the ratio of the expected output power over a period of time, typically a year, to the rated power of the wind turbine generator (Nemes and Munteanu, 2011). As can be seen from Figure 3.2, the historical wind capacity factors for Ireland have ranged from a peak of 34.7% in 2003 to an all time low of 29.1% in 2007 with the average over the 8 year period being 32.2%.

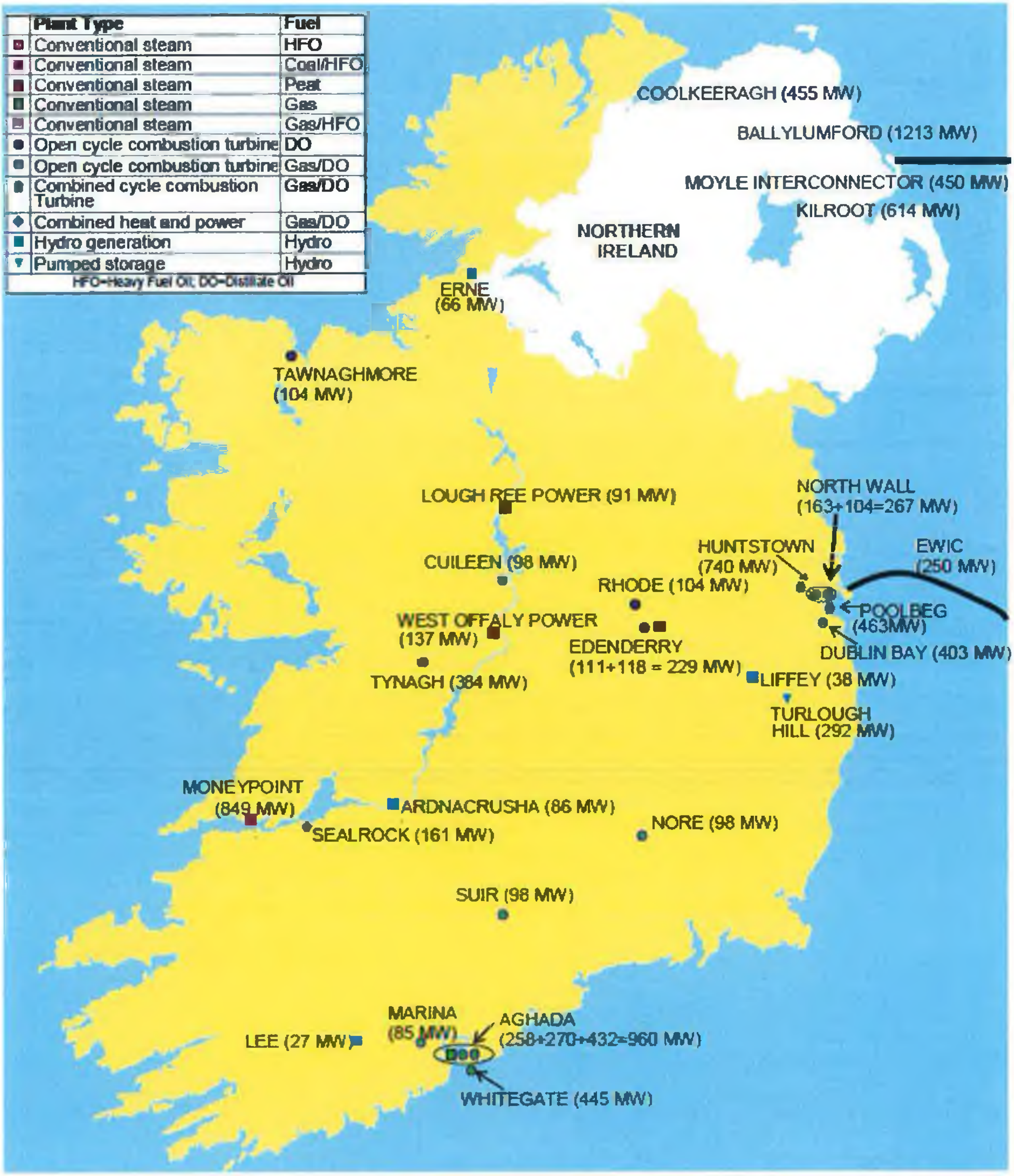


Figure 3.1 Fully dispatchable plant installed in 2013 (EirGrid, 2009a)

In contrast the capacity factors of base load plants stand in excess of 70%. Increasing the capacity factor of a wind farm will also improve the farms output stability and overall reliability of wind energy.

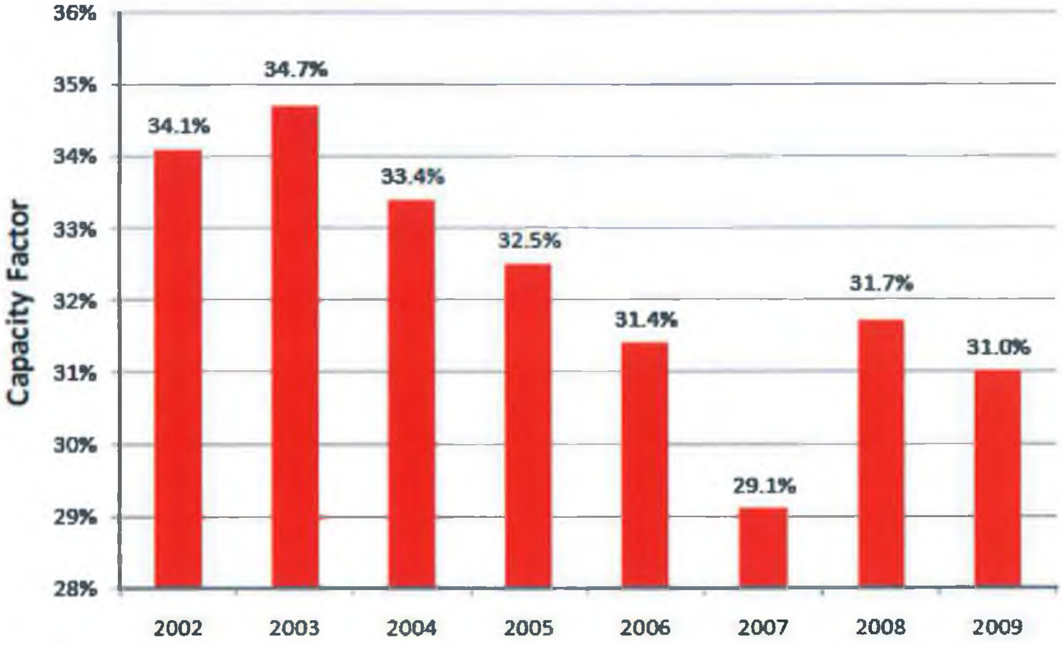


Figure 3.2 Historical wind capacity factors for Ireland (EirGrid & SONI, 2010)

3.3 Modeling Base load Wind Energy Systems

Cavallo (1995), Cavallo (1997) and DeCarolis and Keith (2002) have completed studies to evaluate the economic performance of base load wind energy systems. However, in this study the author will attempt to develop a model of a base load wind system to perform both an energy and environmental analysis as well as evaluating its economic feasibility. The model uses a computer program to simulate hourly wind speeds along with the performance output of a wind farm integrated with energy storage. The Monte Carlo method was used to complete the simulation of the wind speed. This method is based on the use of random numbers. Two types of problems can be handled with the Monte Carlo method, called probabilistic and deterministic according to whether or not they are directly concerned with the behaviour and outcome of random processes (Marmidis et al., 2008). Due to the fact that the solution is directly influenced from the random numbers, a probabilistic problem is dealt with in this paper.

The model compares the wind farm output to the base load required on an hourly basis and attempts to provide constant power output by storing or releasing from storage, the appropriate amount of energy.

3.3.1 Wind-Farm Data

In order to accurately model the performance of a base load wind energy system, extensive data relating to the output from a wind farm must be compiled to capture both the short-term and long-term variations in wind speed. For this reason, this study developed a model to produce hourly wind farm data with varying values of the Weibull scale and shape parameters, '*c*' and '*k*'. Each data set was completed for a one year period.

Hourly power output from wind farms was used to create data sets that simulate the performance of larger wind farms. Additionally data sets were retrieved from the EirGrid download centre of the system demand and generated wind energy to act as a comparative to the simulated data.

3.3.1.1 Weibull Distribution

The likely power output from a wind farm is dependent on the wind speed in the planned wind farm location. Wind speeds can be measured using an anemometer and can be classified using the older Beaufort scale, which is largely based on peoples observation of specifically defined wind effects. However, the measurement of the wind speed solves only part of the problem, it is also necessary to calculate how often winds will be experienced at a location with a certain average wind speed. This element can be modeled using a statistical tool called the Weibull distribution.

The Weibull distribution tool can be used to calculate the probability of a particular wind speed at a particular location and thus work out the number of hours per year that certain wind speeds are likely to be recorded. The likely total power output of the wind farm per year can then be obtained.

Knowing the probability of wind speeds at a location is critical to the design of a successful wind farm so the correct wind turbines can be installed with the optimal 'cut in' and 'cut out' wind speeds. The Weibull distribution is often used to demonstrate the fact that low and moderate wind speeds are very common while strong gales are relatively rare. This is illustrated in Figure 3.3.

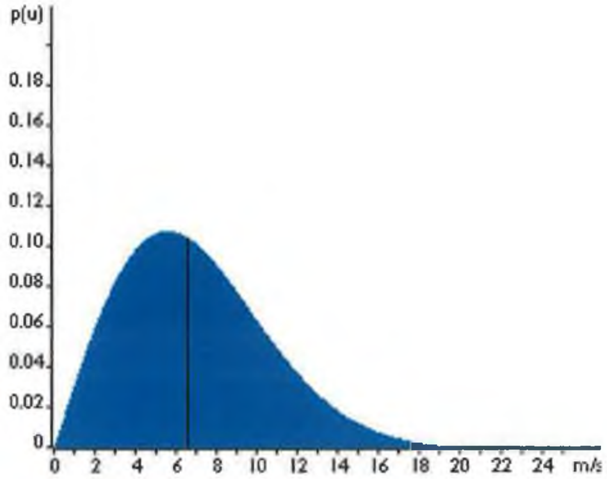


Figure 3.3 Weibull Distribution of Wind Speeds (WindPower, 2011)

The Weibull distribution is described by two parameters. The first of which is the Weibull scale parameter '*c*' which is closely related to the mean wind speed of a particular site. The scale parameter controls the adscissa scale of a plot of data distribution (Chang, 2011). The Weibull shape parameter '*k*' on the other hand is concerned with the width of the distribution. The larger the shape parameter the narrower the distribution and the higher its peak value (Chang, 2011). The use of this mathematical expression is considered very useful since it allows both the wind speed and its distribution to be described in a concise fashion.

Studies have been completed that reveal that in Northern Europe and most other locations around the world the value of *k* to be approximately 2 (REUK, 2011). The value of *k* can range from 1 to 3 with most wind turbine manufacturers typically using a shape factor of 2, which makes the distribution a Rayleigh Distribution. The higher the value of *k*, the higher the mean wind speed will be.

Figures 3.4-3.6 illustrate the histograms of a year's worth of hourly wind data having Weibull distribution generated by a computer program with particular shape and scale parameters. The bin size used is 1m/s. The Weibull probability distribution function f (v) and cumulative distribution function F (v) were calculated using the following formulae:

- Weibull pdf $f(v) = k/c\,(v/c)^{k-1} \exp[-(v/c)^{k}]$
- Cumulative Weibull function $F(v) = 1 - \exp[-(v/c)^{k}]$

It can be clearly seen from the charts that the theoretical curves of both Weibull pdf and cdf calculated with the same parameters match very well with the generated data.

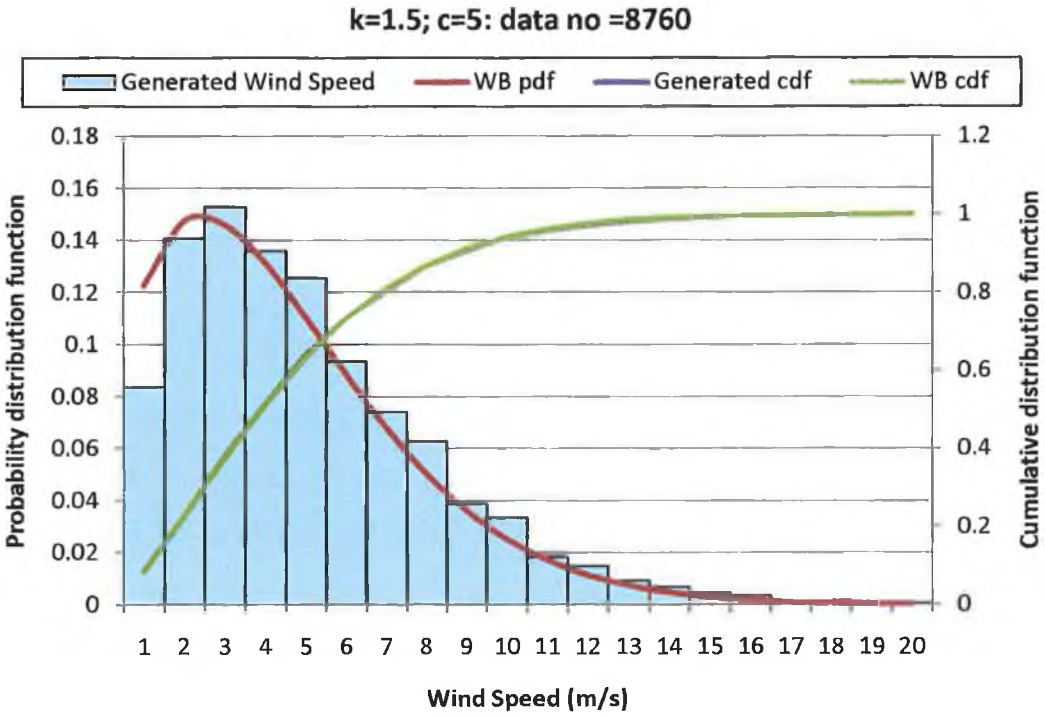


Figure 3.4 Histogram of Weibull pdf and cdf ($k = 1.5$, $c = 5$)

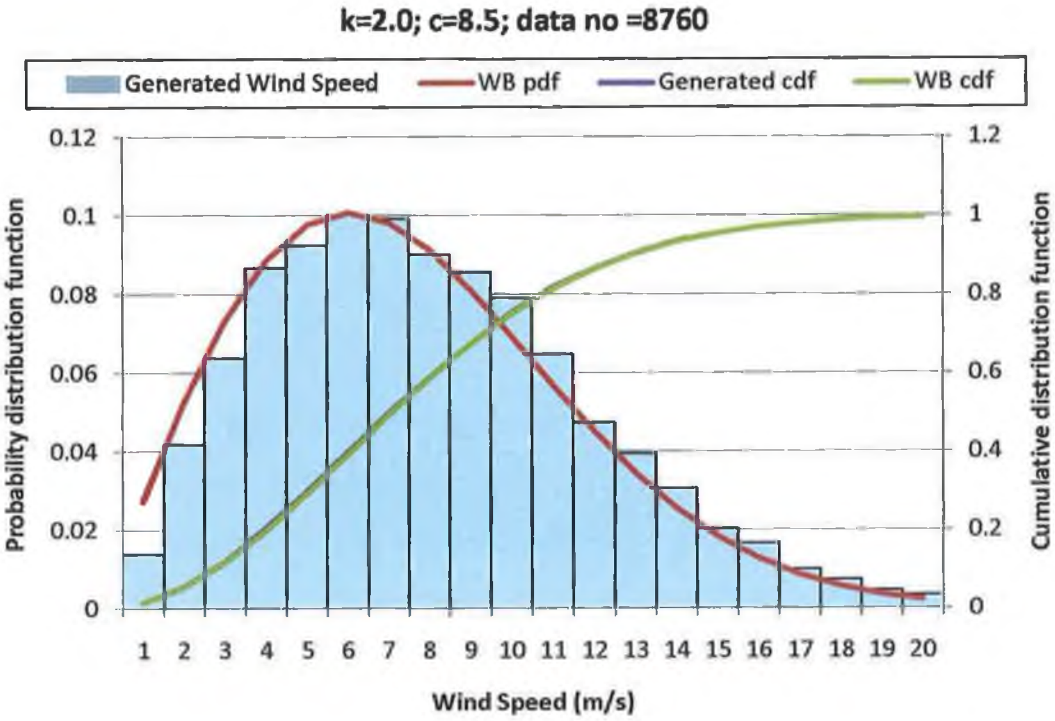


Figure 3.6 Histogram of Weibull pdf and cdf (k=2.0, c=8.5)

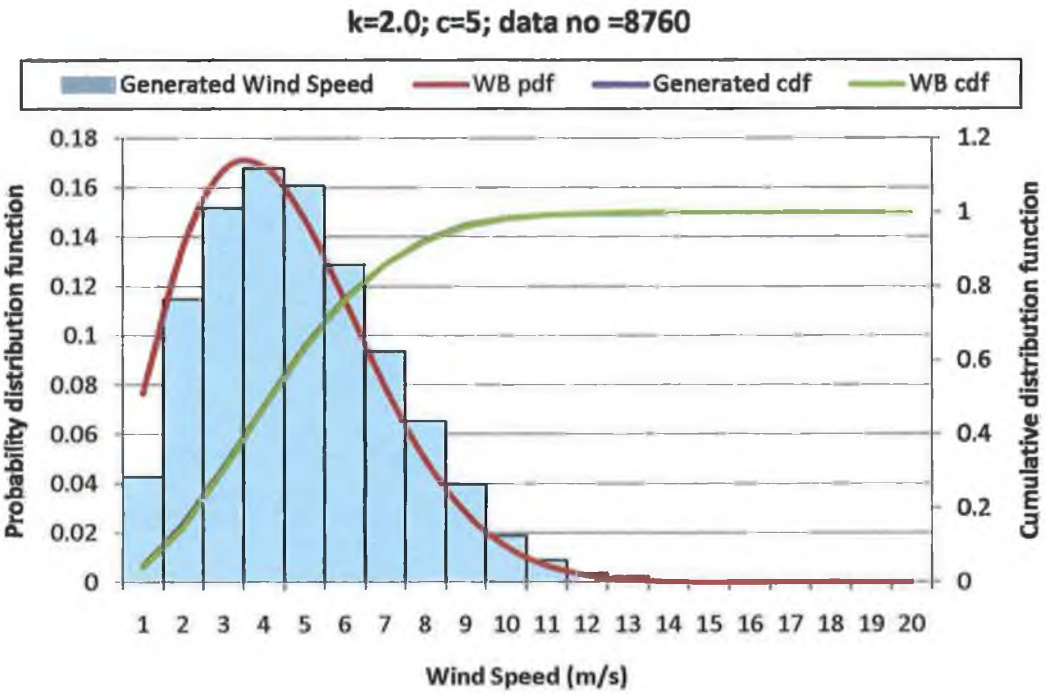


Figure 3.5 Histogram of Weibull pdf and cdf (k=2.0, c=5)

There are many different methods by which the Weibull parameters can be calculated. Chang (2011) reviewed the six different kinds of numerical methods commonly used for estimating Weibull parameters which included the moment, empirical graphical, maximum likelihood, modified maximum likelihood and energy pattern factor method. The results of Chang's study revealed that if the data numbers are small, the graphical methods performance in estimating Weibull parameters is the worst one, followed closely by the empirical and energy pattern factor methods. The performance of all the numerical methods improved as the data numbers became larger. Overall it was found through the simulation test that the maximum likelihood, modified maximum likelihood and moment methods represented the most excellent ability to accurately estimate the Weibull parameters.

Akpinar and Akpinar (2004) used both the Weibull and Rayleigh probability distribution functions to study the wind energy potential of Agin-Elazig, Turkey. Their study revealed that for that particular location the Weibull distribution was better than the Rayleigh distribution function in fitting the measured monthly probability density distribution. It was also found that the Weibull distribution provided better power density estimations in all 12 months rather than the Rayleigh distribution.

3.4 Case Study

For the purpose of this model Ireland was chosen as the case study to quantify the costs and benefits of a base load wind energy system. Ireland is an island electricity system with a rich wind energy resource. Ireland's land mass is around 2% of the total EU land mass but it possesses 6% of EU wind resources (SOI, 2011). Figure 3.7 illustrates the existing and planned wind farms on the island of Ireland.

The Irish electricity system has limited interconnectivity to other systems which allows a controlled study to be carried out and any issues concerning high levels of variable electricity generation should become more apparent than in a system which may have larger interconnection (Nyamdash et al., 2010).

Figure 3.7 Existing and planned wind farms (EirGrid, 2009a)

In the past, the Irish system was comprised of two separately operated but interconnected systems, one in Northern Ireland and the other in the Republic of Ireland. This configuration was made redundant in 2004 when an agreement was reached between the electricity regulators in the Republic and in the North to establish a single 'all island' market for electricity. Consequently, in November 2007 the new 'all island' Single Electricity Market (SEM) was launched. The development of the SEM for the island of Ireland has created a gross mandatory pool market. Under this type of market all electricity generated on or imported onto the island of Ireland must be sold from which all wholesale electricity for consumption on or export from the island must be purchased (All Island Project, 2010). The operation of the SEM is clearly illustrated in Figure 3.8 where the relationship between the generators, suppliers and consumers is presented.

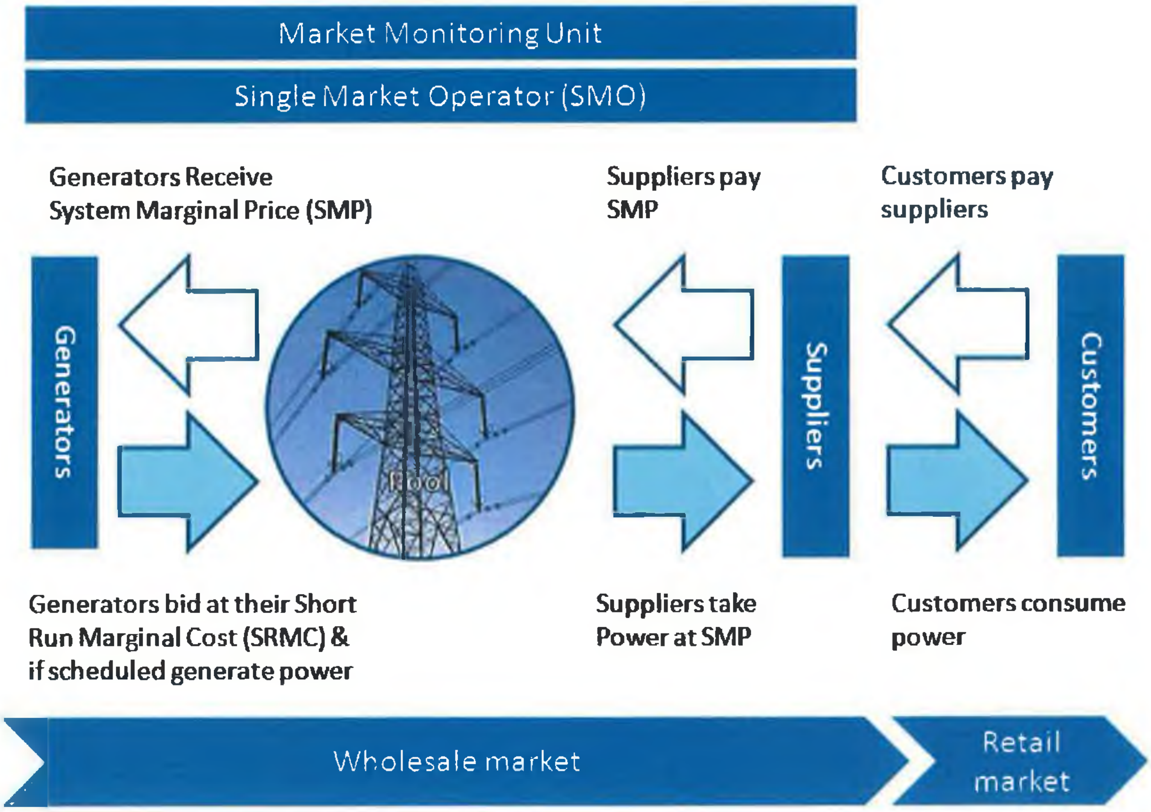


Figure 3.8 Operation of the Single Electricity Market (All Island Project, 2010)

In this research, the 2010 Irish demand profile has been used along with the wind generated for the corresponding period. It is also assumed that there are no network constraints due to the works currently been undertaken by EirGrid under its Grid 25 strategy.

3.5 Model

In order to evaluate a base load wind energy system a program was developed by the author with the assistance of the author's supervisor. Table 3.1 details the various parameters used in the program. The parameters are those required to produce outputs including wind speed, used energy, wind farm output and stored energy. The base load and storage level was set per turbine.

Table 3.1 Program Inputs

Parameter	Symbol	Unit
Shape Factor	*k*	dimensionless
Scale Factor	*c*	m/s
Air Density	ρ	kg/m^3
Blade Radius	r	m
Power Coefficient	Cp	-
Cut-out Speed	-	m/s
Cut –in Speed	-	m/s
Maximum Allowed	-	m/s
No. of turbines	n	-
No. of samples	n	-
Storage Capacity	-	kWh
Storage Base	-	kW
Storage Level	-	kW
Stored Energy	-	kWh

The program was wrote in such a manner that each turbine is required to produce a set amount of energy to meet the base load figure and after that level has been reached a storage level was put in place where any energy above the set figure will be put into storage. In the event that the power output from the wind farm is not sufficient to meet the base load requirement, the requisite energy will be extracted from the storage vessel.

The following formulas were used by the program to obtain the necessary outputs:

- Wind speed = $\{c * ((-\log (1-x)) * (1/k))$
- Area of turbine = $\{\lambda$ * wind turbine radius$\}$
- Turbine Power Output = $\{0.5 * Cp * \rho * A * v^3\}$
- Wind farm output = {power output per turbine * number of turbines}
- Stored Energy = {wind farm output – base load requirement}

A maximum of 20,001 samples was permitted by the program. The author decided that 8760 points would be adequate as this represents the number of hours in a year. In terms of the coefficient of power (Cp), the program allowed for the option of using the ideal Cp of 0.59 (Betz' limit) or the actual Cp of the turbine based on the power output curve shown in Table 3.2. An additional option was also included in the program. This was whether not to overwrite the simulated wind data with actual data sets for the demand and wind generated from EirGrid's download centre.

Table 3.2 Actual Cp values for Vestas V112 3MW

Wind Speed	Coefficient of Power (Cp)
3 m/s	0.25
4 m/s	0.37
5 m/s	0.40
6 m/s	0.43
7 m/s	0.44
8 m/s	0.45
9 m/s	0.45
10 m/s	0.44
11 m/s	0.38
12 m/s	0.30
13 m/s	0.24

The turbine used in the model is the Vestas V112 3.0 MW onshore turbine. The turbines primary technical specifications are presented in Table 3.3. This particular turbine has been designed for high productivity and excellent grid support. The turbine has been designed in such a manner to reduce its noise output without impacting its power production (Vestas, 2011).

Table 3.3 Technical specifications of wind turbine Vestas V-112 3.0 MW

Turbine Model	Rated Power (MW)	Cut-in speed (m/s)	Rated Speed (m/s)	Cut-off Speed (m/s)	Rotor Diameter (m)	Hub Height (m)
V112	3	3	13	25	112	84

The power curve for the V112-3.0 MW is shown in Figure 3.9.

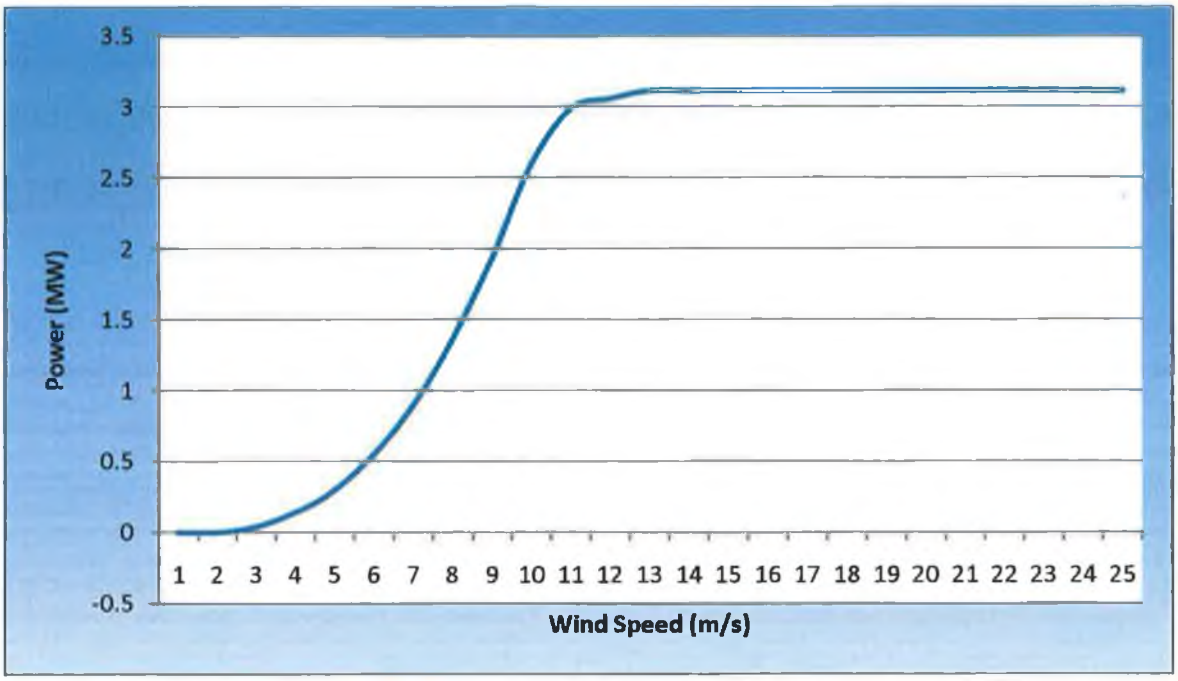


Figure 3.9 Power Output Curve V112 3MW

3.6 Methodology

The model has been devised in such a manner that at each hour the wind farm output is compared to the base load required. If the output from the wind farm exceeds this figure, the energy is placed into storage, and if the wind power is below the required amount, energy is withdrawn from storage. Due to the fact that wind speed is largely influence by seasonal variations and there is a limit to the size of the storage vessel, constant power will not be achieved all of the time. Additionally some wind energy generated will be unused. Figure 3.10 illustrates this issue with a base load requirement of 1000 MW. Most of the energy required is provide by a combination of wind energy transmitted directly and stored wind energy. However, due to insufficient storage, a considerable amount is spilled which results in decreased economic and environmental performance. The amount of spilled energy can be reduced by raising the base load required.

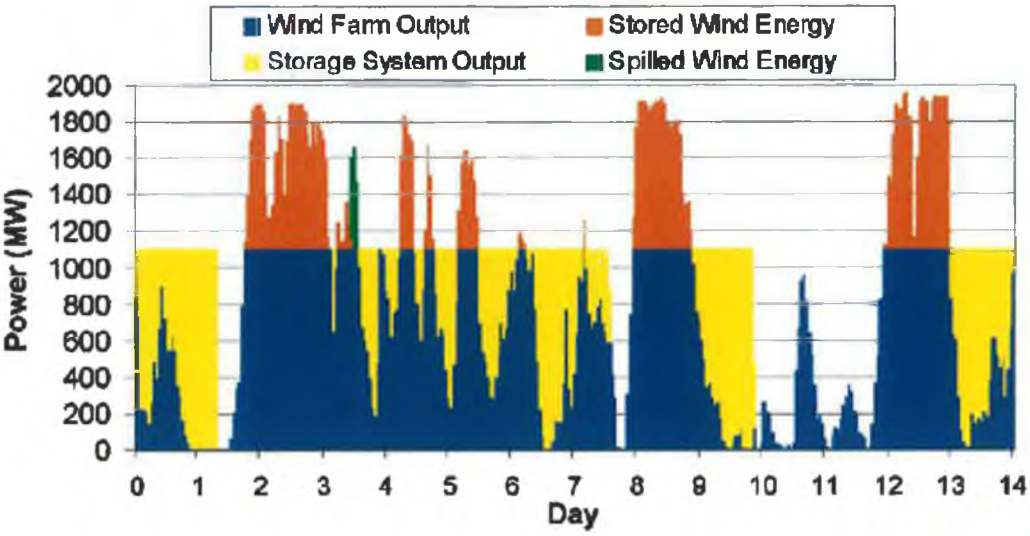


Figure 3.10 Sample base load wind generator (Denholm et al., 2005)

In this research, energy storage is assumed to be the supplementary unit of wind generation with its main function to balance the total wind output. As discussed in chapter 2 there are number of energy storage technologies under development. For the purpose of this paper, pumped hydro, adiabatic CAES, batteries and flywheels were chosen as the energy storage technologies to be combined with the wind generated as they all have the potential to act as large scale energy storage systems. The concept of adiabatic CAES would eliminate the use of fossil fuels in CAES and thus result in no harmful greenhouse gases being emitted and an increased overall fuel saving.

3.6.1 Emissions benefits of a base load wind energy system

The burning of fossil fuels at elevated temperatures in conventional combustion plants leads to the creation of harmful emissions. Table 3.4 presents the tonnes of CO_2 per MWh of electricity supplied by each supplier in Ireland. Airtricity have the smallest emissions figure in Ireland with 0.450 tCO_2 / MWh. The all island overall average is 0.519 tCO_2 / MWh. This figure represents a rise of 3% (0.015 t/MWh) in 2010. This was due mainly to the decrease in renewable generation and the fact that there was a larger share of coal in the fuel mix in 2010 (CER, 2011e).

As the installed capacity of wind generation increases it displaces conventional generation, resulting in a reduction in the level of harmful emissions produced, such as carbon dioxide (CO_2) and sulphur dioxide (SO_2). Denny and O'Malley (2006) have previously completed work on the impact of variable generation on emissions. Both the carbon dioxide and sulphur dioxide emissions from a generator plant depend solely on the chemical content and the calorific value of the fuel (Denny and O'Malley, 2006).

Table 3.4 Suppliers' CO_2 Emissions for 2010 (CER, 2011e)

Suppliers	tCO2/MWh
All Island Average	**0.519**
Airtricity (All-island)	0.357
Airtricity (Northern Ireland)	0.029
Airtricity (Ireland)	0.450
Bord Gáis Energy (All-island)	0.519
Firmus Energy (Northern Ireland)	0.520
Bord Gáis Energy (Ireland)	0.519
ESB Customer Supply	0.522
ESB IE (All-island)	0.550
ESB IE (Northern Ireland)	0.551
ESB IE (Ireland)	0.550
NIE	0.560
Vayu	0.549
Viridian (All-island)	0.523
Viridian (Northern Ireland)	0.498
Energia (Ireland)	0.532

Typical carbon contents values for coal are around 65% with a calorific value of 26 MJ/kg. In terms of gas fired generators, natural gas has a typical carbon content of 70% with a calorific value of approximately 48 MJ/Nm^3 (Denny and O'Malley, 2006).

To assess the impact of a base load wind energy system on the CO_2 emissions of the Irish power system it has been assumed that the portfolio of the conventional plant is such that base load, mid-merit and peaking plants consist of coal (Pulverized fuel ash), peat, open cycle gas turbine (OCGT) and closed cycle gas turbine (CCGT). The CO_2 emissions from typical power plants are given in Table 3.5.

Table 3.5 CO_2 emissions (Denny and O'Malley, 2006)

Plant type	Tonnes/MWh
Peat	1.15
Coal PF	0.92
CCGT	0.36
OCGT	0.41

For the purposes of this paper the author has selected the following generators detailed in Table 3.6 as a representative of the base load units on the Irish power system. When working at maximum output this selection of generators are capable of producing 1560 MW which equates to the base load requirement for Ireland for 2010.

Table 3.6 Generator Information

Unit	Fuel Type	Min. Output (MW)	Max. Output	GJ/MWh	Year of Commission
Moneypoint	Coal	345	855	11.05	1985
Poolbeg	Gas (CCGT)	280	480	6.99	2000
West Offaly Power	Peat	46	137	9.86	2004
Aghada	Gas (OCGT)	10	88	12.15	1982

3.6.2 Fuel savings with a base load wind energy system

The quantity of fuel burnt by conventional thermal units will be reduced with the introduction of a base load wind energy system. The consumption of fuel by each generator was ascertained by analysing the gigajoules (GJ) of energy consumed per MWh. The GJ/MWh value for each of the selected generators is provided in Table 3.6. The fuel savings are based on the fuel prices shown in Table 3.7.

Table 3.7 Fuel costs in €2008/GJ (Denny, 2009)

Fuel Type	Fuel price (€/GJ) ROI
Coal	3.79
Gas	4.97
Oil	6.66
Peat	3.23

3.6.3 The impact of a base load energy system on net load

As illustrated in Figure 3.11, wind power generation can vary through a day depending on the wind speeds encountered. The figure shows the wind energy generated by Irelands wind farms over a two week period in May 2010. The variations are particularly apparent at low wind speeds when the power output in minimal.

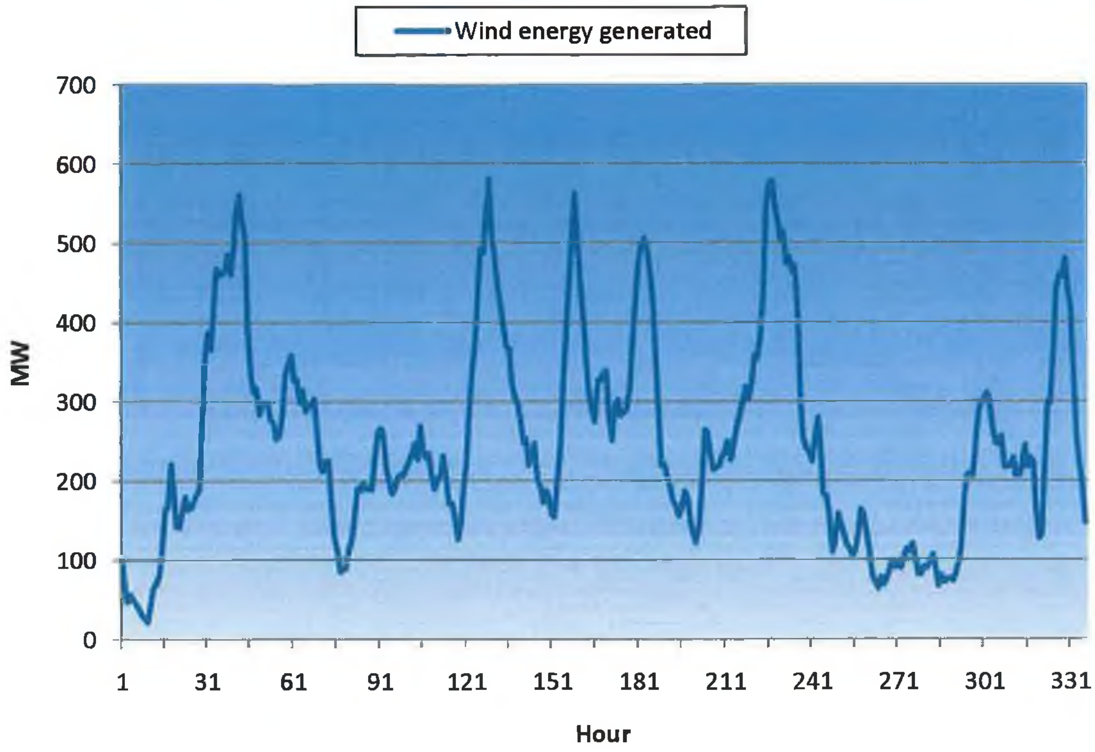


Figure 3.11 Variable nature of wind power

The model presented in this paper was designed in such a manner that the wind energy generated is stored once it exceeds the base load level and is then released when the wind energy generated is below the required base load target. To illustrate the impact of a base load energy system on the net load two scenarios were proposed: “the wind and storage” scenario and “the no storage” scenario.

3.6.4 The impact of a base load energy system on the demand profile

Storing wind power can have a dramatic effect on demand. Storage can flatten out the demand profile and can help to realize the potential of a base load wind energy system. This will in turn reduce the need to run less efficient peak plants. Due to the fact that electricity generated from base load plants is much cheaper than that generated by peaking plants, storage has undoubtedly the potential to reduce the price of electricity Typical storage generators operate on a daily cycle. They take in energy during the night when it is cheaper to do so and then release it during daily peak hours.

The use of a base load wind energy system can also prevent wind energy from being curtailed. On a particular day the wind generated may exceed the demand on the system, hence required it to be curtailed (Figure 3.12). However, an energy storage system can be used to avoid such curtailment as the unwanted energy is stored and then released at a later point in time, possibly during a period of peak demand.

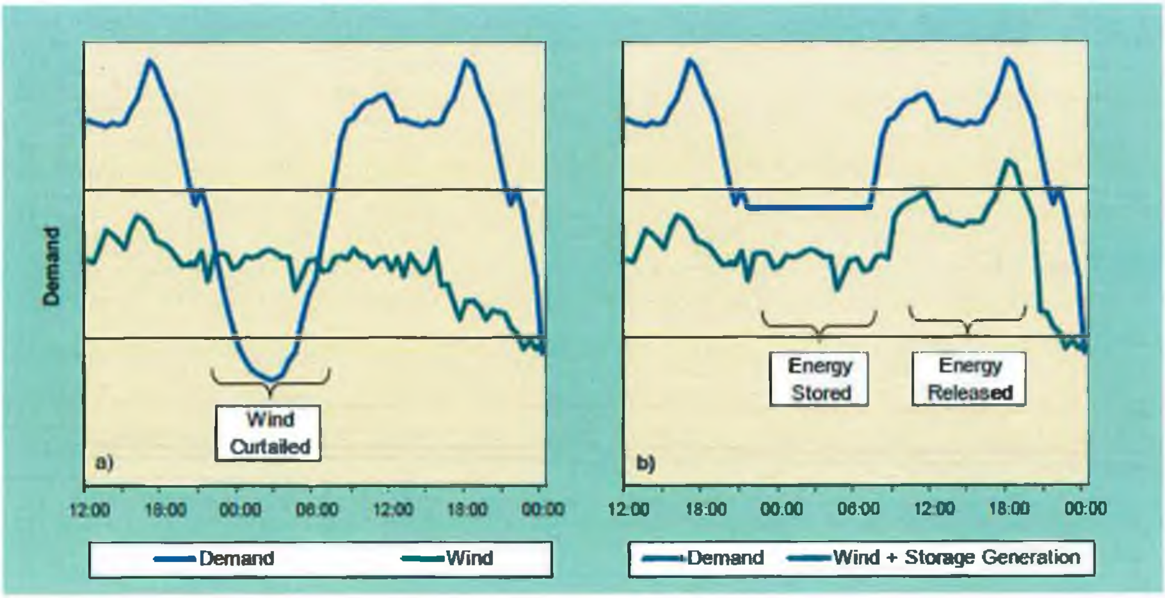


Figure 3.12 The effect of storage on wind curtailment (EirGrid, 2009a)

3.6.5 Economics of future power system options

The electricity markets as they stand today are quite competitive. It is therefore of no surprise that investors are not willing to invest in a project unless the investment costs are justified. Electricity storage offers power system operators a means of creating a system where the least costs and an improvement in security of supply can be realised.

While many different energy storage technologies have been discussed in Chapter 2, the fact remains that only pumped hydro and CAES are at this moment in time suitable for providing a secure supply of electricity on a large scale.

In this paper it is proposed to provide a base load wind energy system to replace each of the thermal units detailed in the previous chapter. The Moneypoint power plant is to be replaced with a pumped hydro facility and the West Offaly Power peat fuelled power plant with a CAES/wind facility. The objective of this is to compare the cost of implementing such systems to the cost of additional thermal units or an additional interconnector.

The capital costs of a base load wind energy system are dependent on the natural resources available at each particular site. In terms of the cost of establishing a wind farm current figures stand at approximately €1,314/kW (Pattanariyankool and Lave, 2010). It is assumed that the transmission system upgrading currently taking place by EirGrid will be sufficient to facilitate these wind farms.

Table 3.8 presents the cost of the four commercial energy storage technologies. Pumped hydro storage and CAES are the least expensive options at €70 per kWh. At this moment in time flywheels and lead acid batteries are much more expensive but these costs will reduce as they become deployed on a wide spread scale.

Table 3.8 Commercial Energy Storage Costs (Rastler, 2008)

Storage Technology	Euros per kilowatt	Euros per kilowatt-hour	Storage hours	Total capital cost (Euros per kilowatt)
CAES	410-510	70	10	420-520
Pumped Hydro	1040-1390	70-140	10	1740-2780
Flywheel	2440-2730	930-1090	0.25	2570-3000
Batteries (Lead Acid)	290-460	230-330	4	1210-1800

As peat and coal power plants are no longer being built, it is assumed that the new conventional plant would be gas fired. Capital costs of €650,000 per MW installed, an availability of 85% and operation and maintenance costs €45,000 per MW per year (Denny, 2009).

In terms of an additional interconnector, the capital costs of such developments are considerable. As previously detailed in chapter 2, transmitting power over long distance underwater requires the use of a High Voltage Direct Current Line (HVDC). Additionally converter stations are required at both ends of the cable so the electricity can be converted from AC to DC and back again.

The total capital costs of an interconnector is difficult to estimate due to many factors including the length of interconnection, market conditions and the type of technology chosen. However, for the purpose of this paper a capital cost of €600m for an Ireland-Great Britain 500MW interconnector (EirGrid, 2009b).

CHAPTER 4

RESULTS

4.1 Introduction

The authors original idea was to develop a base load wind energy system to provide the electricity base load required by Dublin City (540 MW) by investigating the scenario of placing a 270 MW wind farm in Antrim supported by a CAES facility combined with an additional 270 MW wind farm in Cork with a CAES facility utilising the gas fields in Kinsale. The generated electricity was then to be transported through a high voltage direct current transmission line to Dublin City.

However, when an in depth look was taken at this proposal it was revealed that the power system of Ireland and Northern Ireland is a synchronous system in itself and irrespective of whether there is a HVDC line to Dublin the energy provided in it will be consumed by the whole system and not just Dublin.

The author thus decided that it was therefore essential to look at the effect of a baseload wind energy system for the island of Ireland rather than one particular load centre. In order to investigate the costs and benefits of a base load wind energy system, the model described in Chapter 3 was run for each hour for an entire year with the parameters altered to offer up various different scenarios. The operating schedules of the selected generators were then analysed to determine the CO_2 emissions benefits, fuel saving benefits, impact on net load and demand profile and finally an estimation of the cost of a base load wind energy system compared to the construction of an additional interconnector or additional thermal units.

4.2 Impact of varying input parameters on model

The program was run on a number of occasions to determine the effect on the final outputs due to the following:

- Altering the base load and storage level per turbine;
- Ideal Cp vs. actual Cp of Vestas V112 3MW Turbine;
- Using Weibull scale parameters values of 3, 5, 7 and 9 m/s;
- The number of turbines required to provide a base load of 1,000, 1,500 and 2,000 MW;
- The average storage energy over the year using varying scale parameters and both the ideal and actual Cp;
- The capacity factors of the wind farm and the capacity factor of the wind farm combined with storage.

Figure 4.1 illustrates the typical outputs from the program for a two week period. The program inputs and resulting outputs are provided in Appendix A . The power output from the wind farm in highlighted in blue. The intermittent nature of the wind energy is quite visible from the plot of this data series as the area covered by the series is very random due to the varying power outputs. However, the yellow hatch represents the storage system output, which essentially fills the voids left by the wind energy to provide a constant base load of 1,500 MW. Surplus energy is put into storage with the stored wind energy in MWh represented by the green line. Basically this is the accumulated difference between the wind farm output and the base load requirement. For this particular trial of the model the stored wind energy at the end of the second week was approximately 120,000 MWh, which equates to over 3 days storage for a 1,500 MW power output. To store this amount of energy using compressed air a storage vessel or underground cavern with a storage capacity of 24 M m^3 would be required, which is equivalent to 2.5 times the plan area of Croke Park pitch with a depth of 700m.

Additionally, it was discovered that at the end of year 1, 364,772 MWh of energy was stored in the storage vessel, which equates to 10 full days power capacity at 1,500 MW output. From this particular trial it was also discovered that if the base load and storage level per turbine was kept at the same level, for example 389 kW per turbine in this case and the actual Cp values were used, 3,850 Vestas V112 3 MW turbines were required to provide the base load requirements of 1,500 MW and furthermore to ensure a portion of the energy produced by the wind farms went into storage and no interconnection was needed.

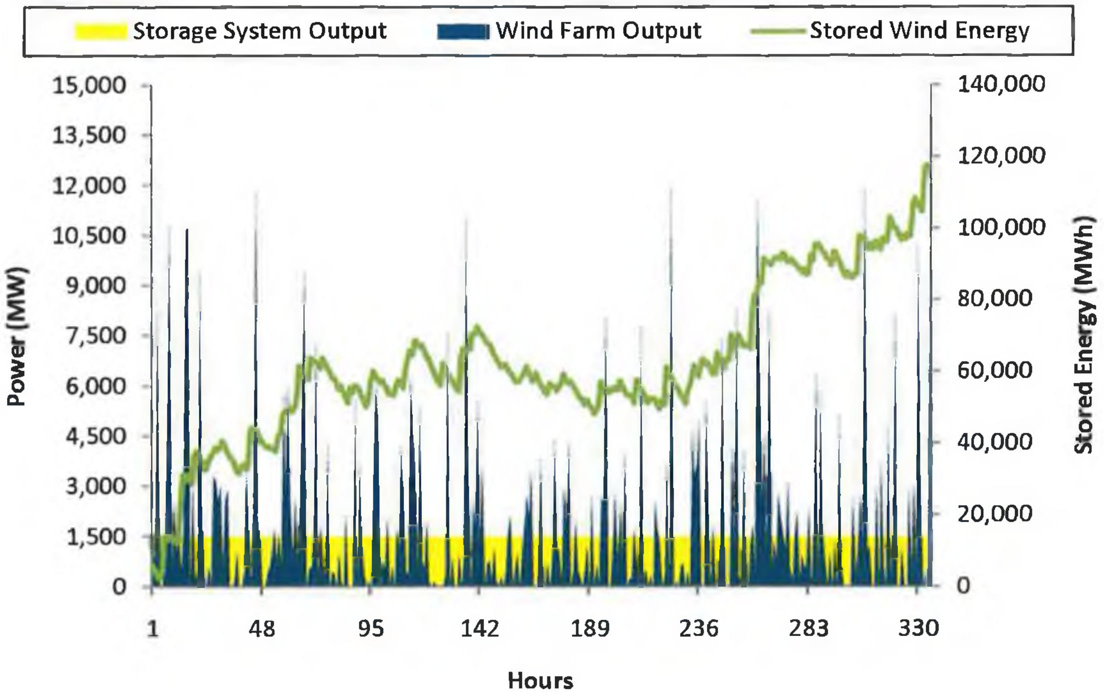


Figure 4.1 Base load wind energy system (Base load = Storage Level)

During the trials it was found that when the storage level per turbine was set to a value greater than that of the base load per turbine the system was no longer capable of being self sufficient or in other words capable of providing a constant base load without any external input. The dramatic effect of altering the storage level from 389 kW to 400 kW per turbine is illustrated in Figure 4.2.

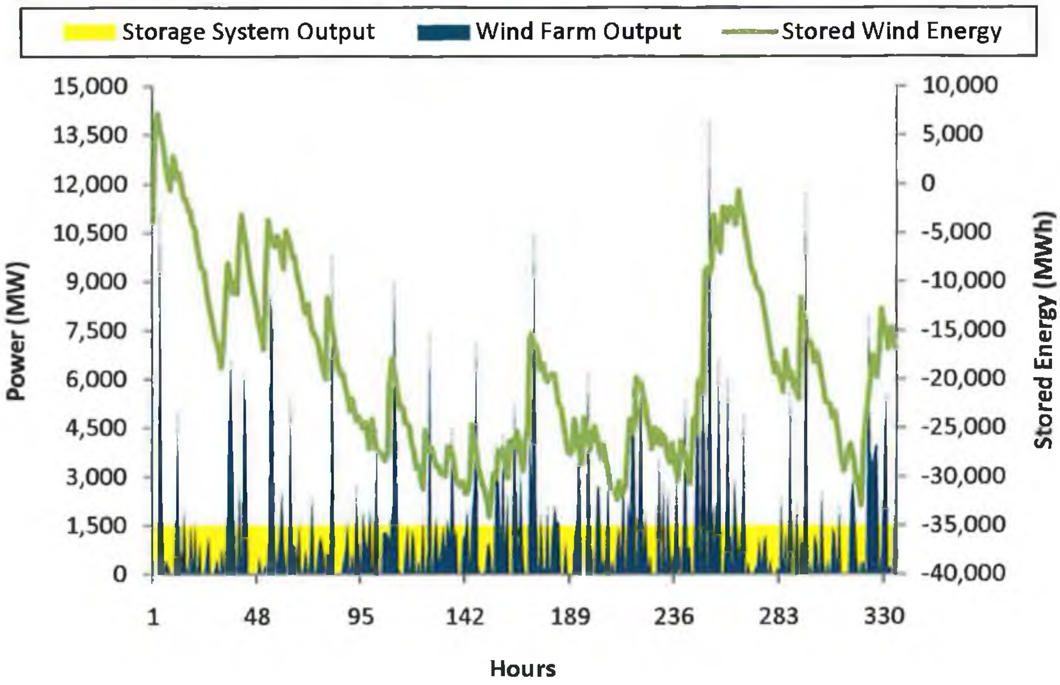


Figure 4.2 Base load wind energy system (Base load ≠ Storage Level)

Using either the actual Cp or ideal Cp can have a massive bearing on the outputs from the program. Figure 4.3 highlights the difference between using the actual Cp for the wind turbine rather than the ideal Cp of 0.59. Over the two week period illustrated in this figure, an additional 105,000 MWh of energy was put into storage by using the ideal Cp value rather than the actual Cp values.

From a more long term point of view, for example at the end of year one, the difference between using both figures was highlighted furthermore by the fact that when the ideal Cp value was used while running a trial of the program it resulted in a stored energy capacity of 147 days (@ 1,500 MW power capacity) compared to the aforementioned 10 days power capacity using the actual Cp values.

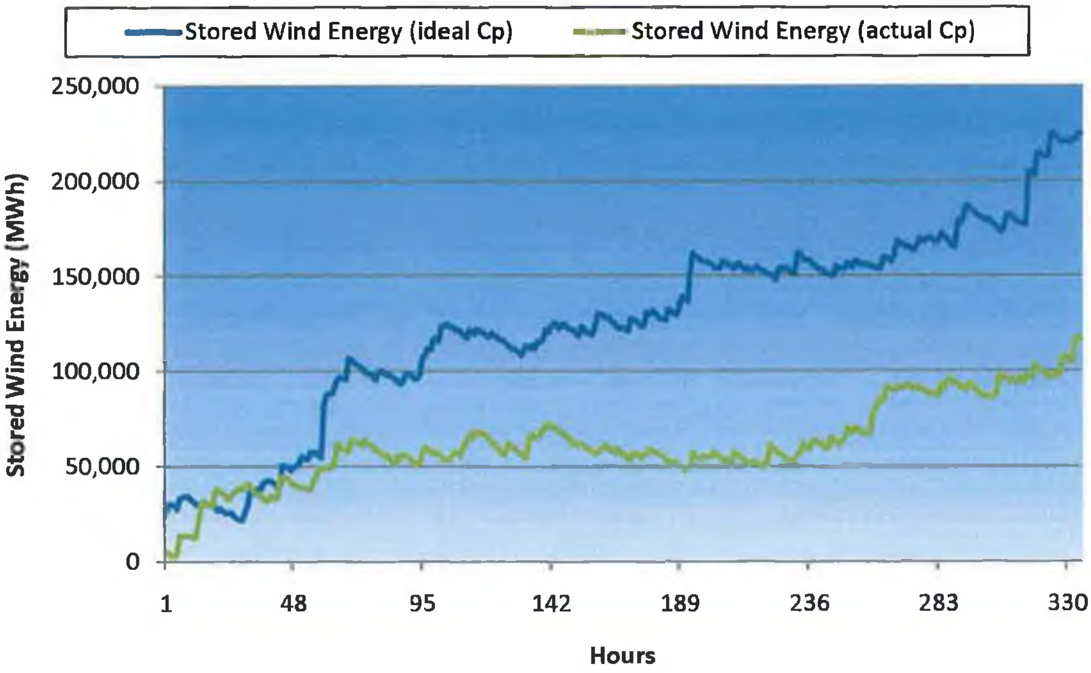


Figure 4.3 Actual Cp vs Ideal Cp

Originally it was planned to analyse the base load energy system using Weibull scale parameter c values of 3, 5, 7 and 9 m/s. However, when the program was run using a scale value of 3 m/s it was found that to provide a base load of 1,500 MW a total of 25,000 V112 3 MW turbines would be required, with each turbine providing a base load of 60 kW. As it was felt by the author that this amount of turbines was not practical, the testing of the Weibull scale parameters c values were limited to 5, 7 and 9 m/s. What this essentially means is that in order for a base load wind energy system to operate efficiently the wind farm must be sited in an area with the greatest average wind speeds. To highlight the effect of the scale parameter on wind farm power output Figure 4.4 was completed. It can be seen from the figure that the wind farm output from the trial using a 'c' value of 9 m/s is quite overwhelming when compared to that of the 5 m/s and 7 m/s trials. The average power output from the 9 m/s trial was 5,543 MW compared to 1,847 MW and 3,756 MW for the 5m/s and 7m/s respectively.

Furthermore, Figure 4.5 illustrates the percentage of time the wind farm is functioning at full power output. For a scale value of 5m/s it occurs less than 1% of the time while maximum output is achieved 11% of the time the farm is in operation using a 9 m/s scale value.

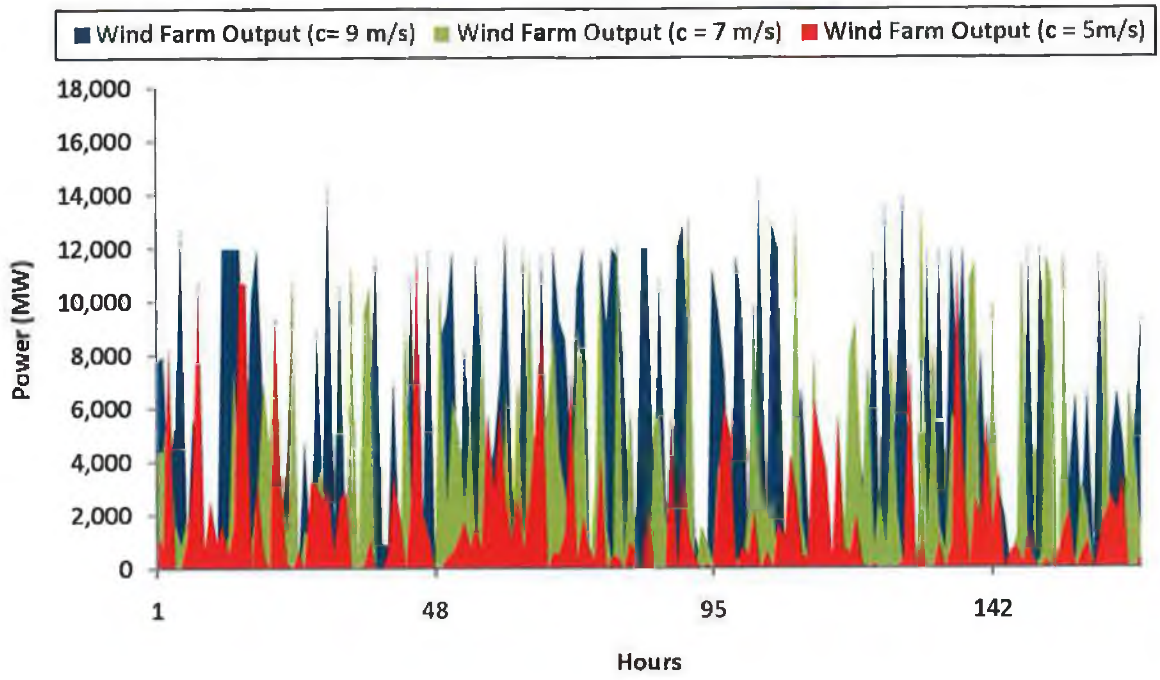


Figure 4.4 Wind Farms Power Output

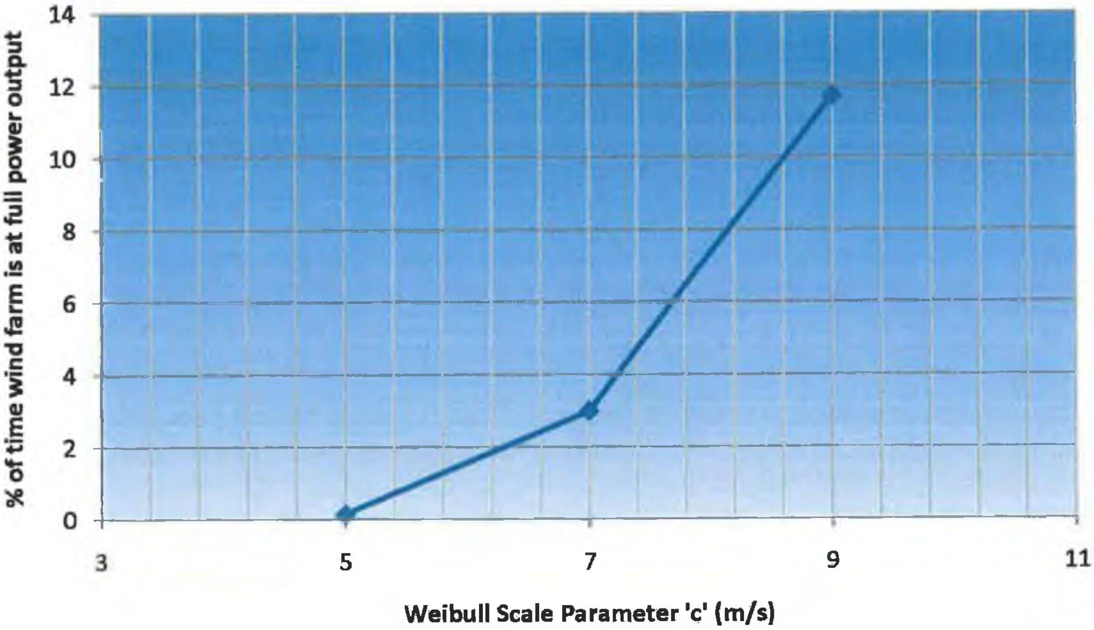


Figure 4.5 Wind Farm Max. Power Output

Figure 4.6 once more reveals the effect of using the ideal and actual Cp values and the effect of the value of the Weibull scale parameter 'c'. Not surprisingly the greatest average stored energy of 3.05E+07 MWh occurs when the ideal Cp value is used along with the Weibull scale parameter c value of 9m/s. In comparison the average storage energy is 1.08E+07 MWh when the actual Cp values are used with a 9 m/s scale figure, a deficit of 1.97E+07 MWh.

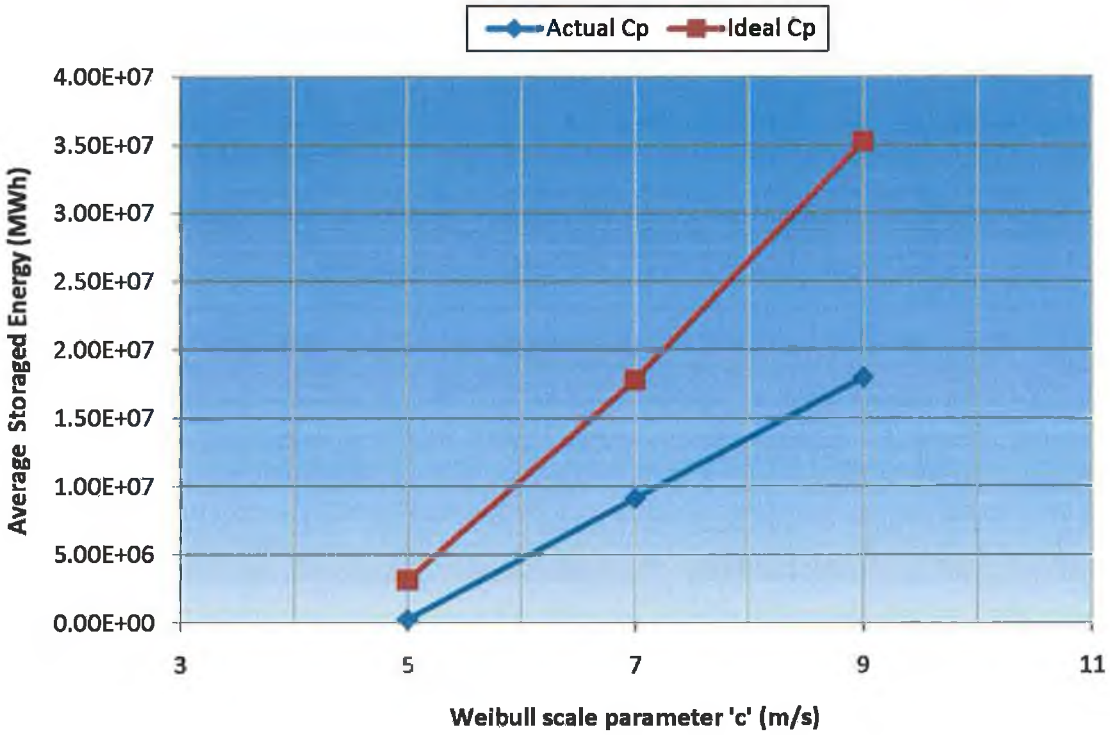


Figure 4.6 Average Storage Volume

Figure 4.7 illustrates the average wind farm power output using both the actual and ideal Cp values. The variation between using either the actual or ideal Cp value is seen best while using a Weibull scale parameter 'c' value of 9 m/s where the difference between the average wind farm power output is in the region of 7,401 MW.

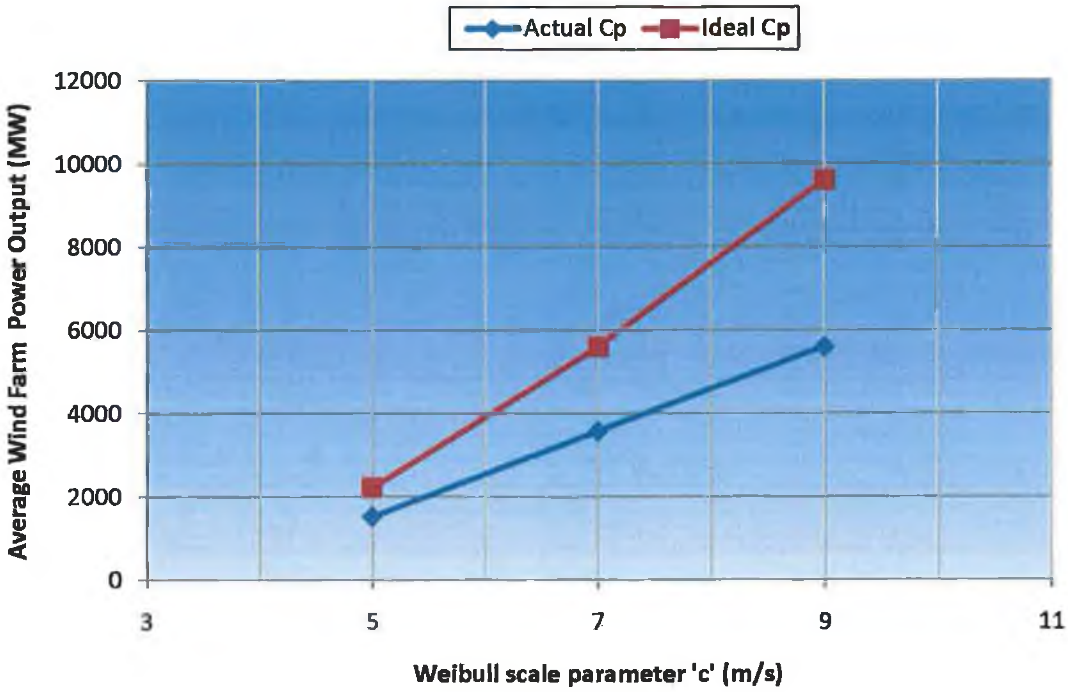


Figure 4.7 Average Wind Farm Power Output

To test the economic feasibility of a base load wind energy system it is important to point out the number of turbines required to provide the required base load. To this effect Figure 4.8 illustrates the number of wind turbines required to provide a constant base load of 1,000, 1,500 and 2,000 MW. For a base load of 1,500 MW, 3,850 turbines are required if the mean wind speeds of the site is 5 m/s. However, if the mean wind speeds are closer to 9 m/s, 750 turbines will be required. Effectively what this means is that sites with a mean wind speed of 9 m/s require 3,100 less turbines than that of a site with a median wind speed of 5 m/s.

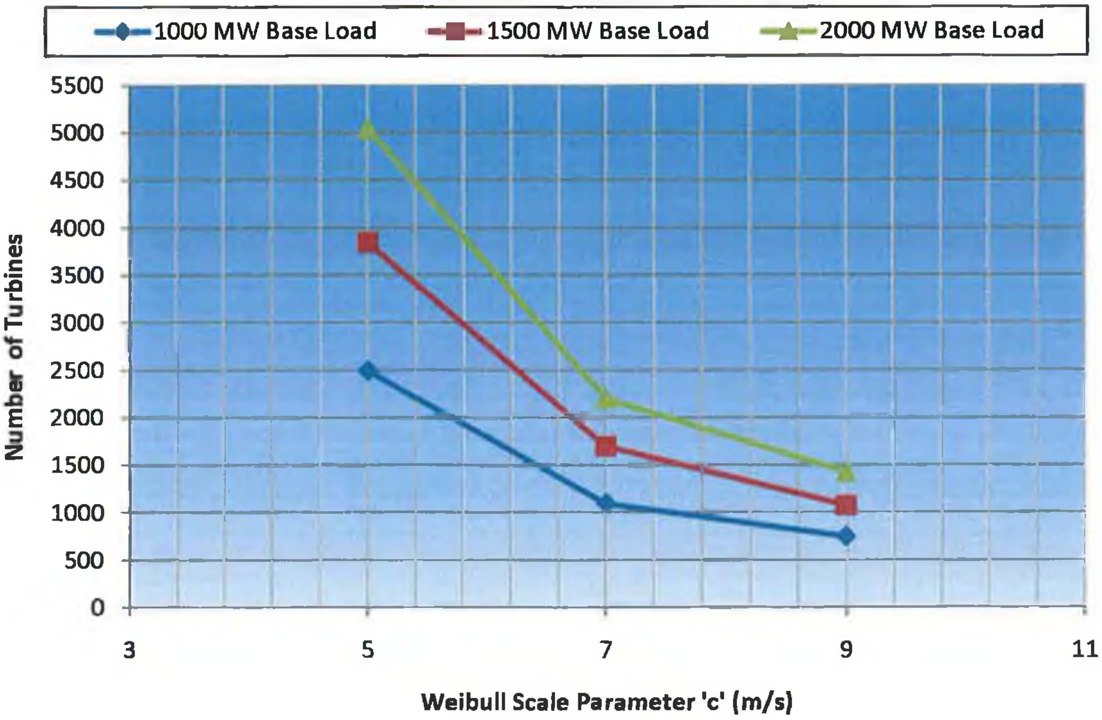


Figure 4.8 No. of turbines required for various base loads

Knowing the capacity factor value is a key factor when examining wind energy potential for a wind farm located in a specific area. The most obvious benefit of a base load wind energy system is the fact that it can greatly improve the capacity factors of wind farms. Figure 4.9 illustrates the capacity factors achieved with Weibull scale parameter ‘c’ values of 5, 7, 9 and 11 m/s. The wind farm can achieve capacity factors of 13, 31 and 49% respectively. However, when the wind farm is combined with a storage system the capacity factors are dramatically increased. In the case of a c value of 5 m/s the capacity factor can increase from 13% to 30%, a 53% increase on the original capacity factor. At the other end of the scale, whilst using median wind speed of 9 m/s, the capacity factor can be increased from 49% to 66%, similar to the capacity factors of existing base load thermal units on the Irish power system.

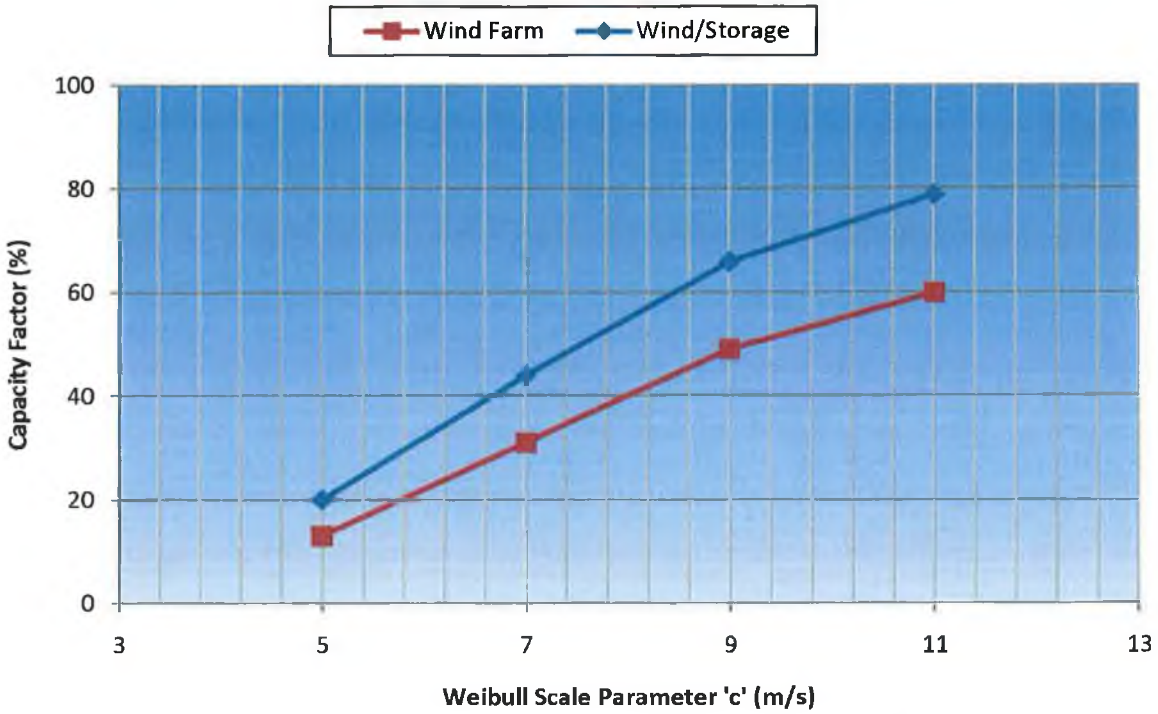


Figure 4.9 Capacity Factors with wind and wind/storage systems

4.3 Emissions benefits of a base load wind energy system

It was assumed that each of the a selected generators in Table 3.6 will be running at full power all year round. The resulting CO_2 emissions from the conventional plants were then calculated for each hour by using specific emissions information for each individual generator. Figure 4.10 illustrates the emissions reduction that could be achieved from the introduction of a base load wind energy system CO_2 to replace the traditional base load units.

From the figure it can be seen that for a base load wind energy system capable of supplying 1,500 MW, a total of 10,100,543 tonnes of CO_2 could be saved if the conventional thermal units were replaced with this system. The greatest savings can be made from replacing the Moneypoint and West Offaly power stations as both coal and peat have much higher CO_2 emissions values than those of the Aghada and Poolbeg gas fuelled power plants.

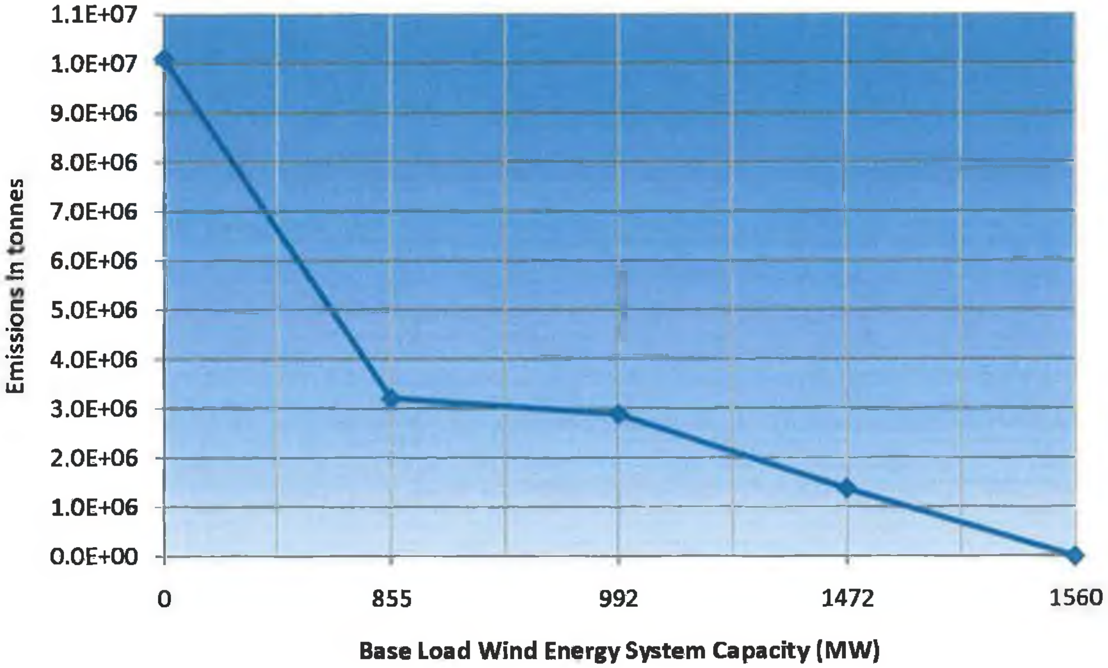


Figure 4.10 Base load wind energy system emission savings

In order to truly express the above emission savings it is necessary to highlight the saving in monetary terms. As previously stated under the Kyoto Protocol's flexible mechanisms, the emissions trading scheme (ETS) was established under which a market has been developed where generators buy and sell allowances for CO_2. Market prices currently stand at around €30 / t of CO_2 (Denny, 2009). The monetary value of the saved emissions is illustrated in Figure 4.11. An estimated 323 million euro could be saved with the displacement of the ever polluting thermal units. In today's economic climate this is quite a substantial amount of money.

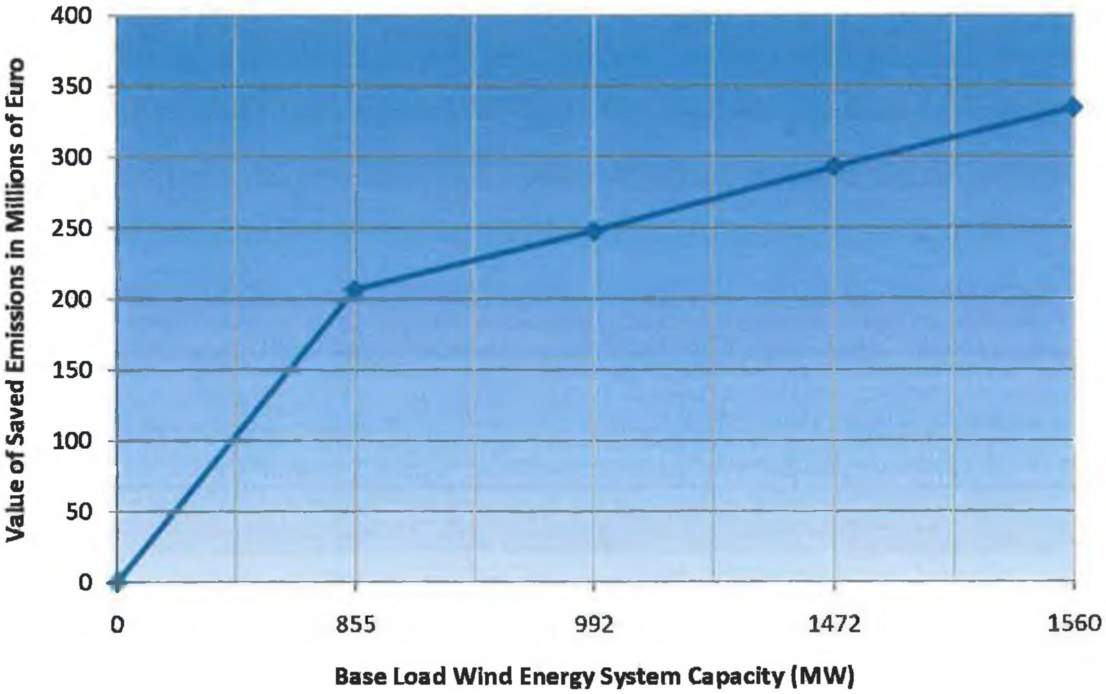


Figure 4.11 Monetary value of emission savings

4.4 Fuel savings with a base load wind energy system

The quantity of fuel burnt by conventional thermal units will be reduced with the introduction of a base load wind energy system. The annual fuel savings for a power system incorporating a base load wind energy system is illustrated in Figure 4.12. The savings are based on the fuel prices shown in Table 3.7.

With the introduction of a base load wind energy system a saving of €545 million could be achieved which further emphasis the potential of the system in monetary terms.

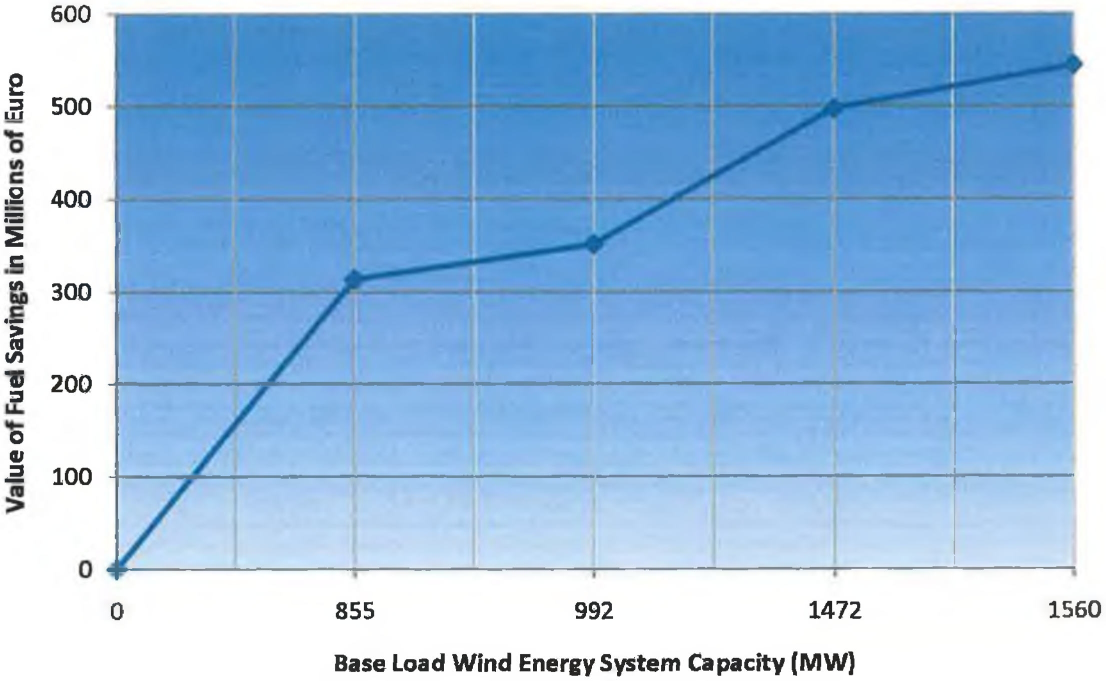


Figure 4.12 Annual Fuel Savings with a base load wind energy system

4.5 The impact of a base load energy system on net load

The impact that wind can have on the net load is illustrated in Figure 4.13. The wind energy can have the affect of shifting the load curve downwards but only slightly. However, Figure 4.14 shows the impact of a system where wind is combined with energy storage to provide a constant energy output. The reduction is the load curve is quite substantial.

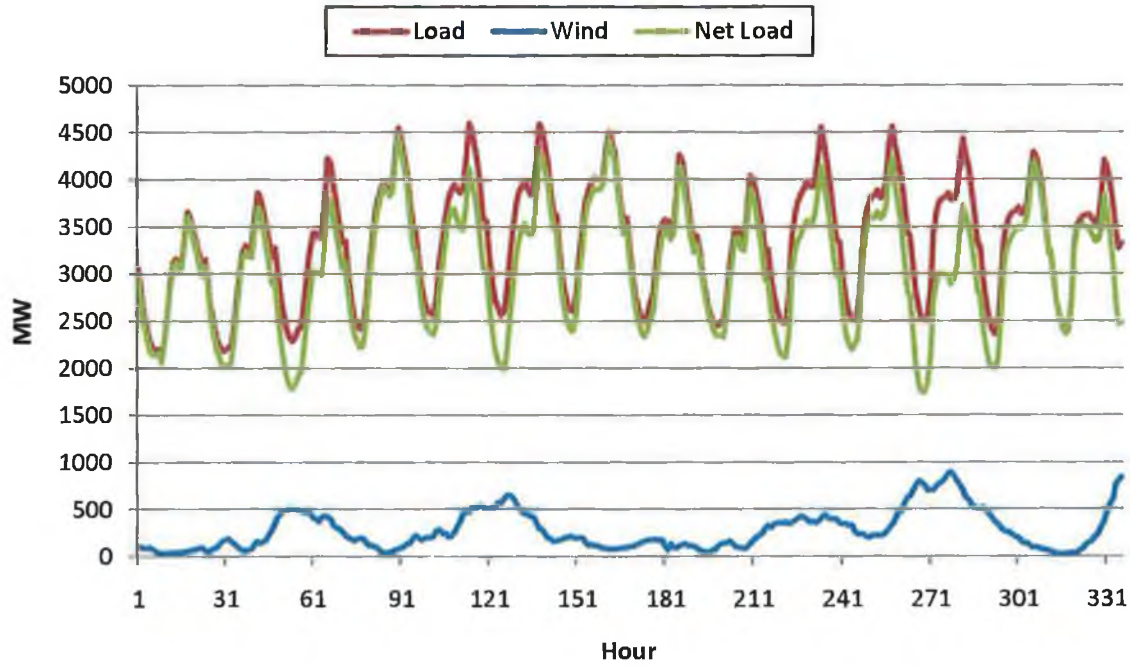


Figure 4.13 Impact of wind power on net load

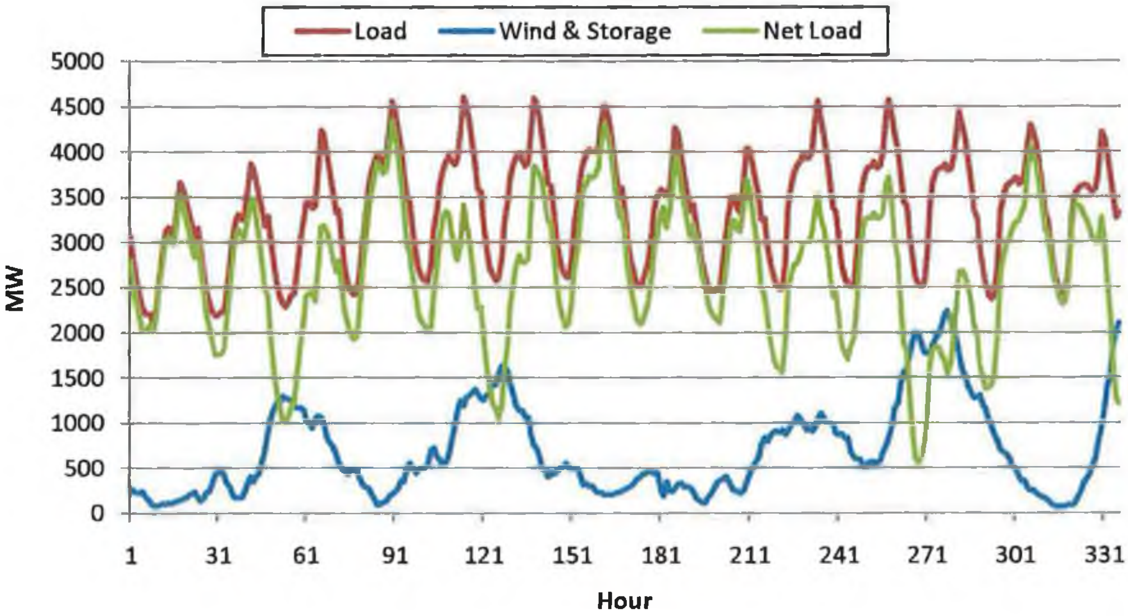


Figure 4.14 Impact of wind and storage on net load

4.6 The impact of a base load energy system on the demand profile

Figure 4.15 illustrates the effect storing wind power can have on demand. The demand profile is flattened out as energy is taking in during off-peak periods during the night and then released during peak hours. Electricity prices can be thus greatly reduced as this reduced the need to run peaking plants.

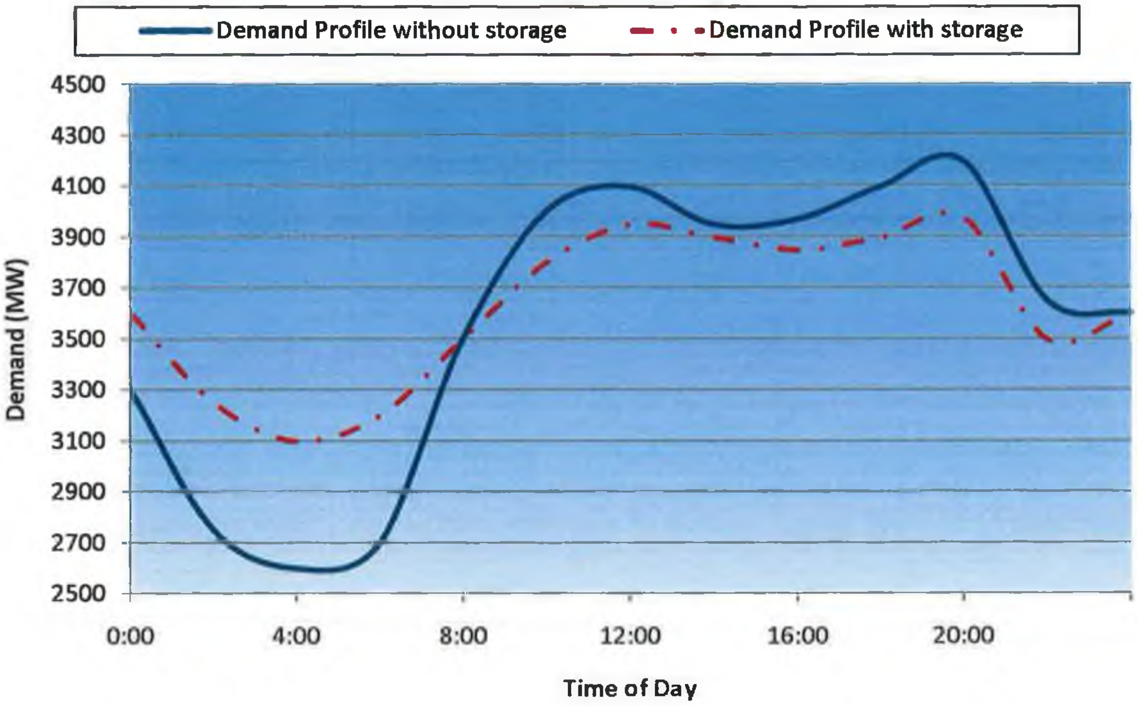


Figure 4.15 The effect of storage on demand

4.6.1 Economics of future power system options

Figure 4.16 presents a cost comparison of the future options available in terms of meeting Irelands ever increasing electricity demands. In the first case, it is proposed to replace the 855 MW Moneypoint coal fuelled power plant with a pumped hydro facility which would cost in the region of 1.9 billion Euros. The author's second proposal was to replace the peat fuelled 137 MW West Offaly Power plant with a Wind/CAES facility with a combined cost of 186 million Euros.

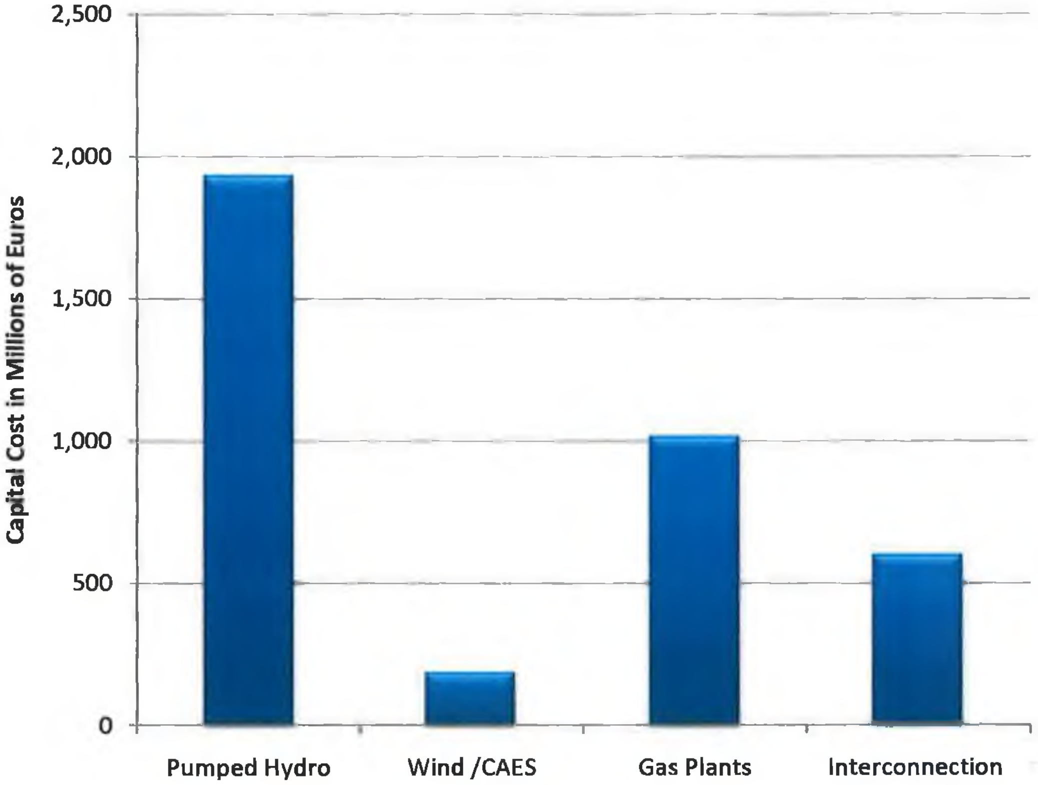


Figure 4.16 Cost comparison of future scenarios

However, it was felt that this did not represent the different options in a fair and reasonable manner. Figure 4.17 illustrates the capital costs in millions of euro's for each of the four options to provide 500 MW to the Irish power system. An additional interconnector has a relatively small capital cost at €600 but as this is just a means of transferring power. Gas plants are the least expensive generation option in simple monetary terms but the figure does not take into account the effect of such plants on the environment and resource depletion. In terms of sustainable energy generation a wind/CAES facility represents the best option if a suitable site can be located.

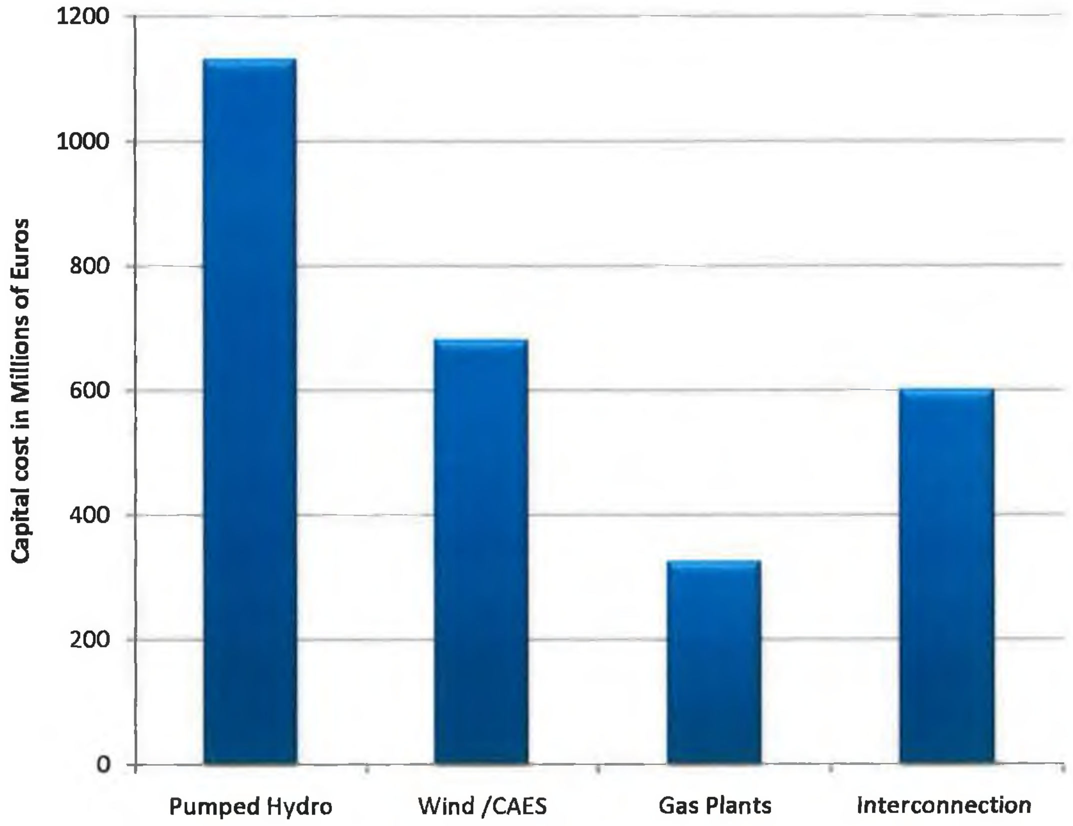


Figure 4.17 Cost comparison of future scenarios (500 MW)

CHAPTER 5

DISCUSSION AND CONCLUSIONS

This thesis presented an analysis of the various different techniques and approaches to integrate renewables into the Irish Transmission system with specific reference to a base load wind energy system. A range of costs and benefits were included and a significant number of different scenarios were tested. A number of applications of the methodology were presented analysing the emissions benefits, fuel savings, impact on net load and demand profile and the economics of future power system options. To ensure that the scope of the thesis remained quite refined it was felt by the author that these costs and benefits were the most direct and thus the most necessary to concentrate on.

Section 5.1 presents a discussion on a number of other issues that may have been taken into account in a wider study and some additional issues which were raised in this thesis are discussed. Section 5.2 reviews the main conclusions of the work presented throughout this thesis. Finally, Section 5.3 outlines some areas for future research arising from the work presented in this thesis.

5.1 Discussion

Every attempt is being made both at European and National Level to promote the use of renewable sources of energy and to coordinate a paradigm shift away from the combustion of fossil fuels. The drivers behind these actions include the much publicised climate change concerns, security of energy supply along with economic reasons.

The European Commission has provided the framework for the integration of renewable energy sources into the electricity grid in the shape of its directive 2009/28/EC. In order to achieve success in any walk of life it is paramount that achievable goals and targets are set. With this in mind, the Commission has set mandatory national targets for the production of energy from renewable sources.

Building on the success of the aforementioned Directive, the Commission has defined the energy priorities for the next 10 years in its communication Energy 2020. The Commission has recognised the need to establish a low carbon energy system and has therefore pushed for greater energy savings in transport and building along with the hope of building a truly pan-European integrated energy market.

The Irish government has consequently made considerable efforts to follow the lead made by the Commission to establish a sustainable energy future for all member states. In the Energy White Paper Ireland has an energy policy built upon the three pillars of security of supply, environmental sustainability and economic competitiveness. Once more, targets have been set that if realised, will be of benefit to society across the board. The most important of these is the target of achieving 33% of electricity consumption from renewable sources by 2020. This is an achievable feat and it could give a much needed boost to the economic state of the country through the creation of additional employment opportunities.

However, being rich in renewable resources and promoting the production and use of them is all good and well but the required infrastructure must be in place to facilitate these resources into the power system. The current Irish transmission system is similar to the economic state of the country, weak and furthermore outdated. In the last three decades the demand on the system has increased dramatically yet the infrastructure has remained largely unchanged. Fortunately, EirGrid has begun to act before it became too late to do so. In Grid 25 EirGrid have a plausible plan for the upgrading of the Irish national grid. The investment of €4 billion is substantial considered the current worldwide economic recession. Without this upgrade all the efforts being made to promote renewable energy sources at national level would have been done so in vain. EirGrid are additionally working on the East-West interconnector which will when complete provide a 500 MW connection between the electricity grids of Ireland and Great Britain. This interconnection can offer Ireland a means of exporting its much vaunted renewable energy sources.

The aforementioned upgrading of the national grid will not only serve to make the power system more reliable and secure it will also increase the popularity of the concept of distributed generation. This concept is not new, it is simply a replication of the activities of the societies that have gone before us when the power plants were designed to supply electricity to customers in the close neighbourhood of the generation plant only. With an effective distributed generation system, electricity can be generated and delivered to consumers in a fair, reliable and environmentally sustainable manner.

With the planned penetration levels of renewable energy sources onto the grid it will experience a shift from steady to intermittent generation. However, energy storage technologies can counter act the undesirable traits associated with renewable energy sources, in particular their intermittent character. Numerous different energy storage technologies are being developed at the moment but out of all these only pumped hydro storage and CAES have been adopted for the purposes of large scale energy storage.

While distributed generation and energy storage are seen by many as the solution to successfully integrating renewable energy sources into power systems another option that is being currently explored exists in the form or demand side or load management. What this essentially involves is taking actions to vary the load to match the power available. This can only be done through the development of customer side energy management that is capable of providing real-time energy prices and network status information to customers. Considerable progress has been made in Ireland in this area of energy management with the CER smart metering trials. The results of which suggest that demand side management represents a feasible option for the integration of renewable energy.

Looking forward, as the green energy sector continues to blossom it is not unreasonable or unrealistic to think that Ireland will someday form part of an interconnected European

Supergrid where the energy harnessed from renewable sources is transmitted over vast distances. In order for this to become a reality a relatively new form of technology in the electricity industry in the shape of HVDC transmission will be required. With this transmission system distance is no longer a limiting factor as power can be transported over 1000's of kilometres using both over head lines and sea or underground cables. In an era where preservation of the environment is paramount, HVDC transmission requires much smaller right of ways than HVAC with a resulting smaller environmental impact. Due to the geographical location of many renewable resources, combining energy storage with a HVDC system will help to realise the full potential of storage as the transmission losses can be kept to a minimum and the direction of power flow can be bi-directional.

It is the author's opinion that in order to successfully integrate renewable energy into the Irish transmission system a combination of energy storage, demand side management and interconnection will have to be achieved. To establish a low-carbon power system in Ireland, energy storage will have to be integrated into the system. It can be used to improve power quality, prevent the associated costs with power failures and enhance the security of Ireland's grid. Despite these obvious benefits it has not received priority status in national policies. Some of the technologies available face barriers to achieving commercial status. If these barriers are not addressed, the technologies potential will never be realised and will therefore be prevented from large-scale adoption. If policy makers were to realise that the emissions from the electricity sector could be greatly reduced by removing these barriers, relevant laws and/or regulations could be introduced to facilitate the expansion of energy storage options.

The operation of peat fired generation in Ireland is currently supported by a levy on all electricity bills known as the public service obligation (PSO). This support mechanism continues to remain in place today despite the fact that the burning of peat produces the greatest CO_2 emissions per MWh in terms of electricity generation. However, if this levy was redirected into funding for the commercialisation of energy storage technologies it could serve a better purpose to secure a sustainable energy future for Ireland.

Changes in the operation of the thermal plants on the Irish power system are inevitable with the increasing wind penetration levels. The base load units are going to be the worst affected plants with each one being affected differentially depending on their characteristics. Increased cycling to combat the variable nature of wind resources will eventually result in increased outages and plant depreciation.

Additionally, as the penetration levels of wind power grow, demand for reserve capacity increases due to the uncertain variability of wind. Furthermore, there is an increased probability that a considerable wind variation may coincide with a possible generation failure. To overcome this, a new addition must be made to the Irish power system to maintain its reliability and safety. The creation of a base load wind energy system is thus required. This system will comprise of wind farms, storage technologies along with the required transmission network. Once operational, this system is capable of providing an alternative to conventional base load power, currently dominated by fossil fuelled systems.

This thesis presented a methodology for evaluating the costs and benefits associated with a base load wind energy system and discussed the potential for such a system in Ireland. It was found that the introduction of a base load wind energy system resulted in the displacement of a number of conventional thermal base load units. The nature of the system, combining generated wind energy and energy storage technologies results in a high capacity factor with low emissions and significant fuel savings.

In the previous chapter the potential costs and benefits were highlighted for a base load wind energy system to be adopted in Ireland. It was seen that the potential CO_2 emissions and fuel savings are significant with the displacement of the conventional thermal units as base load units from the plant mix. The burning of fossil fuels leads to harmful emissions entering our atmosphere. However, the displacement of conventional generation with a carbon neutral base load wind energy system can greatly reduce the environmental impact of electricity generation. Conventional thermal units are also playing their part in the much publicised issue of resource depletion. A base load wind energy system do not require any significant volumes of fuel to function so the introduction of such a system can lead to considerable fuel saving and reduce our dependency on imported fossil fuels.

Wind energy is variable and relatively unpredictable nature results in increased challenges for electricity system operators. The affect of wind energy generation on the net load is thus quite minimal. However, when wind energy is combined with storage its variable nature is altered greatly to produce a more constant power supply capable of reducing the net load significantly.

The key design element of a base load wind energy system is its storage aspect. The electrical energy generated by the wind farms is stored during off peak periods, for instance during the night, and then released at peak periods. This type of system increases the revenues of wind energy generation as it improves the capacity factor of wind energy generation and hence reduces the variability on the system.

The demand on the Irish power system can be dramatically affected by storing wind energy in the aforementioned manner. The demand profile can be flattened with storage and can thus reduce the challenge for electricity system operators. System costs will also be reduced with the flattening of the demand profile as the need to operate expensive and less efficient will be greatly reduced. Power system operators will also no longer have to curtail wind energy generated as it can be directed into storage.

In terms of future power systems options a base load wind energy system offers a economically competitive option when compared to the case of additional interconnectors or the construction of further gas plants to meet the ever increasing demand on the power system. Building additional gas plants will only further increase the harmful emissions from electricity generation and further deplete natural resources. This is not a sustainable or environmentally sound option. Coupling wind energy with a CAES facility represents both economic and environmental sense.

In the current economic climate the introduction of a base load wind energy system has not only the potential to provide the base load requirement of Ireland, it could also in turn lead to the creation of much needed jobs, improvements in local infrastructure and consequently improvements in the standard of living in Ireland once more.

The provision of the base load through the proposed system is only the beginning. Once the energy storage technologies reach commercial status, the system can increase in capacity and thus replace further thermal units on the power system. The long term goal of reducing Ireland's reliance on imported fossil fuels can be realised and Ireland can be protected against volatile international fuel prices and supply variations.

5.2 Conclusions

This thesis presented a methodology for determining the optimal set of variables using a computer program to establish a base load wind energy system to meet the base load requirements using the Irish power system as a case study. The costs and benefits of doing so were detailed with further applications relating to the impact of such a system on net load and the demand profile. The main conclusions arising out of the research and results from the model were as follows:

- An analysis of wind energy generated revealed that the optimum power generation was significantly affected by the Weibull scale parameter 'c' and the use of actual Cp data rather than the theoretical value. Additionally, in order to avoid interconnection or in other words for the system to be self sufficient the storage level per turbine should be set at the same value as the base load per turbine.

- A worst and best case scenario were developed to illustrate the critical values of the variables in wind generation. In the worst case, the Weibull scale parameter 'c' was set at 3m/s and was then compares to a scale value of 9 m/s to illustrate the important of locating wind farms on sites with high mean wind speeds.

- Capacity factor are typically highest on sites with good wind regimes, which basically means sites with high wind speeds and low turbulence, and where down time for maintenance and repairs is kept to the minimum. However this figure is inevitably going to fall in the future as the best sites become fully developed and poorer sites have to be used. In this case the value of energy storage and a base load wind energy system will soar.

- It was shown that the capacity factor of wind farms can be greatly increased by combining them with storage. On sites with low wind speeds a 53% increase in the capacity factor can be achieved while the capacity factor of more favourable wind farms can be increased by 34%. Effectively the capacity factor of wind farms could be increased to match those of the traditional thermal units.

- It was found that the introduction of a baseload wind energy system would lead to a considerable reduction in the CO_2 emissions with the gradual displacement of the existing base load thermal units.

- Additionally, a significant reduction in fuel savings could be achieved with the establishment of a base load wind energy system. The greatest savings were in coal with the displacement of the Moneypoint power station.

- Storing wind energy can help smooth fluctuations in generation inherent with the resource. It can also enhance the reliability and resilience of the grid through short term storage for peak-shaving and power quality as well as providing long term storage for load-levelling and load shifting applications.

- To accommodate 1,075 turbines, the number of turbines required for a base load wind energy system with a power capacity of 1,500 MW, less than 1% of Ireland's land mass would be required. However, this spatial requirement is likely to reduce in the future with on-shore turbines set to increase in the coming years, thus reducing the number of turbines to meet the base load target.

- A base load wind energy system can enable greater levels of wind penetration and facilitate carbon reduction targets for the island of Ireland.

- The societal benefits of storing wind energy are overwhelming. It can lead to reduced system costs, reduced emissions and reduced wind curtailment and congestion on the system. It can also improve the value of our wind assets.

5.3 Future Work

The benefits of a base load wind energy system presented in this thesis were based on a model developed whereby all the energy generated by the wind farm was either utilised to provide the base load requirement or directed into storage. However, a further detailed model could be developed to take into account any wasted energy and conversion losses during the storage and transmission processes.

This thesis assumed that in the near future large scale energy storage will become viable in Ireland due to the continuing technological advancements in that field. However, further work should be completed on the researching of the use of depleted gas fields such as those at Kinsale Head in Co. Cork, to assess their suitability to act as a storage vessel for compressed air. Additionally, close attention should be paid to the progress of the Iowa Stored Energy Park as this project will provide worthwhile information about the utilisation of aquifers for air storage and the coupling of CAES to wind. Furthermore, the use of a depleted gas field to store compressed air in Montana should be monitored due to the fact that this project is a world first and potentially transformational for the bulk energy storage.

As it has become apparent that both Ireland's landscape and geology is not particularly suitable for large scale energy storage in the form of pumped hydro or CAES, the work of people like Seamus Garvey must be given due respect and acknowledgement and further funding as this type of energy storage technology is not geographically constrained and could therefore be a possible worldwide solution to energy storage problems.

Monitor the success of the East-West Interconnection and explore the possibilities of further interconnection to the UK and Europe. As the penetration levels of renewables grow the case for interconnection becomes stronger. Additionally, further research should be completed into demand side management and in particular the putative nationwide rollout of smart meters in Ireland.

This thesis concentrated on the use of wind energy to create a base load wind energy system. However, the methodology used could easily be adapted to other forms of renewable energy such as tidal, solar and wave energy. A comparative study to analyse the costs of benefits of combing energy storage with the aforementioned renewable resources would provide very useful results indicating the forms of renewable generation which is most suited to being stored and thus capable of providing a constant base load.

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APPENDIX A

MODEL INPUTS AND RESULTING OUTPUTS

Parameter		Unit
Shape Factor	2	dimensionless
Scale Factor	5	m/s
Air Density	1.2	kg/m^3
Blade Radius	56	m
Power Coefficient	0.24	-
Cut-out Speed	25	m/s
Cut-in Speed	3	m/s
Maximum Allowed	13	m/s
No. of turbines	3075	-
No. of samples	8760	-
Storage Capacity	-	kWh
Storage Base	389	kW
Storage Level	389	kW
Stored Energy	-	kWh

Hour	Wind Speed (m/s)	Base Load (MW)	Wind Farm Output (MW)	Stored Energy (MWh)
1	6.8	1500	3130	1630
2	4.7	1500	925	1055
3	7.95	1500	5146	4701
4	3.26	1500	221	3422
5	2.59	1500	0	1922
6	5.46	1500	1528	1950
7	6.79	1500	3118	3567
8	3.93	1500	501	2568
9	0.54	1500	0	1068
10	3.64	1500	357	74
11	9.71	1500	9221	7647
12	5.94	1500	2040	8187
13	8.26	1500	5769	12456
14	4.49	1500	792	11748
15	1.97	1500	0	10248
16	6.02	1500	2138	10886
17	4.19	1500	628	10014
18	4.78	1500	978	9491
19	0.9	1500	0	7991
20	1.61	1500	0	6491
21	0.93	1500	0	4991
22	2.65	1500	0	3491
23	6.11	1500	2238	4230
24	8.08	1500	5403	8132
25	4.52	1500	811	7443
26	3.64	1500	358	6301
27	1.23	1500	0	4801

Hour	Wind Speed (m/s)	Base Load (MW)	Wind Farm Output (MW)	Stored Energy (MWh)
28	8.08	1500	5404	8705
29	4.7	1500	926	8131
30	5.12	1500	1234	7865
31	3.43	1500	277	6642
32	0.93	1500	0	5142
33	5.23	1500	1325	4967
34	5.67	1500	1747	5214
35	0.71	1500	0	3714
36	1.53	1500	0	2214
37	7.32	1500	3946	4659
38	4.31	1500	689	3848
39	4.52	1500	812	3160
40	6.17	1500	2304	3964
41	1.13	1500	0	2464
42	11.2	1500	11635	12599
43	7.73	1500	4708	15807
44	0.5	1500	0	14307
45	2.81	1500	0	12807
46	2.1	1500	0	11307
47	5.81	1500	1894	11701
48	6.16	1500	2299	12500
49	1.54	1500	0	11000
50	1.79	1500	0	9500
51	3.92	1500	492	8492
52	7.33	1500	3973	10965
53	4.34	1500	709	10174
54	3.01	1500	155	8829
55	2.52	1500	0	7329

Hour	Wind Speed (m/s)	Base Load (MW)	Wind Farm Output (MW)	Stored Energy (MWh)
56	10.36	1500	10581	16410
57	1.23	1500	0	14910
58	10.7	1500	11095	24505
59	3.42	1500	274	23279
60	4.17	1500	619	22398
61	3.75	1500	408	21306
62	5.93	1500	2033	21840
63	8.1	1500	5444	25784
64	7.74	1500	4727	29011
65	5.64	1500	1712	29223
66	6.94	1500	3345	31068
67	5.81	1500	1896	31464
68	0.74	1500	0	29964
69	2.09	1500	0	28464
70	4.76	1500	960	27924
71	10.12	1500	10210	36635
72	4.4	1500	742	35876
73	4.81	1500	998	35374
74	7.04	1500	3498	37372
75	10.9	1500	11366	47239
76	4.39	1500	735	46473
77	5.23	1500	1326	46299
78	10.61	1500	10953	55752
79	6.46	1500	2662	56914
80	4.42	1500	749	56163
81	7.15	1500	3669	58332
82	4.15	1500	609	57440
83	7.22	1500	3779	59719

Hour	Wind Speed (m/s)	Base Load (MW)	Wind Farm Output (MW)	Stored Energy (MWh)
84	2.77	1500	0	58219
85	10.1	1500	10163	66883
86	3.2	1500	205	65588
87	5.57	1500	1638	65726
88	2.41	1500	0	64226
89	3.39	1500	262	62987
90	5.32	1500	1400	62888
91	3.02	1500	159	61546
92	2.15	1500	0	60046
93	2.61	1500	0	58546
94	2.82	1500	0	57047
95	4.52	1500	808	56354
96	3.25	1500	219	55073
97	2.25	1500	0	53573
98	6.31	1500	2479	54553
99	4.31	1500	693	53746
100	8.18	1500	5611	57857
101	3.08	1500	173	56530
102	0.74	1500	0	55030
103	5.17	1500	1271	54801
104	3.48	1500	294	53595
105	1.81	1500	0	52096
106	1.53	1500	0	50596
107	1.72	1500	0	49096
108	1.84	1500	0	47596
109	3.14	1500	189	46285
110	6.92	1500	3311	48096
111	1.01	1500	0	46596

Hour	**Wind Speed (m/s)**	**Base Load (MW)**	**Wind Farm Output (MW)**	**Stored Energy (MWh)**
112	2.19	1500	0	45096
113	2.37	1500	0	43596
114	10.13	1500	10219	52314
115	5.35	1500	1431	52246
116	5.23	1500	1327	52073
117	6.85	1500	3209	53782
118	5.77	1500	1849	54131
119	7.6	1500	4453	57084
120	3.35	1500	249	55833
121	6.69	1500	2981	57314
122	0.97	1500	0	55814
123	3.19	1500	201	54515
124	7	1500	3432	56447
125	5.97	1500	2081	57028
126	6.54	1500	2777	58305
127	15.17	1500	11994	68799
128	1.13	1500	0	67299
129	1	1500	0	65799
130	6.37	1500	2550	66849
131	5.03	1500	1161	66509
132	8.45	1500	6166	71176
133	3.14	1500	188	69864
134	1.3	1500	0	68364
135	3.76	1500	413	67277
136	3.19	1500	200	65978
137	1.79	1500	0	64478
138	6.32	1500	2484	65462
139	2.3	1500	0	63962

Hour	Wind Speed (m/s)	Base Load (MW)	Wind Farm Output (MW)	Stored Energy (MWh)
140	6.62	1500	2873	65334
141	9.92	1500	9791	73625
142	8.76	1500	6881	79006
143	4.54	1500	820	78327
144	6.33	1500	2505	79331
145	6.1	1500	2220	80051
146	3.26	1500	221	78773
147	1.26	1500	0	77273
148	4.38	1500	729	76501
149	1.76	1500	0	75001
150	5.06	1500	1181	74682
151	6.32	1500	2485	75667
152	2.4	1500	0	74167
153	3.9	1500	483	73149
154	0.98	1500	0	71649
155	2.94	1500	0	70149
156	8.55	1500	6388	75038
157	0.86	1500	0	73538
158	7.09	1500	3569	75607
159	7.86	1500	4952	79059
160	4.59	1500	853	78411
161	4.19	1500	629	77541
162	2.01	1500	0	76041
163	9.29	1500	8154	82695
164	8.04	1500	5316	86511
165	4.46	1500	773	85784
166	6.9	1500	3277	87561
167	4.57	1500	841	86902

Hour	Wind Speed (m/s)	Base Load (MW)	Wind Farm Output (MW)	Stored Energy (MWh)
168	3.61	1500	348	85750
169	4.38	1500	727	84976
170	2.12	1500	0	83476
171	5.17	1500	1276	83253
172	3.7	1500	385	82138
173	5.72	1500	1796	82434
174	1.48	1500	0	80934
175	6.58	1500	2826	82260
176	6.78	1500	3100	83861
177	3.33	1500	243	82603
178	6.82	1500	3166	84270
179	6.2	1500	2338	85108
180	3.94	1500	507	84114
181	2.43	1500	0	82614
182	3.52	1500	310	81424
183	2.81	1500	0	79924
184	1.35	1500	0	78424
185	2.49	1500	0	76924
186	3.35	1500	249	75673
187	1.52	1500	0	74173
188	3.02	1500	159	72832
189	9.87	1500	9653	80985
190	3.04	1500	163	79648
191	10.74	1500	11144	89292
192	11.72	1500	11806	99598
193	3	1500	155	98253
194	9.74	1500	9302	106055
195	4.64	1500	885	105440

Hour	Wind Speed (m/s)	Base Load (MW)	Wind Farm Output (MW)	Stored Energy (MWh)
196	3.95	1500	510	104450
197	3	1500	154	103104
198	0.74	1500	0	101604
199	2.61	1500	0	100104
200	3.86	1500	461	99064
201	3.96	1500	514	98078
202	2.9	1500	0	96578
203	7.97	1500	5179	100257
204	2.62	1500	0	98757
205	7.51	1500	4295	101552
206	1.33	1500	0	100052
207	7.79	1500	4818	103371
208	5.54	1500	1605	103475
209	2.36	1500	0	101975
210	2.94	1500	0	100475
211	5.77	1500	1844	100819
212	3.97	1500	520	99839
213	4.46	1500	774	99112
214	0.71	1500	0	97612
215	3.85	1500	457	96570
216	5.9	1500	1993	97062
217	8.48	1500	6247	101810
218	6.16	1500	2299	102609
219	3.43	1500	276	101385
220	7.05	1500	3510	103394
221	3.04	1500	162	102057
222	5.43	1500	1499	102056
223	7.75	1500	4745	105301

Hour	Wind Speed (m/s)	Base Load (MW)	Wind Farm Output (MW)	Stored Energy (MWh)
224	4.57	1500	840	104641
225	5.57	1500	1636	104777
226	7.73	1500	4693	107970
227	3.71	1500	389	106858
228	5.12	1500	1229	106587
229	2.53	1500	0	105087
230	4.91	1500	1069	104657
231	3.64	1500	358	103515
232	5.48	1500	1551	103565
233	1.93	1500	0	102065
234	9.05	1500	7579	108145
235	1.43	1500	0	106645
236	2.21	1500	0	105145
237	6.59	1500	2832	106477
238	5.24	1500	1331	106308
239	5.96	1500	2061	106868
240	2.15	1500	0	105368
241	8.35	1500	5951	109819
242	4.66	1500	899	109218
243	6.26	1500	2415	110133
244	2.98	1500	0	108633
245	2.85	1500	0	107133
246	2.84	1500	0	105633
247	4.63	1500	881	105014
248	8.33	1500	5916	109430
249	2.4	1500	0	107930
250	4.45	1500	767	107197
251	4.58	1500	849	106546

Hour	Wind Speed (m/s)	Base Load (MW)	Wind Farm Output (MW)	Stored Energy (MWh)
252	4.79	1500	986	106032
253	6.02	1500	2135	106668
254	7.59	1500	4432	109600
255	1.79	1500	0	108100
256	9.16	1500	7850	114450
257	7.78	1500	4789	117740
258	7.16	1500	3688	119928
259	1.26	1500	0	118428
260	4.11	1500	587	117515
261	4.67	1500	901	116917
262	6.58	1500	2821	118238
263	6.1	1500	2225	118962
264	2.24	1500	0	117462
265	6.5	1500	2724	118686
266	7.67	1500	4592	121779
267	1.79	1500	0	120279
268	1.72	1500	0	118779
269	3.45	1500	282	117561
270	2.63	1500	0	116061
271	9.6	1500	8927	123488
272	8	1500	5242	127229
273	3.05	1500	166	125895
274	1.98	1500	0	124395
275	3.42	1500	272	123167
276	2.38	1500	0	121667
277	7.4	1500	4101	124268
278	5.56	1500	1629	124397
279	1	1500	0	122897

Hour	Wind Speed (m/s)	Base Load (MW)	Wind Farm Output (MW)	Stored Energy (MWh)
280	2.37	1500	0	121397
281	6.72	1500	3019	122915
282	5.06	1500	1183	122598
283	3.86	1500	462	121560
284	5.8	1500	1884	121944
285	1.42	1500	0	120444
286	4.13	1500	600	119545
287	6.4	1500	2589	120634
288	6.44	1500	2643	121777
289	5.31	1500	1398	121675
290	7.93	1500	5099	125274
291	7.02	1500	3471	127245
292	3.15	1500	189	125935
293	2.84	1500	0	124435
294	1.97	1500	0	122935
295	3.09	1500	175	121610
296	7.12	1500	3629	123739
297	8.41	1500	6089	128329
298	3.44	1500	279	127108
299	0.59	1500	0	125608
300	3.81	1500	439	124547
301	6.81	1500	3151	126198
302	4.81	1500	1001	125699
303	5.86	1500	1945	126144
304	1.71	1500	0	124644
305	7.83	1500	4894	128038
306	1.49	1500	0	126538
307	3.07	1500	169	125207

Hour	Wind Speed (m/s)	Base Load (MW)	Wind Farm Output (MW)	Stored Energy (MWh)
308	5.43	1500	1502	125210
309	5.77	1500	1847	125556
310	1.51	1500	0	124056
311	2.97	1500	0	122556
312	6.34	1500	2512	123568
313	4.95	1500	1098	123166
314	6.76	1500	3074	124740
315	8.59	1500	6488	129729
316	6.54	1500	2774	131003
317	8.19	1500	5631	135133
318	5.37	1500	1444	135077
319	2.25	1500	0	133577
320	3.25	1500	218	132296
321	4.94	1500	1090	131886
322	3.62	1500	351	130737
323	7.53	1500	4316	133553
324	2.89	1500	0	132053
325	4.74	1500	950	131504
326	8.06	1500	5358	135362
327	2.33	1500	0	133862
328	5.23	1500	1325	133687
329	0.89	1500	0	132187
330	1.01	1500	0	130687
331	0.87	1500	0	129187
332	0.96	1500	0	127687
333	5.3	1500	1385	127572
334	1.52	1500	0	126072
335	2.82	1500	0	124572

Hour	**Wind Speed (m/s)**	**Base Load (MW)**	**Wind Farm Output (MW)**	**Stored Energy (MWh)**
336	1.51	1500	0	123072