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# Development of a Tool for Windfarm Site Analysis in Electrical Networks with High Levels of Wind Power Generation

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# Development of a Tool for Windfarm Site Analysis in Electrical Networks with High Levels of Wind Power Generation

by

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This Report is submitted in partial fulfilment of the requirements of the Master of Engineering in Sustainable Electrical Energy Systems of the Dublin Institute of Technology

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# Abstract

Controlling electrical networks that contain high levels of wind power will be a challenge facing many System Operators in the coming years. The intermittency and uncertainty of the power supplied by wind turbines create difficulties surrounding scheduling of plant, operating reserve and grid integration. The current process for windfarm selection is carried out by an individual stakeholder and lacks the consideration for all other stakeholders involved, which can create problems in the long term when the levels of wind power increase on the network. This paper proposes a collective approach to analysing potential windfarm sites using the key factors which influence the windfarm output and integration into the network. The wind resource and generation outputs are examined using state of the art analysis software to discover and rate the values of the factors which influence these variables. A spreadsheet incorporating these factors is developed and evaluated, which allows site comparisons to be undertaken from a number of stakeholder perspectives, so that the most suitable site may be chosen for development.

# Declaration

I certify that this thesis, which I submit in partial fulfilment of the requirements of the Masters of Engineering in Sustainable Electrical Energy Systems (Programme Ref: DT704) of the Dublin Institute of Technology, is entirely my own work and that any content that relates to the work of other individuals, published or otherwise, are acknowledged through appropriate referencing.

I also confirm that this work has not been submitted for assessment in whole or part for an award in any other Institute or University.

Signature ____________________________

Date ____________________________

# Acknowledgements

I would like to thank several people for their help and advice over the course of this research, without which the process would have been much more difficult. Firstly I would like to thank my project supervisor Dr John McGrory for his supervision, guidance and assistance during the seven challenging months. I would also like to thank Liam-Ronan Fitzgerald for his expertise in all matters computing. Lastly I would like to thank my wife Marci who has supported and encouraged me through the entire ME and for tolerating my rambling lectures on renewable power systems over the last 13 months.

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# Nomenclature

| | |
|---|---|
| CAES | Compressed Air Energy Storage |
| CCGT | Combined Cycle Gas Turbine |
| CER | Commission for Energy Regulation |
| DEHLG | Department of Environmental, Heritage and Local Government (2007-present) |
| DCENR | Department of Communications, Energy and Natural Resources (2007-present) |
| DCMNR | Department of Communications, Marine and Natural Resources (2002-2007) |
| ESB | Electricity Supply Board |
| FES | Flywheel Energy Storage |
| GHG | Greenhouse Gases |
| GIS | Geographical Information System |
| IWEA | Irish Wind Energy Association |
| kV | Kilovolts |
| Km | Kilometre |
| KW | Kilowatt |
| MEC | Maximum Export Capacity |
| MGC | Maximum Generator Capacity |
| MSL | Mean Sea Level |
| MVA | Mega Volt Amperes |
| MW | Mega Watts |
| MWH | Mega Watt Hours |
| NREAP | National Renewable Energy Action Plan |
| NTC | Net Transfer Capacity |

| | |
|---|---|
| NWP | Numerical Weather Prediction |
| OCGT | Open Cycle Gas Turbine |
| OSI | Ordnance Survey Ireland |
| PHES | Pumped Hydroelectric Energy Storage |
| PV | Photovoltaic |
| SEI / SEAI | Sustainable Energy Ireland (past) / Sustainable Energy Authority of Ireland (present) |
| SONI | System Operators Northern Ireland |
| SEM | Single Electricity Market |
| SEMO | Single Electricity Market Operator |
| TRM | Transmission Reliability Margin |
| TTC | Total Transfer Capability |
| UPS | Uninterruptible Power Supply |
| VBA | Visual Basic for Application |

# 1. Introduction

This chapter presents the subject area and scope of this research project. It begins by describing the background of wind energy in Ireland and the targets set out by the Irish Government for 2020. The operating issues which accompany high levels of wind power on the grid are then discussed, and this is followed by defining the goals of the project. The scope of the project will then be reviewed and the chapter concludes with a chapter by chapter outline of the dissertation.

## 1.1 Wind Energy in Ireland

Wind energy began in Ireland in 1992 with the development of the first windfarm in Bellacorrick in Co. Mayo. Since then many changes to the energy markets have assisted in the development of a large number of windfarms throughout the country. The electricity market was deregulated with the establishment of the Single Electricity Market [SEM] allowing private companies to sell electricity to the Single Electricity Market Operator [SEMO]. Global warming, believed to be predominantly caused by the burning of fossil fuels, and dependence on fuel imports has lead governments to offer attractive tariffs for renewable power generation, particularly for wind power. Wind has become a very popular renewable technology in Ireland due to a number of reasons such as: a) Ireland has a high quality wind resource, b) the maturity of the technology has lead to efficient machines and c) the minor impact windfarms have on the environment.

Figure 1, taken from Energy in Ireland Key Statistics (SEAI, 2009), shows the contribution of renewable power to final electricity consumption from 1990 to 2008, that is, the amount of electricity consumed which originated from a renewable resource. Wind generation has increased from 2% of renewable energy gross consumption in 1995 to 71% in 2008 whereas other technologies such as hydro have not increased. Note the hydro has reduced its share over the 18 years as the total electricity demand has increased steadily and no additional hydro stations have been added.

## 1.2 Targets for 2020

The Irish Government published a White Paper in 2007 (DCMNR, 2007) which sets out the Governments Energy Policy Framework to deliver a sustainable energy future for Ireland. A target of up to 33% of electricity was to be generated by renewables by 2020, with wind power providing the pivotal contribution to achieving this target. This target was revised in 2008 to 40% (Government of Ireland, 2008) and it is to be assisted by the governments feed-in-tariff prices. It is estimated that approximately 1800 MW of generation will be required to meet this target, depending on economic growth and demand projections. The Commission for Energy Regulation [CER] use a 31% load factor for wind power generation, which indicates that on average for the year a wind turbine will produce

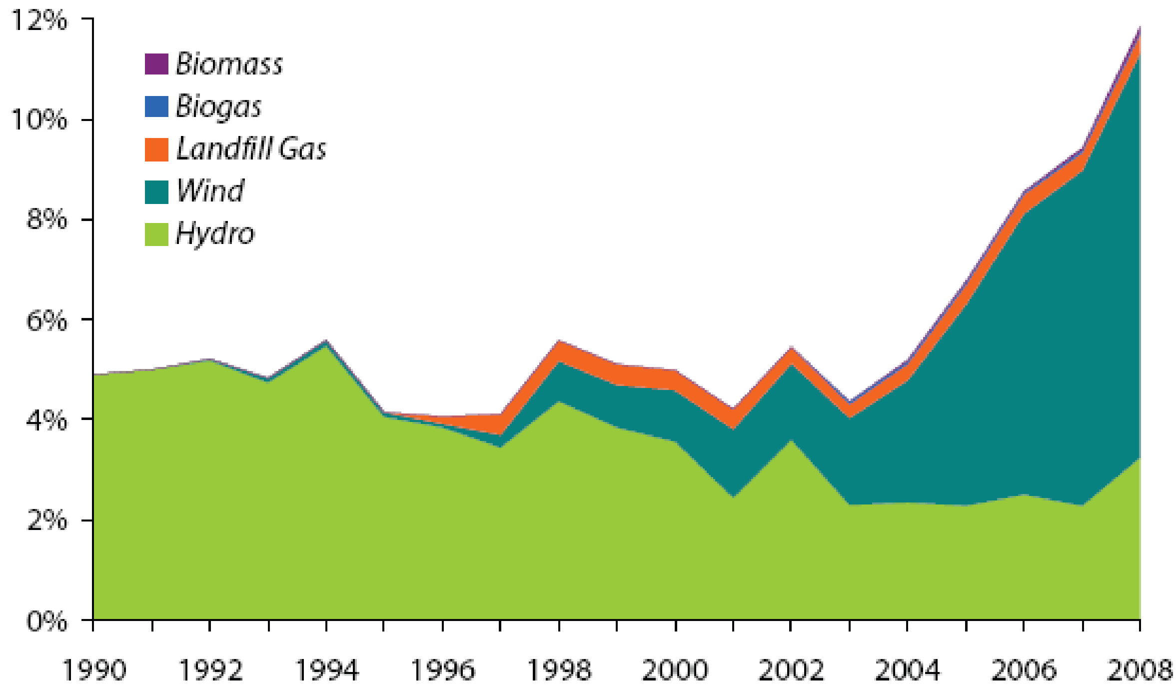



**Figure 1 Renewable Energy Contribution to Gross Electricity Consumption (SEAI, 2009)**

31% of the maximum capacity output. This implies wind generation with a maximum capacity output of 5800 MW is required to meet this 40 % target. The Gate 3 Offer Project, which is the current group of grid connection offers, introduced by the Commission for Energy Regulation [CER], will issue up to 3900 MW of offers to renewable generation projects (CER, 2008), taking wind generation close to 6200 MW should all the offers be taken. Should the majority of these be connected to the grid, there is no doubt the 2020 target of 40% electricity to be generated by renewable technologies will be met.

## 1.3 Wind Energy Issues

The electricity network has been developed over the last hundred years to suit conventional power generation, that is, one large generator feeding numerous loads connected through a series of transmission and distribution systems. Wind power technology differs in a number of ways from conventional power generation, and because of this there are a number of issues with integrating wind power to the current network. In the next decade when wind power will account for a large quantity of the power on the network, it will take a great deal of engineering skill to keep the grid stable due to the fact that at any given moment the electrical production must equal consumption. All of the issues surrounding the integration of high levels of wind power on a sizable network are unknown as the highest penetration in a network to date is 18.9% of domestic electricity supply in

Denmark (Danish Energy Agency, 2008). Below are a number of current problems regarding wind power, which are expected to magnify with increasing wind penetration, and the solutions used to resolve them:

***Intermittent power:*** Wind power is generated by the wind resource which is intermittent by nature hence the power output of a wind turbine will vary accordingly. This is not an issue when the amount of wind power is negligible on a network as it can be controlled by the operating reserve however, when the wind power is greater than the primary operating reserve other steps need to be taken to meet consumption. The System Operator must have enough backup capacity to secure supply should the wind resource fluctuate greatly or even produce little or no power for a given time.

***Incorrect frequency and power factor:*** Most wind turbines operate using induction motors due to cost and robustness. These asynchronous generators do not produce constant frequency and cannot control reactive power required for system balance control. Advances in power electronics and the introduction of new machines such as the Double Fed Induction Generators are minimising these issues.

***Dispersed generation:*** Conventional generation produces large amounts of power in a small area and can be located close to the demand, whereas the wind turbines are less than 5 MW in size and the best wind resources are located in remote areas such as the North and West of the country. This results in network redesign to accommodate large amounts of wind power to be connected to the grid. Huge costs are incurred in the planning and construction of upgrading of the network and the line losses in transmitting the wind power to the demand areas are substantial over time.

## 1.4 Aims and Goals

Many papers have been published over the last number of years regarding the issue of high penetration of wind power on an electricity network (SEI, 2004), (Fox et al., 2007) and (ILEX Energy, 2002). This project investigates the intermittency of wind power and the issues regarding its integration onto the grid. From this research the following goals were developed:

1. To research and analyse the key fundamental factors which influence power output from wind farms in Ireland.

2. To accurately classify, compare and distinguish each of the following combinations of energy production with that of wind generation to increase reliability, availability and efficiency of wind power on the grid:

I. Mixing with other renewable technologies.

II. Combining with the interconnector.

III. Using Fossil Fuel as capacity backup.

IV. Stabilising with Energy storage.

3. To develop an effective tool, system or technique, incorporating the key influencing metrics that could be used for balancing high levels of wind power generation onto the national grid.

4. To evaluate and appraise the developed tool, system or techniques' ability to accurately, effectively and successfully integrate high levels of wind power generation onto the national grid, by using available stored data from existing sites and modelling scenarios.

## 1.5 Scope of Project

The subject of wind power can be viewed from the perspective of a number of different stakeholders such as the System Operator, windfarm developer and financers to name a few. This project considers the issues from the System Operators perspective and it will not consider topics such as: resident's attitudes, planning restrictions, market influence, turbine technologies and any financial issue regarding price of power, development of windfarm and cost of capital.

The System Operator has a number of responsibilities such as the planning of the system, scheduling of the plant and real time control of grid frequency and reactive power. This project deals with the planning of the system including the issue of capacity backup. The project will not explore the areas of frequency and reactive power, as this will introduce turbine technology which is not of concern to the project.

## 1.6 Dissertation Outline

The introductory chapter introduces the subject topic, background and aims of the project. Chapter 2 consists of a literature review of the area of wind power, detailing background information on the variables which influence the power output of windfarms. It also investigates the other forms of power generation which add to the operation of the system and details their influence on the Irish network. The chapter concludes with brief descriptions of the data received and analysis tools used to examine the data.

Chapter 3 begins with the validation of the SEMO data received followed by details of the samples of the data used in the analysis. The results and conclusions of the tests performed on the SEMO and Met Éireann data are summarised in tabular form. The conclusions of the test results are then used to develop the metrics of the tool. Within each metric the factors are discussed and given weights with associated value ranges. The outline of the tool is introduced and the outputs are described.

Chapter 4 sets out to test the tool using a number of chosen sites. The sources used to obtain the information required to input into the spreadsheet are specified. The procedure for a particular chosen site is demonstrated from the collection of the site information through to the spreadsheet input values.

Chapter 5 discusses the results obtained for the sites using the spreadsheet. An optimum site location is discussed followed by a critical examination of the spreadsheet and its shortcomings. The chapter ends with a discussion on further metrics which could be added to the spreadsheet.

Chapter 6 concludes the dissertation and comments on the achievements of the goals. It also indicates the future research that may be undertaken in the area and discusses some interesting results that require further investigation.

## 1.7 Summary of Chapter

This chapter described the wind power background in Ireland and how it has become such an integral part of the Irish electricity system. The targets for renewable technologies over the next 10 years, as set out by the Irish Government, have been discussed and the amount of wind power required for these targets of 40% for 2020 have been quantified. The issues which arise with large wind power penetration onto a network were discussed and the feasible solutions cited. Note there are no proven solutions as high wind penetration on a sizable network does not exist in the world to date. The project deliverables were verified through the goals stated, and these have been focused to certain aspects of wind power integration such as planning capacity backup. A brief chapter outline of the dissertation concluded the chapter.

# 2. Wind Generation and Combinations

The purpose of this chapter is to give an account of wind power technology and other generation technologies available in Ireland, and also to introduce the data and analysis tools which will be used in the following chapters. The chapter begins with a detailed summary of the resource of wind, the power extraction, the variables which affect it and the forecasting techniques used. This is followed by brief descriptions on all other forms of power generation used throughout the country and their penetration in the Irish System. The status of the national grid is also examined including details of the Grid 25 Strategy. The chapter concludes with details of the SEMO and Met Éireann data obtained for investigation and the analysis tools used.

Figure 2 below is a graphical representation of the Irish electricity network showing the power generation on the left, transmission and distribution in the centre, and the load represented by domestic and industrial consumers, on the right. The generation techniques represent, from the top anticlockwise, wind technology, other renewable technologies, interconnection to the UK, conventional facilities and energy storage. Each section shown above is summarised in this chapter and the extent of installation in Ireland recorded.

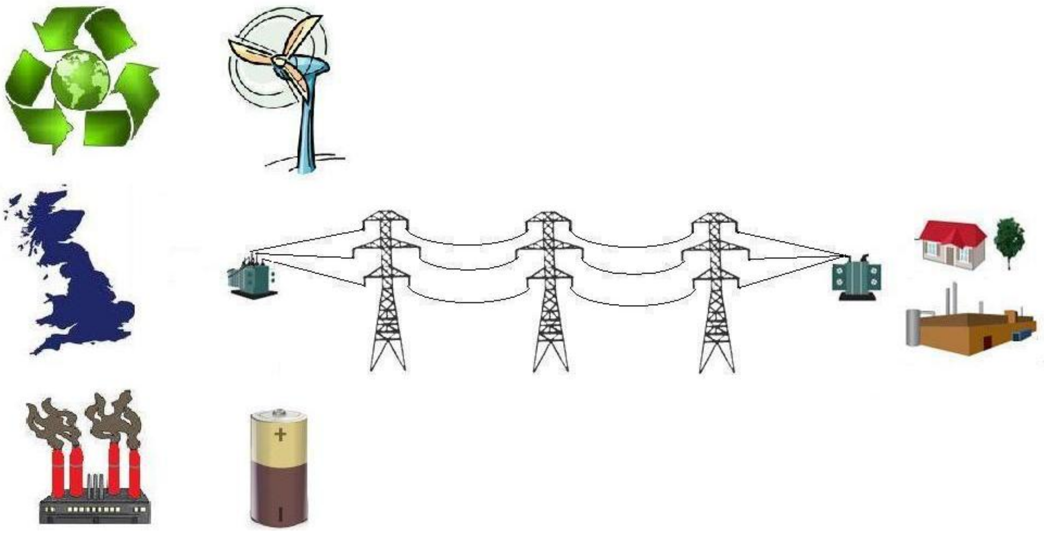


**Figure 2 Graphical Representation of the Irish Electricity System**

## 2.1 Wind Power

The first generation technology to be examined is wind power. The variables which influence wind power output are obtained by deriving the equation for power on a wind turbine, so they may be used during the analysis in further chapters. The techniques and steps required in wind forecasting will be discussed. This will help explain the accuracy of wind power predictability and the requirement for capacity backup. The section will conclude with long term forecasting and the predictions regarding wind speeds in the next few decades.

### 2.1.1 Variables which Influence Power Output

A wind turbine generates power through extracting energy from the swept area of the rotor disc as shown in Figure 3 (Manwell et al., 2009).

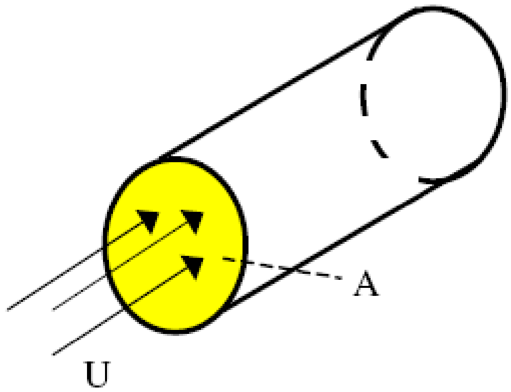



**Figure 3 Wind Turbine Energy Extraction**

The equation for wind power output of a wind turbine is given from the power curve of the generator:

$$P = \frac{1}{2}.\rho.A.C_p.\eta.U^3$$

**Equation 2.1 Wind Power Output**

Where $P$ is the power output (W), $\rho$ is the density of air (kg/m³), $A$ is the surface area the rotor disk (m²), $C_p$ is the power co-efficient of the rotor (%), $\eta$ is the efficiency of the drive train of the generator (%) and $U$ is the wind speed (m/s).

### *a. Density*

The density of the air is dependent on the variables such as atmospheric pressure, the height, the humidity and the temperature of the air and can be calculated using an expanded form of the Ideal Gas Law:

$$\rho = \frac{P_d}{R_d.T} + \frac{P_v}{R_v.T}$$

**Equation 2.2 Density of Air**

Where ρ is the density of air (Kg/m$^3$), $P_d$ is absolute pressure of dry air (Pa), $R_d$ is the specific gas constant for dry air =287.05 J/Kg°K, $T$ is temperature (K), $P_v$ is the pressure of water vapour (Pa) and $R_v$ is the specific gas constant for water vapour =461.495 J/Kg°K

The pressure of the water vapour, $P_v$ is calculated using the following formula:

$$P_v = RH.E_s$$

**Equation 2.3 Pressure of Water Vapour**

Where RH is Relative Humidity (%) and $E_s$ is the Saturation vapour pressure (Pa).

This can be calculated using a number of algorithms, in this paper it is determined using a polynomial developed by Hermon Wobus of the Navy Weather Research Facility, Norfolk, Va, USA.

Using the following formula the pressure of dry air may be calculated:

$$P = P_d + P_v$$

**Equation 2.4 Pressure of Dry Air**

### *b. Area of Rotor Disk*

The area of the rotor disk is dependant only on the length of the blade, a variable which is fixed at time of turbine manufacture.

### *c. Power co-efficient of the Rotor*

Due to the fact not all of the power cannot be extracted from the wind, the power co-efficient is defined as the ratio of the power extracted by the rotor to the power available in the wind. This co-efficient is dependent on the design of the rotor, the wind speed and the speed of rotation. The theoretical optimum for utilising wind by reducing its velocity was first discovered in 1920 (Betz, 1920). Betz stated that the theoretical maximum power that can be extracted from the wind is $\frac{16}{27}$ and this figure is known as Betz Limit. This means for an ideal turbine with no losses the maximum power extraction is 59%. The power co-efficient is different for every turbine manufactured and is fixed for the life of the turbine.

### *d. The drive train efficiency*

This efficiency is dependent on the electrical generator and is fixed at time of manufacture.

### *e. Wind Speed*

This is the dominant factor in the production of wind power as the speed of the wind is to the power of three. According to (Wayne, 1985) wind may be regarded as the air flow that is a response to pressure differentials between different locations on the planet and these pressure differentials are caused by temperature differences.

There are a number of forces which influence wind speed at a particular location and they can be divided into primary, secondary and tertiary circulations (Manwell et al., 2009)There are four main primary atmospheric forces:

**1). Pressure forces**: Hot air rises at the equator and falls as it cools as it gets towards the north and south poles. At the regions of the globe where air is rising low pressure zones are formed and high pressure zones are formed in the regions of descending air. This horizontal pressure gradient drives the flow of air from high to low pressure, which determines the initial direction and speed of the wind.

**2). Coriolis forces:** Due to the rotation of the earth there is a 'Coriolis Effect' which deflects the air to the right in the northern hemisphere and to the left in the southern hemisphere. The magnitude of the Coriolis force depends on the wind speed and the latitude.

**3). Inertial forces:** These are additional forces caused by the curvature of the isobars due to the presence of areas of high and low pressure.

**4). Frictional forces:** Wind speeds vary continuously over height above ground and also the resistance of the ground. Mathematical Equations such as the Log Law and the Power Law can recalculate wind speeds for given heights at given resistances. Figure 4 shows the wind loss close to the ground where z is the reference height and $z_0$ is the roughness constant. From the Log Law the wind speed at height z can be calculated for a given speed:

$$U(z) = U(z_r)\frac{\ln\left({}^{z}/{}_{z_0}\right)}{\ln\left({}^{z_r}/{}_{z_0}\right)}$$

**Equation 2.5 Log Law for Wind Speed**

Where U(z) is the wind velocity at height z (m/s), U($z_r$) is the given wind velocity at height $z_r$ (m/s), z is the height above ground for calculated wind velocity (m), $z_r$ is the height above ground for given wind velocity (m) and $z_0$is the surface roughness constant (mm) - 0.01 for ice to 3000 in a city with tall buildings.

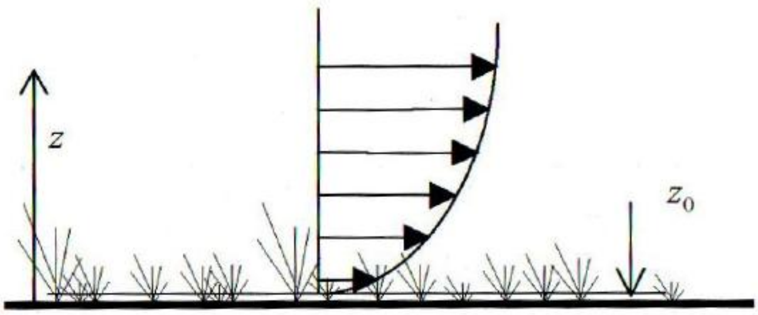



**Figure 4 Wind Characteristic close to ground (Mertens, 2006)**

Secondary forces occur when the centres of high or low pressure are caused by heating or cooling of the lower atmosphere and occur on a seasonal or daily cycle. Examples of these occurrences include monsoons, extra-tropical cyclones and hurricanes. The final or tertiary circulations are local to an area and include land and sea breezes, valley and mountain winds tornadoes and thunderstorms.

### *Wind Intermittency*

One of the main issues regarding wind is the variability or intermittency. As the wind varies the power output of the wind turbine generators also vary. Wind can change instantaneously and the mean wind speed can change on an annual, seasonal, daily and second to second basis. Figure 5 shows measured wind speeds at 30m above flat terrain for the Van Der Hoven Model (Van Der Hoven, 1957) which characterises wind behaviour over the medium and long term. Van Der Hoven concluded the peak on the period of 4 days is due to wind speed fluctuations caused by migratory pressure systems of synoptic weather map scale. The 1 minute peak is caused by a mechanical and convective type of turbulence. Turbulence is caused by the change of the winds kinetic energy into thermal energy through the creation and destruction of progressively smaller eddies.

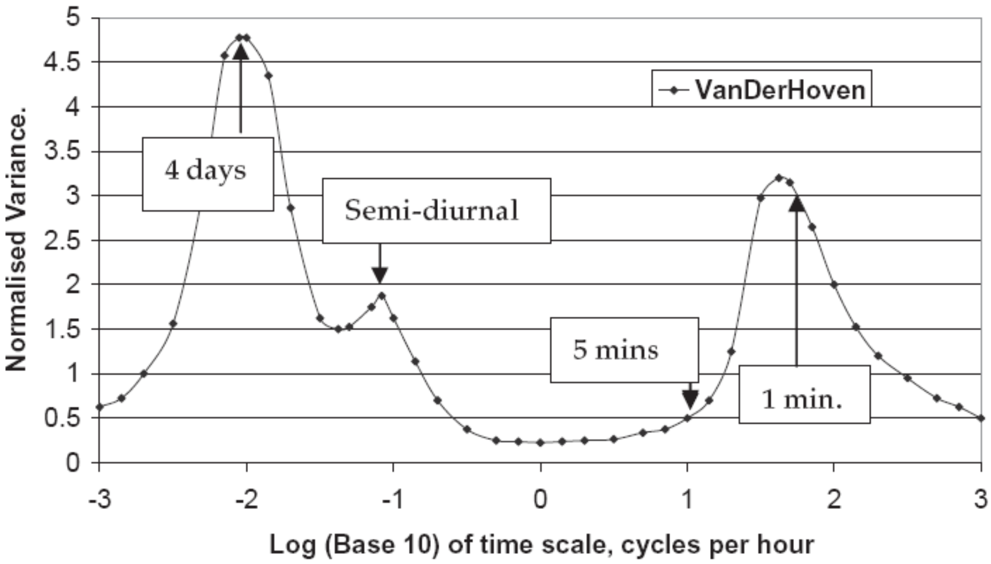



**Figure 5 Power Spectrum of Wind Speed Variation (Freris and Infield, 2008)**

Based on 30 years of wind speed data for an island in South Korea Ko (Ko et al., 2010) concludes that higher wind speeds were recorded during the daytime and the ranges of the diurnal variations in wind speed and wind power density were roughly half of those of monthly variations.

### 2.1.2 Wind Power Forecasting

Predicting the power output from a wind farm is important for a number of reasons. Grid operators require up to the minute forecasts for power balancing, plant scheduling and control of local grid congestion. Operators need lengthy forecasts for planning procedures and overall security of the network. The accuracy of wind power forecasting is very important and according to Fabbri (Fabbri et al., 2005) the error prediction costs can reach as much as 10% of the total generator energy incomes. In 2008 the wind power forecasting in Ireland was modelled using 21 of the 73 windfarms and this gave day ahead accuracies of between 6% - 8% (SONI and EirGrid, 2008).

Figure 6 is a flow chart of the wind power forecasting for Ireland used by the System Operator EirGrid. The System Operator uses two different systems to reduce the accuracy errors. The first three stages correspond to the Numerical Weather Prediction [NWP], power output forecast and the up-scaling. Both predictions are then combined to give the total wind output forecast before they are downscaled to allow the wind farms to individually participate in the Single Energy Market.

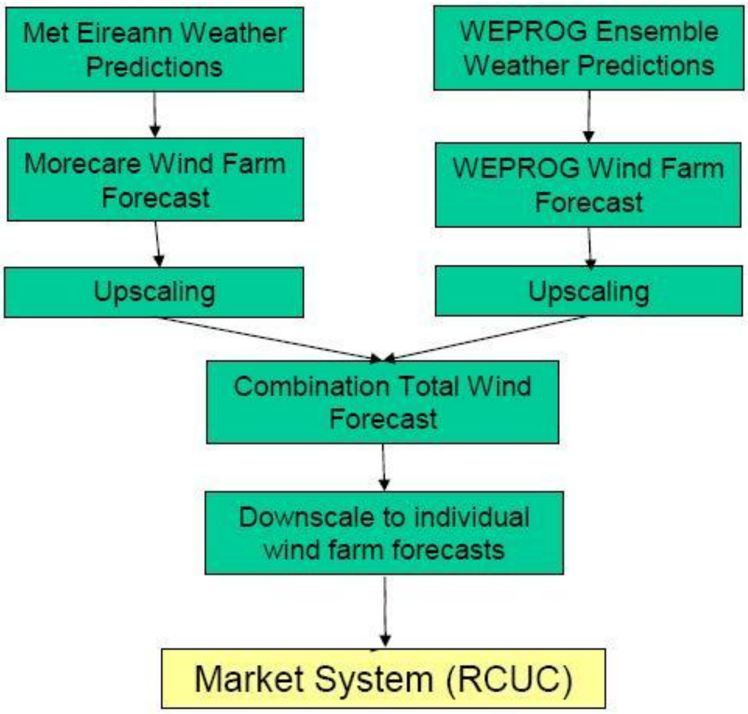



**Figure 6 Wind Forecasting Process in Ireland (SONI and EirGrid, 2008)**

### *Numerical Weather Predictions (NWP)*

The Meteorological Office describes NWP as the future state of the atmosphere as determined by numerical solution of a set of equations describing the evolution of meteorological variables which together define the state of the atmosphere. NWP model consist of fundamental physical equations using many meteorological variables such as pressure, temperature, air moisture, air density and wind velocity. The object of the prediction is to calculate how each variable change as the simulation runs. The cost of this method is very high due to the complexity of the equations and the results are limited by a number of factors such as the spatial resolution of the grid, the fidelity of the simulation and inaccuracies of the initial atmosphere state. The models are usually run by the National Weather Services and most of these run a local area model for their region of interest.

### *Wind Power Output Forecast*

The key aim of the wind power forecasting is to predict the power output of a wind farm given the predicted wind speeds from the NWP model. There are a number of approaches used such as the physical and statistical. The physical approach includes a number of models in relation to different physical factors such as wind speeds at the corrected height and frictions, wind farm shading, turbine power curve and model output statistics. The statistical approach analyses the connection of the wind forecast and power production from time series of the past and describe this connection in a way that enables it to be used in the future. A combination of physical and statistical approaches are currently used in this area and have day ahead target accuracy of between 6% - 8% and within day target accuracy of 4% - 6% (SONI and EirGrid, 2008).

### *Regional Up-scaling*

In many cases these forecasting techniques are not performed for every wind farm due to time and cost constraints. The forecasts are only compiled for a number of represented wind farms and the results are the regionally up-scaled. This minimises the costs but does not decrease accuracy as the power output wind farms in close proximity to each other behave in a similar manner. In 2008 when the Irish grid had up to 73 wind farms connected, the System Operator modelled 21 of these for power forecasting and used regional up-scaling to forecast the total wind power output (SONI and EirGrid, 2008).

## 2.1.3 Climate Change

Long term forecasting, which extends to decades and centuries, introduces the subject of climate change. There are many opinions and theories on what the weather will be like in the coming decades. Global warming, which has increased over the last century due to additional greenhouses gasses in the atmosphere, is increasing the number of extreme weather events throughout the world. The Community Climate Consortium for Ireland published a report in 2008 on the future climate of Ireland (McGrath et al., 2008). The project completed a number of simulation tests on the climate of Ireland in future years and based on the future years of 2021 to 2061 concluded the mean wind speeds will increase in the winter months and decrease in the summer months by about 10% in magnitude.

## 2.2 Other Renewable Energy Technologies

In 2008 the contribution of renewable technologies to gross electrical consumption was 11.9% (SEAI, 2009). Of this amount of energy, wind accounted for 68.1% and hydro accounted for 27.4%. The other 4.5% was made up of biogas, solid biomass and landfill gas. Renewable technologies that produce electricity directly from the resource and not using the conventional methods will be intermittent and will not produce power on demand as required by the System Operator. Hydro, wave, tidal and solar are all intermittent resources while the outputs of biomass and geothermal generators can be controlled. Leijon (Leijon et al., 2010) discusses the utilisation of different renewable resources. The 'degree of utilization' incorporates the electric energy delivered to the grid compared to the installed power on a yearly basis. This is also known as the capacity factor of the plant. Onshore wind has a degree of utilisation of up to 26%, where as a more stable resource as hydro has a degree of utilisation of up to 60%.

### 2.2.1 Hydro

In this section renewable hydro is defined as running hydro and not stored hydro which is described later in Section 2.6.1. Hydro is the most stable form of renewable generation and according to Leijon, et al., has a Degree of Utilisation of up to 60%. Hydro power, considered a mature resource has been used in most developed countries for decades.

According to The TSO's Generation adequacy report (EirGrid, 2009) there is 216 MW of dispatchable Hydro electrical plant and it estimates 21 MW of small hydro generation. The dispatchable plant is located at Ardnacrusha (86 MW), Eirne (66 MW), Liffey (38 MW) and Lee (27 MW). It is estimated (Sayigh, 2009) that in developed countries there can be as much electricity generated from small scale hydro plant as from large scale hydro plant, so this area is open to possible expansion. The possible reason for the lack of small scale may be due to the lack of economic incentives and possible environmental implications.

### 2.2.2 Wave

Ireland has a considerable wave resource and in Daltons study of the output of a Pelamis wave energy converter (Dalton et al., 2010), Ireland gave the highest energy output and capacity of the international locations simulated. Leijon gave wave technology a Degree of Utilization of between 35% and 68%, but this is only a rough estimate as there are no commercial units in operation. The revised government renewable strategy in 2008 set a target of 500 MW of ocean energy by 2020. A full size test site for pre commercial technologies has been set up off the coast of Belmullet in Co. Mayo and it is thought the 500 MW will be connected to the mainland through this line. Due to the large number of government bodies responsible for the ocean planning permission and licensing has been very difficult to acquire although an ocean energy strategy has been developed to help with this.  The most advanced technologies are Wavebob, Pelamis and Seabased shown in Figure 7 below.

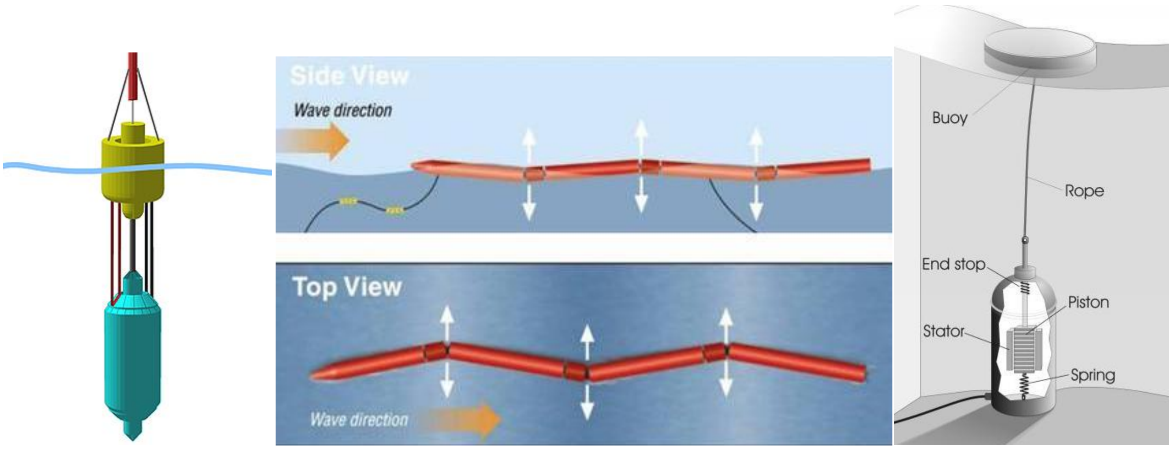



**Figure 7 Wavebob, Pelamis and Seabased technologies**

### 2.2.3 Tidal

Tidal energy is predictable and has little environmental impact they are highly attractive renewable energy source.  Tidal Energy systems need to be located in areas where the flow of the water is restricted giving rise to strong currents of at least 2 m/s to be feasible (DCMNR,2005) such as bay entrances, headlands or between land masses.  One such example is Strangford Lough in Northern Ireland and with a flow rate of 4 m/s has a 1.2 MW turbine operating since 2007.  In a 1991 study commissioned by the EU to estimate the feasibility of tidal barrages across the EU countries, the majority of potential tidal power output (90%) was within the UK and France.  According to the 2005 report (DCMNR, 2005)  tidal energy has a very limited potential in Ireland, although the tidal energy resource is concentrated on the east coast which is close to the largest electricity demand.  Due to this report there has been little research completed into tidal energy in Ireland and there are no immediate plans to generate power from this resource.

### 2.2.4 Photovoltaic and Solar Thermal

Photovoltaic [PV] systems convert solar energy into electricity using semiconductor materials.  The power output of the PV module is determined mainly by the level of incident radiation.  PV market is currently very small in Ireland and is not present in an industrial capacity.  In 2006 there was an installed photovoltaic capacity of 0.3 MW (Rourke et al., 2009).   PV is currently an expensive technology to convert solar energy to electricity and according to the IEA (International Energy Agency, 2007) will not be expected to be competitive until after 2020, except for a number of niche markets.

Solar thermal systems for generating electricity use solar concentrators to produce high temperatures to drive steam turbines. There are two main technologies: parabolic troughs and power towers. Parabolic troughs focus solar radiation using reflectors to a receiver and the fluid in the receiver transfers the heat to a boiler. A solar power tower uses a field of concentrating mirrors to reflect and concentrate the light to a central receiver on a tower. An example of the former is the 50 MW parabolic trough plant in Andasol, Spain, and there is an 11 MW solar power tower located in Sanlucar la Mayor, Spain. This technology is predictable and useful in hot countries as the electricity demand increases with temperature, due to air conditioning power requirements however, due to the intermittent sunshine in Ireland electricity generation using concentrating solar power is impractical (Rourke et al., 2009).

### 2.2.5 Biomass

Biomass differs from other renewable technologies in that it can be stored and transported quite easily. It can take the form of gas, alcohol fuels, wood and waste and it can be used as a direct substitute for fossil fuels such as natural gas, oil and peat. Its main advantage over other renewable technologies is that it can be used to generate power similarly to conventional plant allowing control over the power and frequency outputs.

The current amount of power generation from biomass in Ireland is difficult to calculate as it is mixed with peat in a number of plants (Edenderry, Lough Ree and West Offaly) and the operators do not publish the concentration of the fuel burned. The Irish Government have set target of co-firing the 3 peat plants with up to 30% biomass produce by 2015 (DCMNR, 2007).

There is an ethical issue regarding the use of large quantities of biomass for energy production. Biomass requires a large quantity of land for production and as a result competes with conventional crops. This influences the price of basic food and animal feeds which can lead to additional poverty in undeveloped nations. The UN reviewed the likely impacts of bio-energy in terms of food security and put forward policies to reduce the negative impacts of the progress towards biomass fuels(UN-Energy, 2007).

## 2.2.7 Geothermal

Geothermal energy is energy which is extracted from the earth's core in the form of heat. It is similar to biomass in that the heat can be stored and the energy conversion process can be controlled. The resource is easily accessible in areas close to tectonic plate boundaries however, in Ireland depths exceeding 5000 m are required to get the temperatures required for steam turbines. Figure 8 is a modelled temperature map of Ireland at 5000m below the surface. These drilling depths are extremely expensive, and unfortunately make electrical power from geothermal energy uneconomical in Ireland. There are currently no geothermal electrical generation facilities in Ireland and the government have a target of up to 5 MW by 2020,(DCENR, 2009) , which suggests the technology has no commercial practicality.

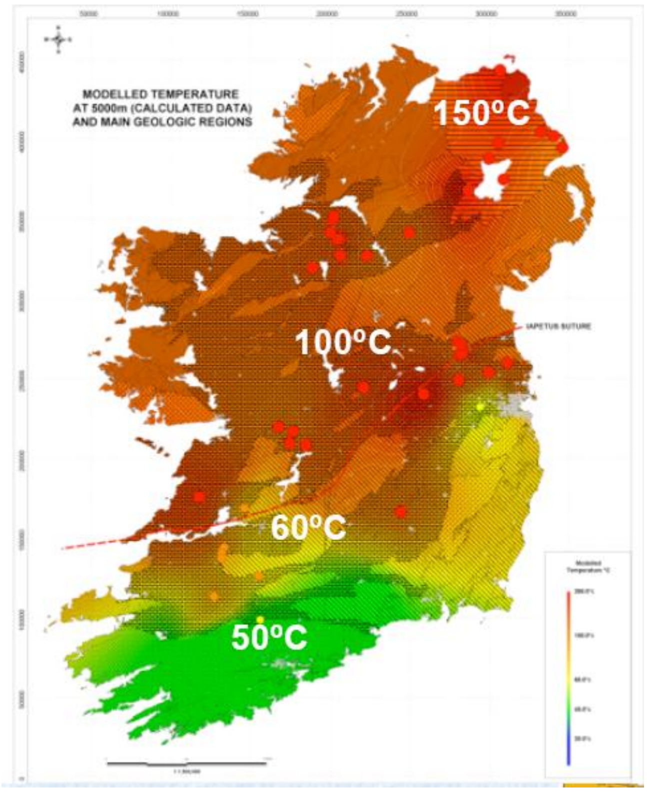



**Figure 8 Modelled Temperature at 5000m below surface (Jones, 2010)**

## 2.3 Interconnector

For many countries with system operational difficulties interconnection is a valuable commodity, as it facilitates the exporting of excess power and the importing power when required. There are various definitions of transfer capability for interconnectors and this paper deals with the Net Transfer Capacity [NTC]. The NTC of a line is the Total Transfer Capability [TTC] less the Transmission Reliability Margin [TRM]. The current connector which connects the island of Ireland to mainland UK is the Moyle Connector. It connects the BallycronanMore Convertor in Northern Ireland to Auchencrosh Station in Scotland. This connector began to transmit power in 2002 and can import and export up to 500 MW of electricity (Harvey et al., 2001). Currently in construction, the East West Interconnector will be operational 2012 with import and export capacity of 500 MW. It connects the Woodland 400kV Station in Co. Meath to Connah's Quay in Wales. According to Ecofys (Bomer et al., 2010) the maximum imports via interconnectors (for the whole island) have to be restricted to a maximum of between 500 MW and 1350 MW due to the amount of intermittent generation expected on the network. This limit is required to avoid frequency instability after loss of generation.

The current link between the Republic of Ireland and Northern Ireland links Louth to Tandragee and became operational again in 1995 after being out of service for more than twenty years. This interconnector consists of two 275 kV circuits with a combined rating of 1500 MVA. Due to constraints it has an import capacity of 450 MW and an export capacity of 450 MW. There is a second north to south interconnector being constructed at present and is due for completion by 2013. It connects Woodland 400kV station to Kingscourt in Co. Cavan and then to Turleenan in Co. Tyrone and this will increase the North/South interconnection to a combined capacity of 3000 MVA. As the system must cater for a loss of either of the two circuits at any time the maximum possible interconnector capacity will be 1500 MVA.

There are two additional lines which exist linking Swanlinbar to Enniskillen and Letterkenny to Strabane, which connect weak areas of the systems, and are not used as interconnectors between both systems. Figure 9 below shows the interconnector links between the UK, Ireland and Northern Ireland.

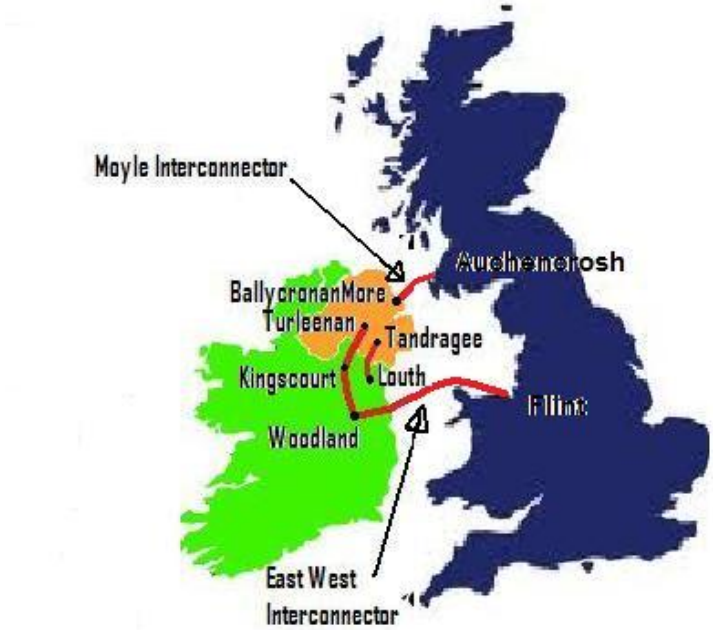



**Figure 9 Locations of Interconnectors between Ireland and UK**

## 2.4 Conventional Generation - Fossil Fuel Backup

The majority of generation plants in Ireland are thermal power stations which use fossil fuels such as natural gas, coal, oil and peat as a primary source of fuel. The advantage of this type of conventional plant includes: a) high energy density, b) availability and low cost, c) transportation and storage and d) control of the power output and frequency. In 2008 this type of generation accounted for 87.3% of consumer electricity output (SEAI, 2009), while the remaining was made up from renewable generation (11.9%) and electricity imports (0.8%). Many of the conventional steam generators support the system on a day-to-day basis providing Ancillary Services such as frequency and voltage control. Operating reserve is used to control the frequency of the system when the demand load changes throughout the day. It is also used to provide capacity reserve for the system when the wind power fluctuates. As the wind power and other intermittent generation technologies become more influential in the grid, the quantity and costs of this operational reserve will become unsustainable.

ILEX Energy (ILEX Energy, 2002) compiled a report for the Department of Trade & Industry in the UK to quantify the capacity and costs required to maintain adequate security of supply in a system supplied by considerable intermittent sources such as wind power. The calculations assumed the additional capacity was provided by open cycle gas turbines and the additional costs were up to an additional £10 per MWH for 30% intermittent generation.

Pavlak (Pavlak, 2010)considers the use of zero carbon baseload generators such as nuclear, coal gasification with carbon sequestration and natural gas combined with carbon sequestration. However due to the inertia of these machines they do not have fast response times to deal with wind fluctuations for on time operation control. The turbine best suited for use to balance wind power intermittency is open cycle gas turbines.

### 2.4.1 Open Cycle Gas Turbines

An Open Cycle Gas Turbine [OCGT] differs from the combined cycle gas turbine [CCGT] in that they have a combustion turbine only. The CCGT burn gas at temperatures of around 1000°C to drive a turbine and the exhaust gases are used to heat steam through a conventional turbine. The OCGT use the first cycle of the CCGT and thus have faster response times and lower capital costs which make it ideal for use as peaking plant. The OCGT are less efficient then the CCGT and are therefore more expensive to operate. Natural gas is the most common fuel although both can be run on biomass fuels which can be considered carbon neutral.

On the Irish network there is up to 828 MW of OCGT currently in operation with an additional four new OCGT stations to be operational in the next four years, Edenderry (111 MW), Nore (98 MW),Cuileen (98 MW) and Suir/Cahir (98 MW) (EirGrid, 2009).

## 2.5 Energy Storage

Energy storage is expensive and decreases the efficiency of electricity production due to the losses incurred in charging the storage plant. However the storage plant is controllable and has very fast reaction times, which makes it a very suitable combination with wind energy which is intermittent and unpredictable. Energy storage plants are also used in ancillary services such as operational reserve, black starts and voltage control. According to Kondoh (Kondoh et al., 2000) each storage technology has a suitable range from daily load to less than one hour applications.

### 2.5.1 Pumped Hydroelectric Energy Storage

Pumped Hydroelectric Energy Storage [PHES] is the largest electrical energy storage available throughout the world and is considered the most reliable form of storage. It has the advantages of fast start-up times, is carbon neutral and has the ability to supply on demand. The biggest disadvantages are the initial construction costs and environmental implications.

Within Ireland there is a single PHES facility located at Turlough Hill in the Wicklow Mountains. The station consists of 4 generators which can supply up to 292 MW of electricity for a maximum of 1.59 GWH. The plant operates on a daily cycle, generating electricity during high demand periods during the day and using electricity to pump the water from the lower to the upper reservoir at night. Figure 10 shows a typical 24 hour cycle for the station, indicating the times of generation and pumping. Note the demand curve is shown as a dashed line in the background. In the Generation Adequacy Report 2010-2016 (EirGrid, 2009) there are no modifications shown to the output of Turlough Hill station in the short to medium term. Connolly (Connolly et al., 2010) developed a computer program to locate additional PHES sites within Ireland, and within an 800 Km² area in the Southwest located five potential sites with a combined storage of up to 8.63 GWH. There are new PHES plants in planning for Knocknagreenan (70 MW) and Kippagh Loch (70 MW) Co. Cork.

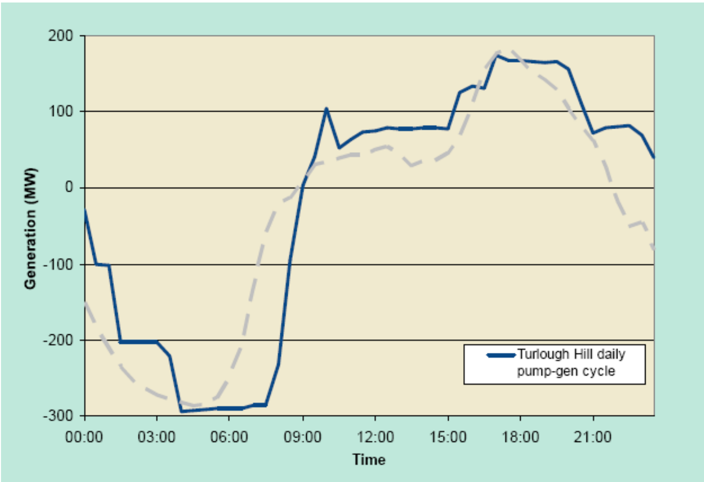



**Figure 10 Daily Cycle for Turlough Hill Power Station (EirGrid Gen Ad Report2010)**

The Spirit of Ireland organisation are examining the possibility of using inland saltwater reservoirs located close to the west coast to take advantage of the natural glacial valleys in the areas. The idea is based on building an upper reservoir that could store between 50 and 90 GWH of electricity and use the sea as the lower reservoir. The size of station is very large but due to the high construction costs 50 GWH is the minimum size that would make the idea economically feasible. This station output would be too large for the Irish market and so it is hoped to sell the electrical power to the UK market. EirGrid (EirGrid, 2009)carried out a study into the potential benefit to Ireland with 40% renewable generation penetration and found there would be little value in adding large amounts of pumped storage at this level.

### 2.5.2 Compressed Air Energy Storage

Large scale Compressed Air Energy Storage [CAES] can be a less expensive alternative to PHES as the construction costs can be up to 80 times less where appropriate geological conditions exist (Garvey, 2010). Similar to PHES, electricity is used to compress the air into a holding tank, underground cavern or underwater membrane at low demand times and the compressed air generates electricity during peak times. There are only a small number of CAES plants currently operational in Germany (290 MW) and the USA (110 MW). The most suitable underground caverns are formed in salt mines and unfortunately there are no such deposits in the Republic of Ireland however, there are a number of salt mines in Northern Ireland which would suit this technology. It would be possible to use gas fields such as the Kinsale and Corrib when they become depleted, although they may be used for storage of natural gas instead.

### 2.5.3 Other Storage Technologies

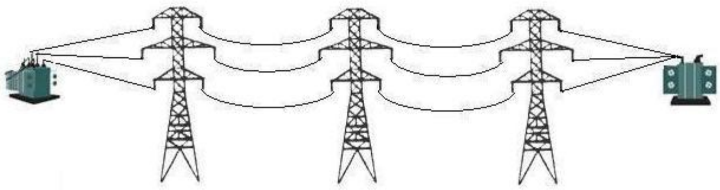
Other energy storage technologies include hydrogen production, flow cells, batteries and flywheels. Technologies such as super capacitors, Superconducting Magnetic Energy Storage [SMES], and thermal storage are not discussed in this paper as they are commercially unavailable for large scale storage.

**Hydrogen** can be produced through the electrolysis of water using electrical energy. The hydrogen can then be stored in many different forms such a gas or a liquid. The advantage of hydrogen as an energy storage technology is it can be transported and even used as transport fuel. Hydrogen is not widely used as efficiency levels are below 50%.

**Flow cells** are electrochemical storage devices that store the energy in their electrolytes, which can be fully discharged and recharged. They have the advantages of flexible layout, long life cycles and quick response times which suits the intermittency of wind technology.

**Batteries** convert stored chemical energy into electrical energy. There are a wide range of batteries available such as lead-acid, nickel-cadmium, nickel-metal hydride, lithium ion and lithium ion polymer. Batteries are used in many ways such as Uninterruptable Power Supply, UPS, and mobile electronics however they are rarely used in electrical storage due to the energy density and short cycle life.

**Flywheels Energy Storage** [FES] stores mechanical energy in the form of rotational motion using fast rotating heavy rotors or flywheels. The system delivers energy to the flywheel, accelerating the rotation high speeds and extracts the energy from the flywheel when it is required. Flywheels are an expensive technology and are used rarely, only for specific situations.



## 2.6 Grid

The transmission and distribution networks are the infrastructure which transfer the power supplied by the generators to the consumers. It is an expensive utility to install and maintain and requires extensive planning to minimise line losses caused by the resistances of the conductors. Networks have been designed to take large amounts of power from a small number of power facilities and distribute to the whole country. Wind power disrupts this process as windfarms produce much smaller amounts of power over are widely dispersed area throughout the country which leads to many constraints on the network. This results in major planning and alterations to the national grid to accommodate high levels of wind power and is the main reason that obtaining a connection to the grid is the most time consuming element of the planning a windfarm.

In 2008 the Irish Government published the All Island Grid Study which examined the feasibility of incorporating high levels of renewable technologies to the power system. The outcome of this report became the basis for the GRID 25 Strategy which was planned by the transmission operator, EirGrid, to develop and upgrade the transmission network up to 2025. This plan is to double the capacity of the transmission network and link areas of high renewable energy resource to the areas of high demand. The current connection process which has been developed by the Commission for Energy Regulation [CER], known as the Gate Offer Project, is Gate 3 and this is now closed for applications.

Figure 11 show the transmission network for the island of Ireland. This map has been scaled down to fit in the document so the area names are not legible. From the map it can be seen the network has been designed for the generation and consumption close to the urban centres such as Limerick, Cork and Dublin. Many optimum sites for windfarms are located away from the urban areas, in isolated rural areas, hence the requirement to upgrade the network.

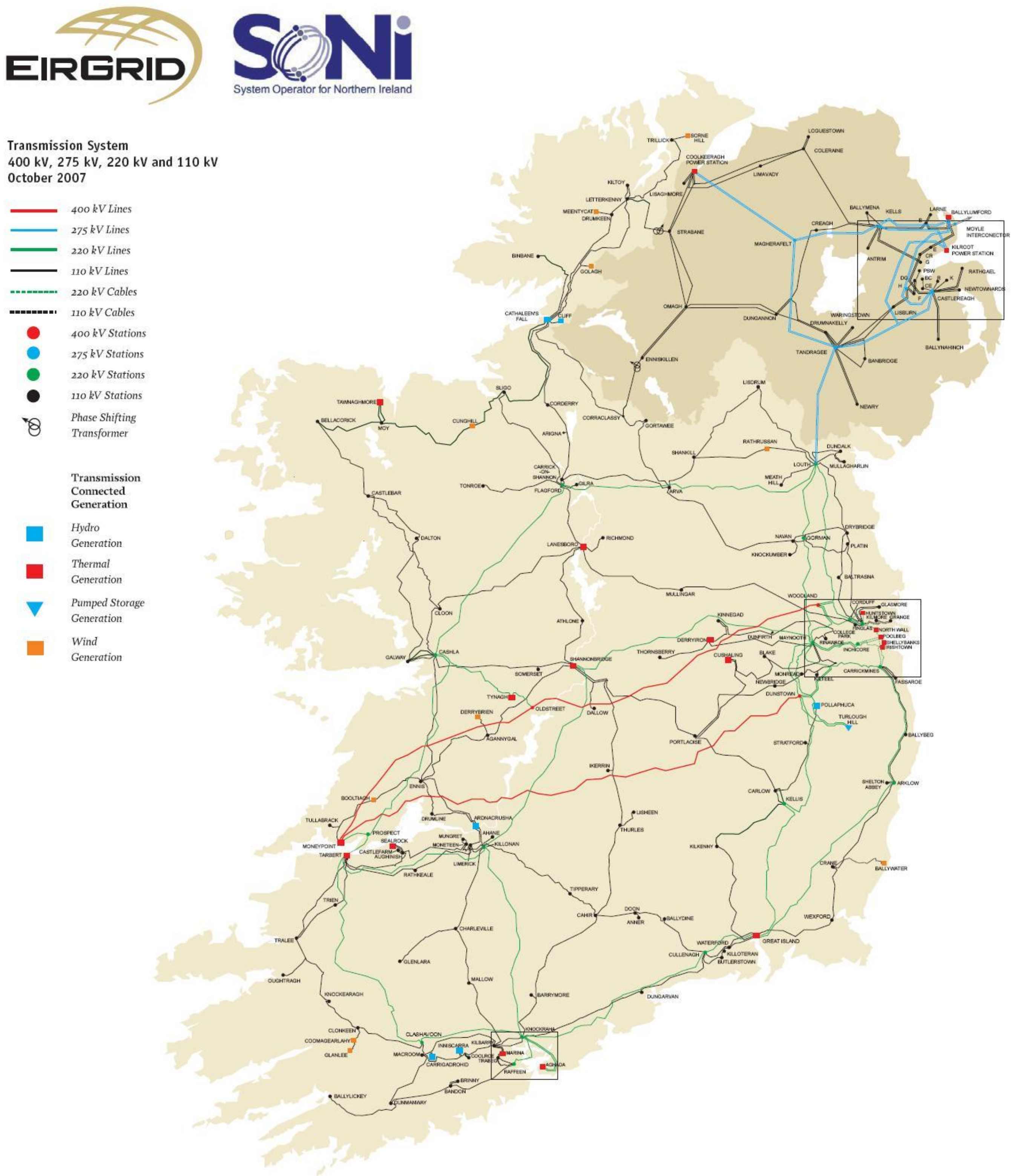



**Figure 11 Transmission System Map of Ireland (SONI and Eirgrid, 2010)**

## 2.7 Data Received

Data was required to analyse the key fundamental factors which influence power outputs from Irish windfarms, to assist with the selection of the metrics and weighting factors for the tool. A number of areas were required to be examined such as environments and geographical effects on the power output of a wind farm. Wind power data was supplied by the Single Electricity Market Operator and the environmental data was provided by MET Éireann. The last two complete years of data, 2008 and 2009, were requested.

### 2.7.2 SEMO Data

Data was requested from the SEMO on the breakdown of wind generation for each wind farm within Ireland in 15-30 intervals for the selected years. A disk was received on 10/05/2010 with two Access files and an Excel file. The Access files contain a database of metered generation 'Values' at 30 minute intervals for every participant within the Single Electricity Market for 2008 and 2009. The Excel file received from the SEMO, named Mapping Spreadsheet, contains information on each market participant including facility name, fuel type, minimum and maximum output and connection point. This allowed a list of windfarms to be complied for analysis.

### 2.7.3 MET Éireann Data

The environmental data received from MET Éireann consists of one Excel file with hourly recorded data from six weather stations located around the country, Malin Head, Belmullet, Valentia Island, Johnstown Castle, Birr and Gurteen. Within the Excel file there is a worksheet for each of the stations which store the recorded weather conditions. The recorded variables are wind direction (10's of degrees clockwise from North), 10 minute average wind speed (Knots/s), temperature (°C), relative humidity (%) and mean sea level pressure (mBar).

## 2.8 Analysis Software

Table Data Analysis tools and Microsoft Excel were used to analyse the SEMO and MET Éireann data to search for the main influencers, relationships, sequences and associations within the datasets. Microsoft Excel acts as the user interface and can store, source and test the data however, the analysis is performed using SQL Server Analysis Services. Microsoft SQL Server is a relational model database server that provides database services to other computer programs. Analysis Services is part of the SQL Server and includes various algorithms such as decision trees, clustering algorithm, Naive Bayes algorithm, time series analysis, sequence clustering algorithm for use in data mining.

### 2.8.1 Table Tool Analysis

The Table Analysis Tools provides tasks such as Analyse Key Influencers, Detect Categories, Fill from Example, Forecast, Highlight Exceptions, Scenario Analysis, Prediction Calculator and Shopping Basket Analysis. The tasks leverage SQL Server to perform powerful analytics on the data. Below is brief descriptions of the main task used.

#### *Analyze Key Influencers*

This tool analyzes the patterns in data that have the strongest influence on a certain outcome by detecting the influence of the other columns on the values of the target column. An influencers report is generated and ranks the key influencers based on their importance.

## 2.9 Summary of Chapter

This chapter discussed the current methods of electrical power generation and the emerging technologies that will become major participants this process in the coming years. The many different types of power production which affect the operation of the system and their penetration on the Irish network were described. Wind, which will become the dominant participant in the system, is effected by a number of variables, most of which are within the design of the turbine. The intermittency of the wind is due to the wind fluctuations and to a lesser extent air density. Other renewable technologies do not supply power as irregularly as wind so they can assist the System Operator when balancing high levels of wind power on the network. The Interconnection, which will more than doubles its capacity in the next few years, will be a key instrument in the control, as will OCGTs which are increasing in capacity by an additional 50% in four years. Energy storage is the optimum tool for operating the system and although there are many technologies available only a few suit large scale power systems and these are very expensive. As the methods of generation change the grid infrastructure is evolving through the Grid 25 Strategy, which involves upgrading and adding to the existing transmission network. The data and its sources that are used in the analysis in the coming chapters were described and the way in which it was received. The chapter concluded with a description of the analysis software tools that are used to carry out the investigation into the data to discover the key influencers on a windfarm output.

# 3. Develop a Tool for Analysing Windfarm Sites

This chapter studies and explores the data received from the SEMO and Met Éireann using basic mathematical and software analysis. Data mining software is applied to the data to determine the key factors which have influence on the wind power output, and using these results along with the research in Chapter 2 the tool is developed. The tool consists of a spreadsheet with influencing metrics which are divided up into a number of factors, each having an individual weighting depending on their importance to the windfarm output. This spreadsheet can then be used to compare and contrast different sites for possible windfarm locations.

The chapter begins with the validation of the SEMO data, which was carried out to ensure the data received was adequate for use in the analysis due to a number of concerns with the data. Following this, both sets of data were examined and formatted to remove any irregularities which would bias the results. The data used for the analysis was then detailed and locations of the windfarms and weather stations are shown in a map of Ireland. This is followed by a summary of the tests carried out on the formatted data. Further details on the tests including the aims, methods, results, analysis and conclusions are available in Appendix 1. The conclusions of these tests coupled with the information detailed in Chapter 2 are used to develop the tool for balancing high levels of wind power onto the Irish Grid. The next section describes each metric to be incorporated into the tool, including the factors within each metric, the weightings and the values to be given to factors. This is followed by the creation of the tool as a spreadsheet in Microsoft Excel. The output of the spreadsheet and its significance is then discussed.

## 3.1 Validation of SEMO Data

It was decided to validate the SEMO data as there were no details given with the data, such as the units of the recorded values and the range of the generation facilities, which caused some concern. The SEMO data was validated against the Wind Generation Download Centre available on the EirGrid website (www.eirgrid.com). The data available on the EirGrid website is recorded in Mega Watts for every 15 minute intervals. When both sets of data were compared there was a large discrepancy as the EirGrid data was over double the values of the SEMO data. This was queried with the SEMO and they confirmed the recorded values given in Mega Watt Hour for the 30 minute intervals and the data consisted of SEMO participants only. This was adapted to MW units by dividing by the time interval (½ an hour), to give the Mega Watt output of each farm for the 30 minute interval. This was then plotted on a graph with the EirGrid data for a number of random dates and the graph for 01/03/2009 is shown in Figure 12.

As the data varies significantly throughout the day plotting the values gives rough and jagged curves which are difficult to analyse. To smooth out the curves, a Visual Basic for Application [VBA] is used in Microsoft Excel which uses cubic spline interpolation. Microsoft Excel uses a cubic spline for interior points but dampens it at the edges of the range, so cubic spline routines are used to un-dampen the edges of the range giving a more rounded smoother curve. The program used was developed by David J Braden (Braden, 1999).

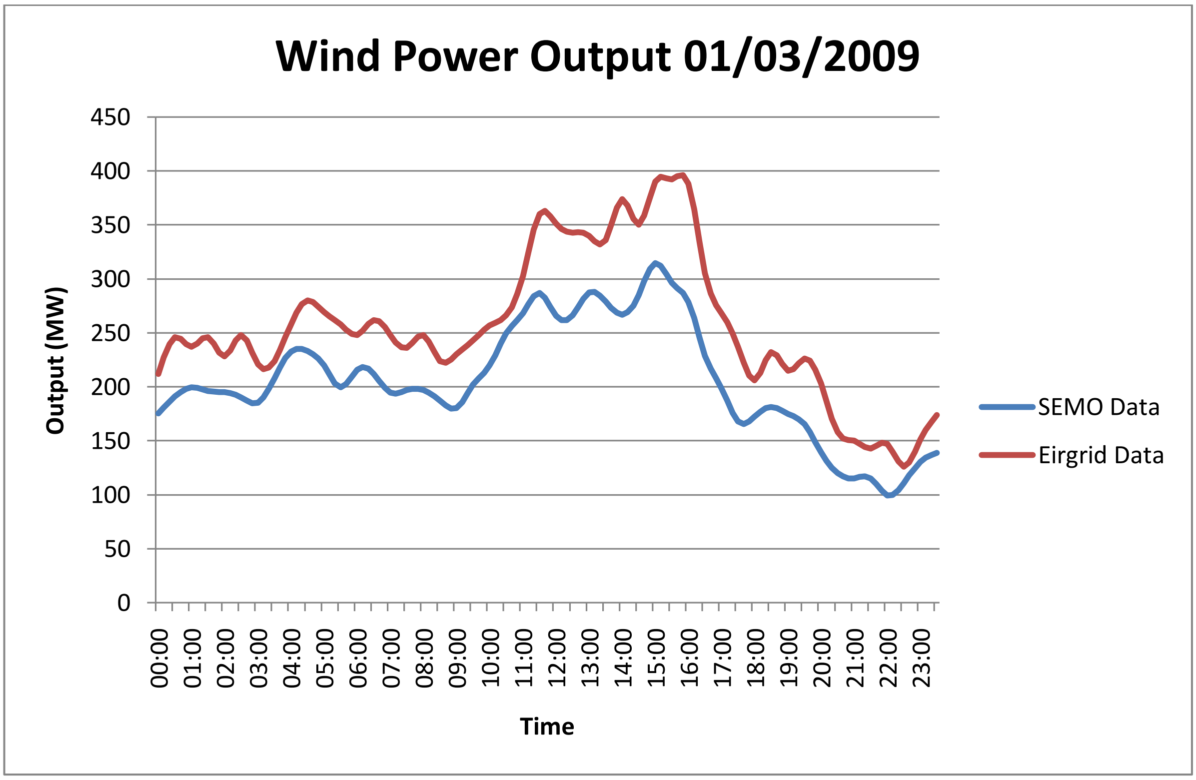



**Figure 12 Wind Output for SEMO and EirGrid Data 01/03/2009**

From Figure 12 above it can be noted:

Both curves have a very similar pattern and the EirGrid data is 30% greater than the SEMO data for the majority of the time. The SEMO data never exceeds the EirGrid data which confirms the information that the SEMO data only includes the SEMO participants and the EirGrid data includes the SEMO participants and the smaller wind generators. The difference between the two curves is the wind generation that is not sold on the SEM, which is considered micro-wind.

Both curves are very close in timing, although the SEMO data is leading by 30 minutes for a time at 3am and lagging by 30 minutes at 9am. This suggests there is no obvious time difference between the two sets of data just a small timing shift which could be caused by the small wind generators.

The validation of the SEMO data confirms the recordings are indeed in MWH and only include the SEMO participants and not the total wind generation available in the country.

## 3.2 Data used in Analysis

The data received was filtered to remove any elements which would bias the analysis in any way or did not make sense. The sections below describe the data which was extracted from the files for analysis.

### 3.2.1 SEMO Data

As many of the windfarms became operational during the period in which data was recorded, January 2008 to December 2009, the results of these units may bias the overall results because the output was recorded as zero until the windfarm began exporting to the SEM. For the tests carried out on the SEMO data, the sample of windfarms analysed were the units operational on the 01/01/2008, which are detailed in Table 1. The 22 windfarms were operational by the end of 2007 and have a maximum capacity of 590MW. The locations of these windfarms are shown in Figure 13 and are spread very well throughout the North, West, South and North-East of the Country.

When comparing the data against the Met Éireann data, the intervals for the SEMO data had to be changed to 60 minutes to suit the Met data. To get the MW values for intervals of 60 minutes the two MWH values within the 60 minutes were added together, i.e. adding the MWH values at 13:00 and 13:30 of a certain day to get the MW supplied for the hour between 13:00 and 14:00.

It was noted during the initial analysis that there were periods in which the windfarm outputs were generating capacity factors well in excess of 150%. For the time intervals 1:00 and 1:30 on 25/10/2009 the recorded capacity values for the windfarms were twice the values of the adjacent time periods. This may have suggested a) the output was doubled for the time intervals, b) the output was measured in MW or c) an incorrect reading was recorded. The time intervals were removed from the analysis as there was no obvious reason for the spike and they may have biased results.

### 3.2.2 Met Éireann Data

The data received from Met Éireann consisted of worksheets for each of six weather stations throughout the country. The weather station at Birr was terminated during 2008 and the data was joined with Gurteen, so the data both for both stations is the same. Gurteen and Birr recordings are also missing a number of random records over the two year period. The details of the weather stations used in the analysis are in Table 2 and the locations are shown on Figure 13.

**Table 1 Windfarms used in Analysis**

| Item | Facility Name | Windfarm Name | County | Max Generator Capacity (MW) |
|---|---|---|---|---|
| 1 | GU_400020 | Kingsmountain windfarm phase 1 | Sligo | 25 |
| 2 | GU_400030 | Cuillagh | Donegal | 11.88 |
| 3 | GU_400041 | Gartnaneane | Cavan | 10.5 |
| 4 | GU_400050 | Bindoo | Cavan | 48 |
| 5 | GU_400060 | Midas | Kerry | 32.4 |
| 6 | GU_400070 | Meentycat | Donegal | 72.4 |
| 7 | GU_400080 | Richfield | Wexford | 27 |
| 8 | GU_400110 | Arklow Banks Windfarm | Wicklow | 25.6 |
| 9 | GU_400130 | Ballywater Windfarm | Wexford | 42 |
| 10 | GU_400380 | Beam Hill Windfarm | Donegal | 14 |
| 11 | GU_400390 | Moanmore Windfarm | Clare | 12.6 |
| 12 | GU_400400 | Raheen Barr | Mayo | 18.7 |
| 13 | GU_400410 | Taurbeg Windfarm | Cork | 25.3 |
| 14 | GU_400420 | Booltiagh Windfarm | Clare | 19.45 |
| 15 | GU_400430 | Coomagearlahy | Kerry | 42.5 |
| 16 | GU_400440 | Derrybrien Windfarm | Galway | 60 |
| 17 | GU_400450 | Barnesmore Windfarm | Donegal | 15 |
| 18 | GU_400460 | Cark Windfarm | Donegal | 15 |
| 19 | GU_400470 | Carnsore Windfarm | Carnsore | 11.9 |
| 20 | GU_400490 | Tursillagh Windfarm Phase 1 | Kerry | 15.18 |
| 21 | GU_400550 | Sorne Hill Wiindfarm | Donegal | 38.9 |
| 22 | GU_400560 | Tursillagh Windfarm Phase 2 | Kerry | 6.8 |

**Table 2 Weather Stations used in Analysis**

| Item | Station ID | Station | County |
|---|---|---|---|
| A | 545 | Malin Head | Donegal |
| B | 1034 | Belmullet | Mayo |
| C | 305 | Valentia | Kerry |
| D | 475 | Johnstown Castle | Wexford |
| E | 1475 | Gurteen/Birr | Offaly |

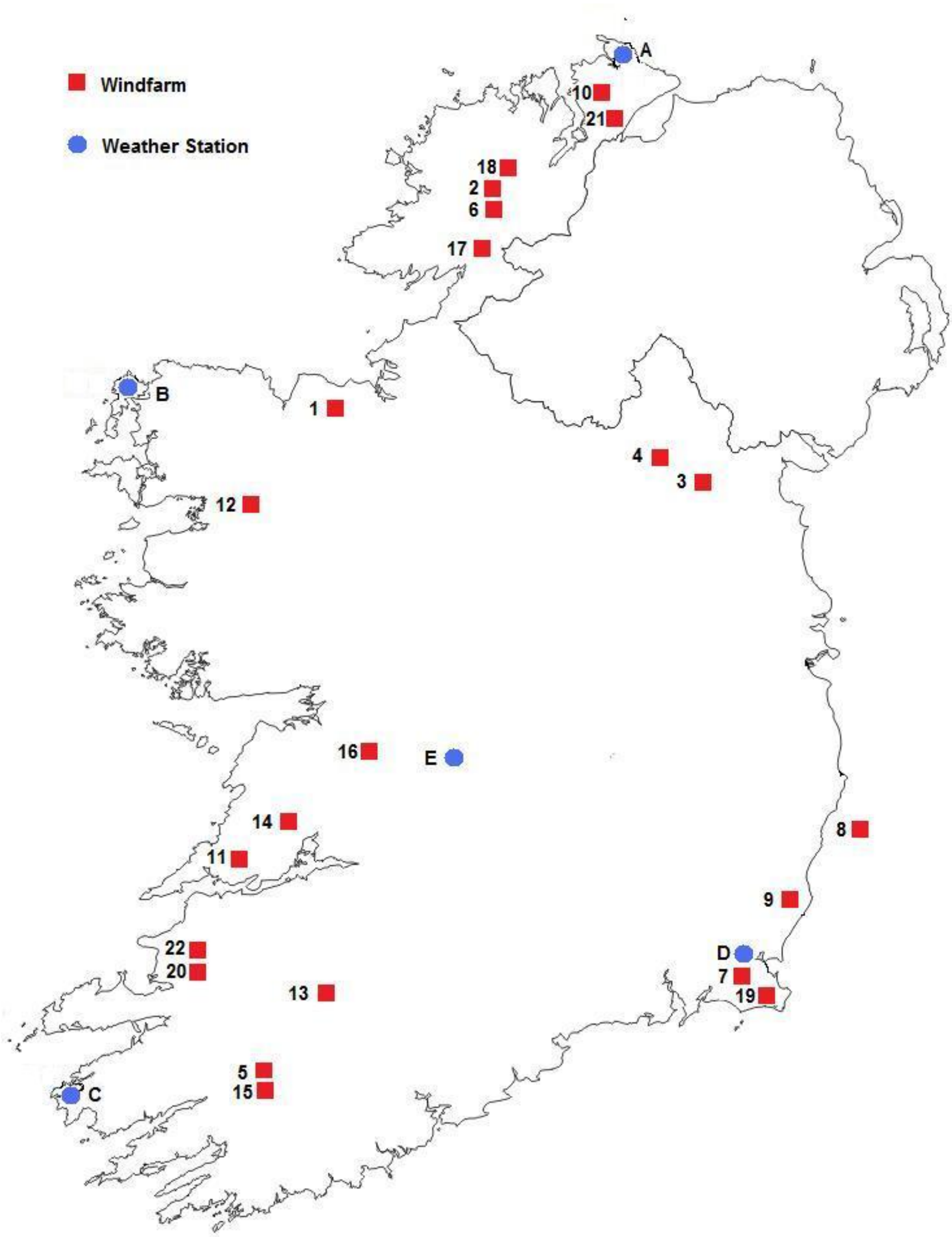



**Figure 13 Locations of Windfarms and Weather Stations used in Analysis**

## 3.3 Results of Data Analysis

The tests carried out are described in Appendix 1 and are summarised in Table 3 below.

**Table 3 Results on the Analysis of Data**

| Test | Description of Analysis | Analysis Tool | Result |
|---|---|---|---|
| 1 | Capacity values of windfarms including capacity value of wind power | Microsoft Excel | The capacity values ranged from 17.75% to 39.68% with a capacity value of wind power of 29.42% |
| 2 | Range of wind speeds and air density recorded in weather stations. | Microsoft Excel | Wind Speeds ranged from 0 to 31.8 m/s with a mean of 5.2 m/s. Air density ranged from 1.17 $kg/m^3$ to 1.35 $kg/m^3$ |
| 3 | Find prevalent wind direction recorded in weather stations. | Microsoft Excel | The most common wind direction is the South-west. |
| 4 | The relationship between the capacity values of Windfarms. | Analyze Key Influencers, Table Tool Analysis, Microsoft Excel. | Windfarms located close to each other give similar levels of capacity values for the same time intervals. |
| 5 | The relationship between windfarm power outputs and the weather conditions recorded in nearby weather stations. | Analyze Key Influencers, Table Tool Analysis, Microsoft Excel. | Wind speed is the strongest influence on power output of a windfarm. |
| 6 | The relationship between windfarm power outputs and the weather conditions, excluding wind speed, recorded in nearby weather stations. | Analyze Key Influencers, Table Tool Analysis, Microsoft Excel. | The wind direction was the most common key influencer for the windfarms however the direction was different for each windfarm. |
| 7 | Patterns between conventional generation capacity values and the capacity value of wind power. | Analyze Key Influencers, Table Tool Analysis, Microsoft Excel. | Results gave no conclusive influencers. |
| 8 | Comparison of the capacity value of each windfarm to the capacity value of wind power. | Analyze Key Influencers, Table Tool Analysis, Microsoft Excel. | Windfarms closest to the centre of the country had the strongest influence. |

## 3.4 Metrics

Using the results of the previous analysis and other published research as detailed in Chapter 2 a number of metrics have been chosen to be included in the tool. Each metric will be divided up into factors, each factor having value limits and an overall weighting. Each value will range from 0 to 10, with 10 the maximum possible value and will be scaled accordingly. The weightings will differ from factor to factor depending on its importance and the weighting values are summarised in Table 4 below.

**Table 4 Weighting Scale for factors**

| Weighting | Description |
|---|---|
| 5 | This is given to the most influential factor for that metric. |
| 4 | This is given to a lesser influencer factor for the metric but one which is very important. |
| 3 | This is assigned to important factors which affect the metrics. |
| 2 | This is given to a lesser important factor which affects the metric. |
| 1 | This is given to the factor which has little influence on the metric but not of negligible importance. |

### 3.4.1 Geographical

This metric evaluates the windfarm site from the environmental and physical aspects which can have a direct effect on the power output of a windfarm. They include features that affect the windfarm caused by external conditions and its surroundings. These factors include wind speed, windfarm orientation, terrain distance to the network and potential for expansion.

The range of air densities recorded over the weather stations is less than 10% for the 2 years analysed and the stations recorded the same average air density. Although air density does have an effect on the power that can be extracted from the wind, as detailed in Equation 2.1, it will not be included in the metric as the air density difference between each location is negligible.

#### *Wind Speed*

Test 5 indicated the wind speed is the key environmental influencer in the power output of the windfarms. The result of this test is supported by Equation 2.1, as the wind speed, U, is multiplied to the power of three. Test 2 results gave the range of wind speed recordings for Malin Head from 0 m/s to 31.8 m/s over the data analysed. This result gave the range of wind speeds over the period recorded and explain the huge range of power output from the windfarms in the area. As this factor is the most influential it has been given a weighting of 5.

The average wind speed for a potential site can be found using the SEAI Wind Map. For this exercise the wind speeds at a height of 50 m will be used for the tool. This wind speed must be adjusted so that the maximum wind speed will have a factor value of 10 and the minimum a factor value of 0. The maximum wind speed at 50 m is 14 m/s and the minimum is 0 m/s, therefore the wind speed will be multiplied by the variable $({}^{1}/_{1.4})$ to get the factor value.

### *Orientation of Windfarm*

Test 3 results indicated that the most common direction of wind direction is blowing from an angle of 230° from North, which is a South-westerly direction. This result compares well to the wind description of Ireland on Met Éireann Website where it is states the prevailing wind direction for Ireland is between south and west.

The most influencing weather factor when wind speed was omitted for Test 6 was the wind direction. The Arklow Banks Windfarm gave the wind direction of 168°-222° from North while Tursillagh Phase 1 gave the wind direction of 70°-155° from North as the key influencer for the higher outputs of windfarm capacity. This suggests the windfarms are orientated in such a way that wind direction has an influence on the power output. This may be due to the layout of the turbines, the local geographic conditions or just a coincidence and requires additional investigation which is not in the scope of this paper. It will be assumed for this paper that the layout of the turbines on a windfarm produces an optimum wind direction, which will have an influence on the power output. This factor will estimate an optimum direction, in which the majority of the turbines are facing, and will give a value to the windfarm based on the wind direction results. The values for the orientation of the windfarm are shown in Table 5. Note a windfarm with a North-easterly orientation also has a South-westerly orientation.

As Test 6 results deduce the wind direction is the second key influencer factor behind wind speed, a weighting factor of 4 will be given to this metric. The orientation of a windfarm will be determined by studying the layout drawings of the turbines within the windfarms as detailed in Section 4.3.1.

**Table 5 Range of Values for Windfarm Orientation**

| Wind Direction | Percentage of Time | Factor Value |
|---|---|---|
| North | 1.4% | 2.50 |
| Northeast | 1.5% | 2.61 |
| East | 1.6% | 2.84 |
| Southeast | 2.2% | 3.90 |
| South | 4.2% | 7.32 |
| Southwest | 5.7% | 10.00 |
| West | 4.0% | 7.12 |
| Northwest | 2.1% | 3.66 |

### *Terrain*

The influence of the terrain could not be examined using the data analysed as it would be necessary to compare identical windfarms with many different type of terrain and this data was unavailable. As detailed in Section 2.1.1 the lie of the land in the vicinity of a windfarm can influence the output of the windfarm, as it can greatly reduce the wind speed due to the resistances of hedges, trees and buildings. This factor is measured using the approximate surface roughness lengths given in Table 2.2 of Manwell (Manwell et al., 2009).

A value of 10 is given to open sea terrain as this is the smoothest terrain available in Ireland. The different terrain values are then reduced to zero as the ground resistances increase to high structures located in urban environments. These values are shown in Table 6 below and it can be noted that as factor value increases as the terrain becomes more severe. The terrain value will be given a weighting of 3 as although it is not as influential as the wind speed or orientation it can greatly affect the wind speed at turbine hub heights. The terrain of a site can be viewed from aerial photographs available on the Ordnance Survey Ireland website.

**Table 6 Range of Values for Terrain Factor**

| Terrain | $Z_o$* | Factor Value |
|---|---|---|
| Open Sea | 0.2 | 10 |
| Lawn Grass | 8.00 | 8 |
| Rough Pasture | 10.00 | 7 |
| Fallow Field | 30.00 | 6 |
| Crops | 50.00 | 5 |
| Few Trees | 100.00 | 4 |
| Trees and Hedges | 250.00 | 3 |
| Forest | 500.00 | 2 |
| Suburbs | 1500.00 | 1 |
| Inner cities | 3000.00 | 0 |

* the values of $Z_0$ have been taken from Wind Energy Explained Table 2.2 (Manwell et al., 2009).

### *Distance to Transmission Network*

This metric examines the strength of the local network and the power losses in connecting the site to the network. In assessing the strength of the local network the distance between the site and the closest transmission station is measured. The transmission network in the area gives an indication of the strength of the network in the region. The distance to the network can affect the power supplied to the system by the windfarm as large distances can have significant line losses. The distance from the windfarm site to the network can be measured using the transmission map in Figure 11 and Google Maps. The values given for the site are detailed in Table 7. This factor is important as the costs of planning and construction of additional high voltage lines to connect a windfarm are very high and are to be avoided if possible. The weighting of this factor is 2.

**Table 7 Value Factor for Distance to Transmission Network**

| Distance to Network (Km) | Factor Value |
|---|---|
| <10 | 10 |
| <20 | 8 |
| <30 | 6 |
| <40 | 4 |
| <50 | 2 |
| >50 | 0 |

### *Potential for expansion*

This factor takes the possibility of future expansion of the development which would increase the wind power output from the windfarm. Test 4 concluded that windfarms located close to each other give similar levels of capacity output. This suggests that one advantage of a windfarm extension is the site could be analysed easily using the existing windfarm data. Other advantages of adding to an existing windfarm are the site infrastructure, such as roads and power lines, and a network connection are in place. The potential for expansion is made on the basis there is an equal size of available land next to the site to allow additional turbines to be installed at a further date.

The value of the factor will be given based on the planning permission and access to the surrounding lands. If the land next to the site is accessible a value of 5 is given and if the land is inaccessible a value of 0 is awarded. Similarly if planning permission is available to the surrounding lands a value of 5 is given and if planning permission would be unavailable a value of 0 is granted. The maximum value for the factor is 10. This factor would not be considered as important as any of the other factors and will be given a weighting of 1.

## 3.4.2 Operational

This metric evaluates the windfarm site from the point of view of the system operator and the issues which arise with intermittent wind power. The average capacity value of the windfarms for the data analysed was 29.42% and this fluctuated between 0% and 92%. The issue of operation is the single biggest topic of concern for electrical systems with large wind penetration as there is a requirement for backup when the wind is not blowing, which could occur at peak load. The factors which will influence the operation of the network are the capacity backup available in the system, the forecasting of the wind power and the distribution of the windfarms throughout the country.

### *Backup Capacity*

Test 7 set out to examine the relationship between the capacity value of the wind power and conventional plant output, to observe the systems response to high and low levels of wind power on the network, either through operation strategy or just coincidence. The result of this test gave no conclusive influencers meaning there was no strategy or coincidences. It should be noted the level of wind power on the network in 2008 and 2009 was low and did not require a strategy as it was accommodated within the system operational reserve.

From the National Renewable Energy Action Plan [NREAP] the level of wind required for the 2020 target is 7145 MW for both onshore and offshore wind generation (DCENR, 2009). The projected

2020 targets for each of the technologies below will be compared to this wind power target and this proportion will be used in the analysis of a proposed site as described in the summary below.

Should all the targets for each generation method be met, there should be enough backup capacity to allow the integration of the high wind levels on the network without any difficultly. The following sections confirm the targets for 2020 and a method is developed to value the backup capacity factor.

### *Other Renewable Energy Technologies*

The capacity value of a renewable technology can be calculated by multiplying the total maximum generator capacity by Leijon's Degree of Utilization (Leijon et al., 2010). This capacity value is the equivalent amount of conventional generation for that technology which can be used as backup for wind power generation. Table 8 lists the Degree of Utilization values for each renewable technology.

**Table 8 Degree of Utilization for Renewable Technologies(Leijon et al., 2010)**

| Renewable Technology | Degree of Utilization % * |
|---|---|
| Hydro | 60 |
| Wave / Marine Currents | 35 |
| Solar | 12 |
| Geothermal | 85 |
| Biomass (Conventional) | 85 |

*Values taken from Leijon (Leijon et al., 2010).

### *Backup Capacity - Interconnector*

The Moyle interconnector was included in Test 7 and the power transfer did not relate to the capacity of wind power produced. As discussed in Section 2.3 (Bomer et al., 2010) recommends that imports via the interconnectors should be limited to less than 1350 MW. This suggests the maximum capacity backup the interconnector can provide is 1350 MW.

### *Backup Capacity - Conventional Fossil Fuel Generation*

According to the System Operator (EirGrid, 2009) there will be up to 1233 MW of OCGT is operation in Ireland by 2020, the majority of which will be peaking plant used to assist in meeting demand when it is highest. All other types of plant such as oil, peat and combined cycle gas turbines are used as base and medium loads and will not assist the System Operator in the balancing of the power in real time. These base and medium load plants will assist in the wind power balancing when the forecasting can predict the wind power accurately over a number of days and weeks. For this exercise only the OCGT units will be considered for wind power backup.

### *Backup Capacity - Energy Storage*

Within the Irish system there are plans to extend pumped hydro from the current 292 MW to 432 MW by 2020. The study completed by EirGrid on the potential benefits of pumped storage to Ireland (EirGrid, 2009) concluded pumped storage was not required to curtail large amounts of renewable technology penetration, which is perhaps the reason for the lack of investment in this area.

### *Backup Capacity - Summary*

This factor examines the level of wind against the targets set out in the National Renewable Energy Action Plan, and should targets in other areas not be met the value factor will decrease. Table 9 below gives the proportion of each generation method against wind power for 2020. The value for the backup factor shall be obtained based on the proportion of the technologies at the time of the site analysis compared to the values in Table 9. Each method (Other Renewables, Interconnector, OCGT and Energy Storage) will be given a value of 2.5 if they exceed the proportion and 0 if they do not. These proportions are the most important factors in the operation of the network for the future as they ensure that wind power grows proportionally with control of the grid, hence it will be given a weighing of 5.

**Table 9 Proportion of Generation Methods to Wind in 2020**

| **Generation Method** | **Degree of Utilization *** | **Maximum generator capacity (MW) **** | **Capacity Value (MW)** | **Total (MW)** | **Proportion of wind** |
|---|---|---|---|---|---|
| | | | | | |
| **Wind** | | | | 2073 | 100% |
| Onshore | 28% | 4737 | 1326 | | |
| Offshore | 31% | 2408 | 746 | | |
| **Other Renewable Technologies** | | | | 650 | 31% |
| Hydro | 60% | 216 | 130 | | |
| Ocean | 35% | 500 | 175 | | |
| Solar | 12% | 10 | 1 | | |
| Geothermal | 85% | 5 | 4 | | |
| Biomass | 85% | 400 | 340 | | |
| **Interconnector** | | 1000 | | 1000 | 48% |
| **Open Cycle Gas Turbines** | | 1233 | | 1233 | 59% |
| **Energy Storage** | | 432 | | 432 | 21% |

*Values taken from Leijon (Leijon et al., 2010).

** Values taken from Table 10 Non-Modeled 'Export Scenario' (DCENR, 2009).

## *Forecasting*

Test 4 concluded that windfarms located close together gave very similar levels of capacity values over the intervals examined. This suggests the forecasting of one windfarm located in a cluster of windfarms can lead to very accurate predictions, rather than windfarms scattered around the country which can lead to large forecast error. Forecasting is very expensive and that is why in 2008 the System Operator only modelled 21 of the 73 windfarms which gave day ahead accuracies of between 6% - 8% (SONI and EirGrid, 2008).

The factor considers not only the distance other windfarms are located from the site, but the size of the windfarms in the locality. Table 10 lists values given to this factor based on distance to other windfarms and the size of the windfarms within that distance. A site with 100 MW of maximum wind generator capacity within 5 Km will obtain a maximum value as the wind power forecasting of this new site will be predictable whereas a potential site with less than 40 MW of maximum wind generator capacity within 30 Km will obtain a zero value as the wind power forecasting will be difficult for that site.

The weighting for this factor is 4 because it is very important as the error prediction costs can reach up to 10% of the total generator energy incomes (Fabbri et al., 2005).

**Table 10 Factor Values for Forecasting**

| Maximum Generator Capacity (MW) | Distance to Windfarm (Km) | | | | |
|---|---|---|---|---|---|
| | **5 Km** | **10 Km** | **20 Km** | **30 Km** | **40 Km** |
| 20 MW | 4 | 2 | 0 | 0 | 0 |
| 40 MW | 6 | 5 | 2 | 0 | 0 |
| 60 MW | 7 | 6 | 4 | 2 | 0 |
| 80 MW | 8 | 7 | 4 | 2 | 2 |
| 100 MW | 10 | 8 | 5 | 4 | 4 |

## *Distribution of Windfarms*

Test 8 gave the centrally located windfarms as the key influencers on the capacity value of wind power, that is, the windfarms which are located centrally gave capacity values close to the combined capacity value of all the windfarms. The distribution of the windfarms is important as the wind speeds are rarely similar throughout the country. As the wind speeds throughout the country are rarely identical, distributing or spreading the windfarms throughout the whole country will increase the range of wind speeds, which will cause less variation in the total wind capacity value over time, allowing less complicated operation of the grid. Note the distribution of the windfarms does not increase the overall wind power capacity value, but does reduce the range of the capacity value and this in turn reduces the amount of reserve required for system operation.

To get a range of values for this factor it can be related to the distance from the centre of the country. The centre of the country can considered to be Athlone town, which will give a value of 0 for this factor. The values will increase by a value of 1 for every 20 Km distance between Athlone. Table 11 below displays the values for the factor against the distances from Athlone town.

It should be noted the factor for the distribution of windfarms can contradict the factor for extensions to windfarms, especially when an isolated location is examined and the cost of the connection of the network is compared against the balancing of the system. The distribution of the windfarms is considered to be more important, as according to the ILEX Report (ILEX Energy, 2002) for systems with high levels of wind power penetration the balancing and capacity costs dominate all other costs. For this reason the distribution of windfarms factor will carry a weighting factor of 3.

**Table 11 Factor Values for Distance from Athlone**

| Distance from Athlone Town (Km) | Value Factor |
|---|---|
| <20 | 1 |
| 20-40 | 2 |
| 40-60 | 3 |
| 60-80 | 4 |
| 80-100 | 5 |
| 100-120 | 6 |
| 120-140 | 7 |
| 140-160 | 8 |
| 160-180 | 9 |
| >180 | 10 |

### 3.4.5 Ethical

This metric considers the roll of the windfarm and its consequences on the Earth's atmosphere and local communities. These factors cannot be easily quantified but the introduction of renewable technologies to a region does have a positive effect on the lives of the people and the environment. Each of these factors will be given a weighting of 1, as they do not directly affect the power output of a potential site or the operation of the network.

### *Greenhouse Gas Reductions*

The reduction of Greenhouses Gases [GHG] is very important as it is believed to be the main cause of climate change. Although windfarms add carbon to the atmosphere during construction, they are carbon free once they begin operation. The larger the windfarm the larger the fossil fuel displacement and this is the basis of the values for this factor. The site will be given a factor value of 1 for every 10 MW of maximum generator capacity within the proposed windfarm up to a maximum value of 10.

### *Regional Development*

This factor is important of rural areas of the country which have high levels of migration due to low levels of employment. It is more important in the current climate as many young people are facing emigration due to the condition of the economy. The development of a windfarm can take a number of years from planning to construction creating many jobs locally. Turbines have life spans up to 30 years and require regular maintenance which can be supplied locally. The values of the factor will be similar to the GHG, given a value of 1 for every 10 MW of maximum generator capacity within the proposed windfarm up to a maximum of 10.

## 3.5 Outputs

The value for each factor can be inputted into the metric spreadsheet shown in Table 12 below. The spreadsheet is produced in Microsoft Excel and the value of each factor is multiplied by the weighting giving a factor score. Each factor score is then added for each metric and the total score is given for the windfarm at the bottom of the spreadsheet. The maximum score is 290 if all the factors give a maximum value of 10, although this is not possible as no locations can provide the maximum factor value. The maximum possible score is difficult to obtain without analysing all potential sites in the country however any site which can score in the region of 200 or above would be a worth pursuing.

The output can be used to analyse the suitability of the windfarm from the point of view of capacity output and system operation. A comparison of a number of similar windfarm sites can be completed to determine which location can be more appropriate for development.

Table 12 Spreadsheet for Analysing Potential Windfarms

| | | | | | |
|---|---|---|---|---|---|
| **Wind Farm Name** | | | | | |
| **Address** | | | | | |
| **Capacity** | | | | | |
| | | | | | |
| **Metric** | **Factor** | **Factor Value (1-10)** | **Weighting (1-5)** | **Score (1-50)** | **Total Metric Score** |
| | | | | | |
| **Geographical** | | | | | |
| | Wind Speed | | 5 | 0.00 | |
| | Orientation of Windfarm | | 4 | 0.00 | |
| | Terrain | | 3 | 0.00 | |
| | Distance to Network | | 2 | 0.00 | |
| | Potential for Expansion | | 1 | 0.00 | |
| | | | | | |
| | | | | **Total** | 0 |
| **Operational** | | | | | |
| | Backup Capacity | | 5 | 0.00 | |
| | Forecasting | | 4 | 0.00 | |
| | Distribution of Windfarms | | 3 | 0.00 | |
| | | | | | |
| | | | | **Total** | 0 |
| **Ethical** | | | | | |
| | Greenhouse Gas Reductions | | 1 | 0.00 | |
| | Regional Development | | 1 | | |
| | | | | | |
| | | | | **Total** | 0 |
| | | | | | |
| | | | | **Total Score for Windfarm** | 0 |

## 3.7 Summary

This chapter analysed the SEMO and Met Éireann data and, using the conclusions of the tests in addition to the previous research, developed a tool for analysing a potential windfarm site.

The SEMO data was validated using similar data available on the EirGrid website and both sets of data were then formatted to remove discrepancies which could prejudice the results. The analysis of the data was then performed and consisted of 8 tests to discover clusters, relationships and influencers within the data. These results and conclusions were used to develop the tool in the latter half of the chapter. The metrics for the tool are 1) Geographical, 2) Operation and 3) Ethical. The Geographical metric consists of 5 factors which influence the output of a windfarm and include wind speed, orientation, terrain, distance to the network and expansion potential. The Operation metric deals with the operation of the network with a high penetration of wind power and consist of backup capacity, forecasting and the distribution of the windfarms. The Ethical metric includes factors such as greenhouse gas reductions and regional development. Each factor is given a range of values and given a weighting to compare to the other factors in the tool. The tool was then developed as a spreadsheet in which a value for each factor is inputted. The output of the spreadsheet presents a score which can be used to compare a number of potential windfarm sites to find the most suitable location for development.

# 4. Windfarm Site analysis using Spreadsheet

This chapter will investigate a number of windfarm sites to assess the tool developed in Chapter 3. The process of information gathering for the spreadsheet will be explained and a step by step procedure for one of the sites will be described in detail.

The chapter begins describing the sites which will be analysed by the tool. The sites consist of operational windfarms and a number of fictitious randomly chosen sites. The operational windfarms will include new build and additional phases to existing windfarms given in the SEMO data which were not analysed in earlier chapters. The fictitious windfarms will contain sites close to large urban areas, midland and coastal areas, to give the range of possible outputs from the tool. The resources which obtain the information required for the input data to the spreadsheet will be described in Section 4.2. These consist of the many existing information resources, many of which are available online and free to use. Following this a step by step demonstration of a windfarm site will be discussed in detail. It describes the procedure required to use the tool using all the resources and calculating the values for each factor.

## 4.1 Sites to be tested

Table 13 below lists the sites that were analysed using the spreadsheet. The sites are located throughout the country, are of various sizes and are a mixture of real and fictitious windfarms.

Coomagearlahy, also known as Kilgarvan, is 42.5 MW windfarm located in the Derrynasaggart mountains in Co. Kerry and is owned and operated by SWS Natural Resources. Phase 3 is the second addition to the windfarm and consists of 10 turbines with a maximum generation capacity of 30 MW and became operational in 2009.

Flughland Windfarm Phase 1, which is also owned and operated by SWS Natural Resources, is a 4 turbine windfarm with a maximum generation capacity of 9.2 MW. The windfarm is located near Sorne Hill on the Inishowen Peninsula in Co. Donegal and begun exporting power in 2009.

Lisheen Windfarm is an 18 turbine 36 MW windfarm located in Co. Tipperary. This windfarm has been chosen for the demonstration and a further summary is detailed in Section 4.3.

The latter 3 windfarms are fictitious and were created to compare and contrast different locations using the spreadsheet. Knocktopher Phase 1 is a 40 MW windfarm with a south orientation located in the lowlands of Knocktopher Co. Kilkenny. The average wind speed in the area is 6.5 m/s which has the lowest of the sites tested.

Kilmashogue Phase 1 is a 20 MW windfarm with a south orientation on Kilmashogue Hill in south Dublin, close to Dublin city. The windfarm is located in a wooded area and has an average wind speed of 9 m/s.

The final site to be analysed is Knockanore Phase 1, a 100 MW windfarm located on Knockanore Hill in north Kerry, close to the Atlantic Ocean. The average wind speeds are the highest of all the analysed sites at 10.25 m/s and the turbines have a southwest orientation.

**Table 13 Detail on Sites Analysed using Spreadsheet**

| Item | SEMO Facility Name | Unit Name | Maximum Generator Capacity (MW) | County |
|---|---|---|---|---|
| 1 | GU_400731 | Coomagearlahy Phase 3 | 30 | Kerry |
| 2 | GU_400800 | Flughland Phase 1 | 9.2 | Donegal |
| 3 | GU_400840 | Lisheen Phase 1 | 36 | Tipperary |
| 4 | Fictitious | Knocktopher Phase 1 | 40 | Kilkenny |
| 5 | Fictitious | Kilmashogue Phase 1 | 20 | Dublin |
| 6 | Fictitious | Knockanore Phase 1 | 100 | Kerry |

## 4.2 Sources of Information for Input Data

The input data required for the spreadsheet is obtained from a number of existing online resources detailed below. The tool utilises existing resources which are available free of charge and online, which make the process of analysis inexpensive and fast. The geographical data is available through sources such as the planning authorities, Sustainable Energy Authority Ireland, Ordnance Survey Ireland and EirGrid. The Operational data is obtained from the System Operator, EirGrid, and the Ethical data is based on the maximum generator capacity which is known for the analysis. Below is a description of where to find the information required for the spreadsheet input.

### *Planning Authority*

The planning applications for most windfarm developments are available to view online on the local planning authority's website. Most authorities have an online live planning database which allows third parties to locate the site using a Geographical Information System [GIS] and view the application. Within the planning application the drawings which illustrate the layout of the turbines are available. These drawings are used to estimate the optimum direction for the turbines which is used for the orientation factor. The precise location of the windfarm is also given in the planning application which will be used for the other such as the SEAI Wind Map and the Ordnance Survey

Ireland [OSI] satellite images. This resource is also used when exploring the possible expansion of a windfarm to ensure any adjacent land to the windfarm can apply for planning permission.

Each planning authority has a different system for planning enquiries and in some instances the information may not be available online. In these circumstances it is possible to write to the planning office and request the drawings, although this would be slow procedure and charges may be applied.

### *SEAI Wind Map*

In 2003 the SEAI completed a wind map for the country which provides detailed information on wind speeds for every location within Ireland. The Wind Map was developed by Truewind Solutions and ESBI Engineering. The map consists of GIS data files of mean wind speed at heights of 50 m, 75 m and 100 m above ground on a 200 m grid covering Ireland and points up to 20 Km offshore on a 400 m grid. The Wind Map is available to view on the SEAI website (http://maps.seai.ie/wind) and is free of charge to use. The Wind Map also provides onshore electoral and authority divisions, conservation and protected areas, locations of Irish Wind Energy Association [IWEA] windfarms, and offshore navigation channels and departmental exclusions zones. For this exercise only the wind speeds at a height of 50 m will be used for the tool.

### *Ordnance Survey Ireland*

OSI are the national mapping agency of Ireland and have a comprehensive range of digital mapping services available online. Using the public viewer in the OSI website (http://maps.osi.ie) the terrain of an area may be examined. The ORTHO 2005 viewer is collection of orthophotography released in 2005. This is the most recent free of charge imagery available from the OSI and may be inaccurate as the terrain of an area may have changed over the last five years.

### *Google Maps*

Google Maps is a basic web mapping service application provided free of charge by Google. This technology is used to measure the distance between the proposed windfarm site and other items such as 1) the transmission network, 2) other windfarms and 3) the centre of the country. The distance can be measured accurately using the My Maps section in the website. This gives measurement in miles which can be easily adapted to Km by multiplying by $^5/_8$.

### *EirGrid*

EirGrid, the System Operator, offers a number of input data requirements for the tool such as the Transmission Map and the connected generation technologies. The All-Island Transmission System Map illustrates the transmission system, 110 kV and higher, for the whole island as operated by EirGrid in the Republic and SONI in Northern Ireland. The latest version of the map was released in January 2010 and is available for download on the EirGrid website (http://www.eirgrid.com). This map is used to locate the closest point of connection for the proposed windfarm site to the transmission network. The point of connection is recorded and the distance between both points can be measured in Google Maps for use in the Distance to Network factor.

The EirGrid website also provides data on the connected generators to the Irish network which is required for the Backup Capacity and Forecasting factors. The document entitled 'Irish Electricity System Summary of all Generators', which is regularly updated on the website, gives the Maximum Export Capacity [MEC] and details on the fuel type for each connected generator to the grid.

## 4.3 Analysis of Lisheen Windfarm using Spreadsheet

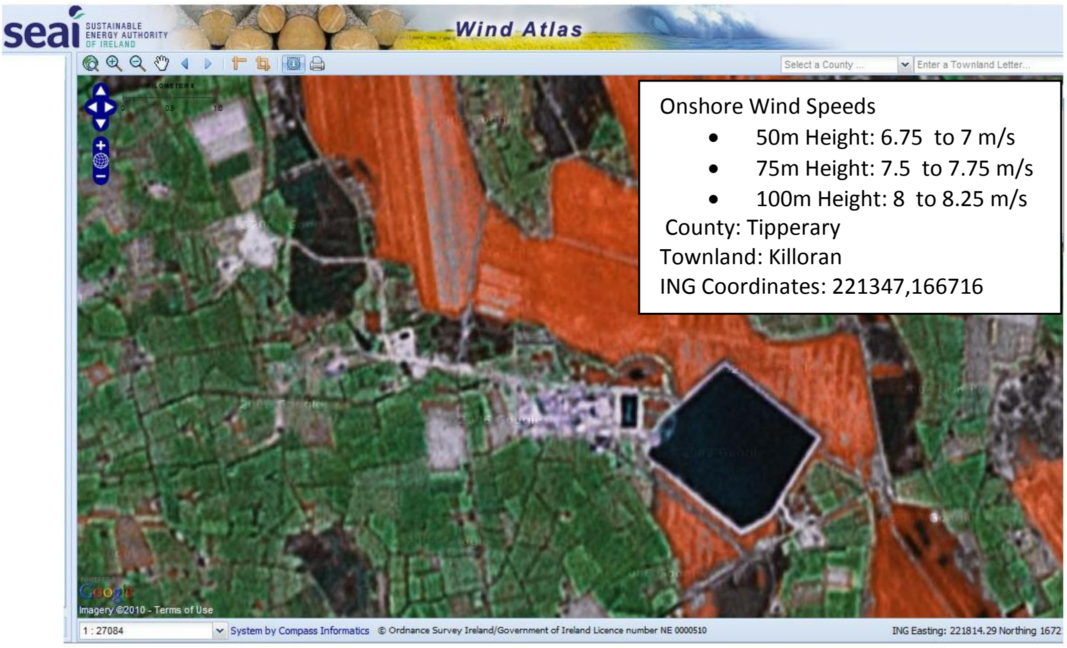
The following sections are a step by step demonstration of the use of the spreadsheet for a windfarm which has been developed in the last number of years. The site chosen for this exercise is Lisheen Windfarm which is located on the site of the Lisheen Zinc Mine in Co. Tipperary. The windfarm was acquired by SWS Natural Resources in 2008 and became operational in April 2009. It is located on the townlands of Barnalisheen, Cooleeny, Derryfada, Derryville and Killoran and consists of eighteen 2 MW turbines with a combined maximum capacity of 36MW. Planning permission was granted by North Tipperary County Council in January 2007 and the application file number is 06510773. As the windfarm is spread over a large area, variables such as wind speed and terrain may vary so the location of Turbine no. 14 was chosen for the analysis.

### 4.3.1 Geographical

#### *Wind Speed*

Using the SEAI Wind Map the average wind speed was observed for the location of the windfarm and is shown in Figure 14 below. The wind speed at height of 50 m above ground lies between 6.75 m/s to 7 m/s. The upper wind speed is used for this area and when multiplied by $\left({}^{1}/_{1.4}\right)$ gives a value of 5 for the Wind Speed factor.

Figure 14 SEAI Wind Map for Lisheen Windfarm




### *Orientation of Windfarm*

The orientation of the windfarm was examined from the plans of the windfarm which were obtained from the planning application. Using the application file number the planning files were viewed on the North Tipperary County Council website. Within the drawings submitted in the application was the Index to Site Location Map and this gives the position of each of the 22 turbines. The optimum direction of the turbines was examined and this is indicates by the red line on Figure 15. The orientation can be observed as a southwest (or northeast) direction. The value for this factor can be taken from Table 5 which gives a value of 10.

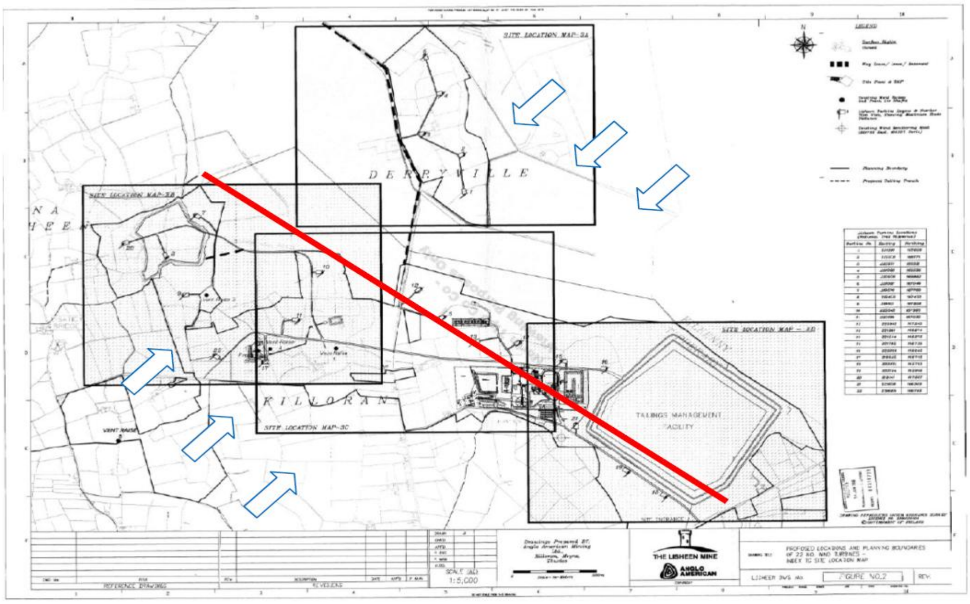



Figure 15 Index to Site Location Map for Lisheen Windfarm with Orientation Line

### *Terrain*

The terrain was determined by studying the orthophotograph taken in 2005 which is available on the OSI map. Studying Figure 16 it can be noted the area is made up of fallow fields, crops and few trees and using Table 6, a value of 4 is obtained for the Terrain factor.


**Figure 16 Orthophotograph of Lisheen Windfarm (OSI ORTHO 2005 map)**

### *Distance to Network*

This factor examines the distance to the transmission network as shown in Figure 11. Note the Transmission Map detailed in Figure 11 was updated in January 2010 but as this windfarm was operational prior to that date the network prior to the construction of this windfarm must be examined. The transmission network was connected to Lisheen Mine prior to the construction of the windfarm due to the nature of the industry which gives a distance of less than 10 Km. The factor value is obtained from Table 7 and the value for this factor is 10.

For analysis of a potential windfarm Google Maps may be used to measure the distance between the Transmission Network and the site.

### *Potential for Expansion*

This factor requires examination of the area surrounding the windfarm. Using the GIS in the North Tipperary County Council website the area adjacent to the windfarm was examined for restrictions and zoning. The access to the adjacent lands and the terrain were examined on the OSI orthophotograph in Figure 16. It was concluded from these analyses that there were no obvious obstructions for expanding the windfarm further do a value of 10 was given for this factor.

## 4.3.2 Operational

### *Backup Capacity*

In 2009 wind power contributed less than 10% of the electricity production in Ireland which would suggest no problems with capacity backup. The proportions of the four generation methods were compared to wind power before the Lisheen windfarm became operational in April 2009. Table 14 below is a summary of these figures based on the template shown on Table 9 in the previous chapter. In 2009 it can be seen the proportion of other generation methods compared to wind power are much higher than 2020 levels. This suggests there is ample amount of capacity backup for safe operation of the grid with the levels of wind power in operation. Each generation method obtains a value of 2.5 giving an overall value of 10 for this factor.

**Table 14 Proportional of Generation Methods to Wind in 2009**

| **Generation Method** | **Degree of Utilization *** | **Maximum generator capacity (MW)** | **Capacity value (MW)** | **Total (MW)** | **Proportion of wind in 2009** | **Proportion of wind in 2020 **** |
|---|---|---|---|---|---|---|
| | | | | | | |
| **Wind** | | | | 262 | 100% | **100%** |
| Onshore | 28% | 909 | 255 | | | |
| Offshore | 31% | 25 | 8 | | | |
| | | | | | | |
| **Other Renewable Technologies** | | | | 130 | 49% | **31%** |
| Hydro | 60% | 216 | 130 | | | |
| Ocean | 35% | 0 | 0 | | | |
| Solar | 12% | 0 | 0 | | | |
| Geothermal | 85% | 0 | 0 | | | |
| Biomass | 85% | 0 | 0 | | | |
| | | | | | | |
| **Interconnector** | | | | 450 | 171% | **48%** |
| | | | | | | |
| **OCGT** | | | | 824 | 314% | **59%** |
| | | | | | | |
| **Energy Storage** | | | | 292 | 111% | **21%** |

*Values taken from Leijon (Leijon et al., 2010).
** Figures were calculated in Table 9

### *Forecasting*

At the time of planning this windfarm the majority of the windfarms were built on the North and West coast of Ireland. This would suggest there would be few windfarms in the vicinity of Lisheen and it would get a low score for this factor. There was 934 MW of wind power operational for the time of this analysis which consisted of 37 windfarms. Of these windfarms, the closest windfarm to Lisheen windfarm was Derrybrien Windfarm which is located over 70 Km away in Co. Galway. This distance creates difficulties with forecasting of the windfarm power output and using Table 10 this factor receives a value of 0.

#### *Distribution of Windfarm*

Lisheen Windfarm is located in North Co. Tipperary and is close to the centre of the country so it was expected to get a low score in this factor. With the assistance of Google Maps the distance between Lisheen Windfarm and Athlone Town is 48 miles or 77 Km. Using Table 11 this gives a value of 4 for this factor.

### 4.3.3 Ethical

#### *Greenhouse Gas Reductions and Regional Development*

Lisheen Windfarm has a maximum capacity of 36 MW and this gives values of 3.6 for each of the factors in this metric. The 36 MW of wind offsets approximately 10 MW of fossil fuel generation which decrease the greenhouse reductions for electricity generation. The planning, construction and operation of the 22 turbines have created jobs locally which help with the economic and social development of the local area.

## 4.4 Summary of Chapter

This chapter analysed the spreadsheet developed in Chapter 3 using a number of windfarm sites. It began by selecting 6 sites for the investigation. Three of the sites consisted of windfarms which have begun operation in the last 12 months and the latter 3 windfarms were potential sites located in three different areas of the country. This was followed by a brief description of the sources of the information required to value the factors in the spreadsheet. They consisted of existing, free of charge resources which are available on the World Wide Web for straightforward and fast recovery of the information. Public service organisations such as the SEAI, OSI, EirGrid and planning authorities form the basis for the information collecting while tools available such as My Maps on Google Maps help extrapolate the data required for the spreadsheet. To demonstrate the procedure involved in implementing the spreadsheet, one of the sites is chosen and the method of operation is described in detail. Each metric and factor for Lisheen windfarm is valued using the methods as described in the previous sections and the results are displayed and discussed in the following chapter.

# 5. Results and Analysis

This chapter presents and discusses the results obtained from the spreadsheets for the sites analysed. Firstly the spreadsheet for Lisheen Windfarm is shown and the value provided for each factor is discussed. The results of all the sites analysed are then summarised followed by a detailed discussion on the differences between the scores of each of the sites and the factors which differed between each site. The optimum site location for the spreadsheet is then considered based on the scoring within the spreadsheet. This is followed by a critical observation of the spreadsheet and its limitations in the selection of potential windfarm sites. The chapter concludes exploring the possible metrics that have been excluded from the spreadsheet and the way in which they may be included in future revisions of the tool.

## 5.1 Lisheen Windfarm Phase 1

Table 15 below is the spreadsheet for Lisheen Windfarm. Lisheen windfarm scores 176 which is made up of: 107 out of a possible 150 for the Geographical metric, 62 out of a possible 120 for the Operational metric and 7 out of a possible 20 for the Ethical metric. The wind speed factor only scores 4.9 as the average wind speed the area is 7 m/s which is a little above average for the country. This is due to the fact Lisheen is located considerably inland and also on low lying land. The orientation of the windfarm scores top marks as the layout of the turbines face the prevailing winds. The terrain consists of trees and hedges, which is the norm for farmland, and this causes resistances which slow the wind speeds and causes turbulence, hence the low value of 4 for that factor. There is a transmission station located at the zinc mine next to the windfarm which is gives the factor a value of 10. The potential for expansion also scores full marks as there is ample amount of land next to the windfarm that could be developed without any difficulty. It was noted during the investigation into the area surrounding the windfarm, that SWS Natural Resources have applied to the planning authority for an extension to the windfarm.

The Capacity Backup factor received a value of 10 due to the low levels of wind power on the grid in 2009, before the windfarm became operational. Lisheen obtained a value of 0 for the Forecasting factor because there are no windfarms close to it. This implies a separate forecast would have to be completed for the windfarm every day or the forecasting could be combined with its closest neighbours, in which case the forecast error would be large leading to additional operational costs. The scoring for the last metric, which deals with the ethical issues of the windfarm, is based on the size of the windfarm.

**Table 15 Spreadsheet for Lisheen Windfarm Phase 1**

| | | | | | |
|---|---|---|---|---|---|
| **Wind Farm Name** | Lisheen Windfarm Phase 1 | | | | |
| **Location** | Lisheen Co. Tipperary | | | | |
| **Capacity** | 36 MW | | | | |
| | | | | | |
| | | | | | |
| **Metric** | **Factor** | **Factor Value (1-10)** | **Weighting (1-5)** | **Score (1-50)** | **Total Metric Score** |
| | | | | | |
| **Geographical** | | | | | |
| | Wind Speed | 4.9 | 5 | 24.50 | |
| | Orientation of Windfarm | 10.0 | 4 | 40.00 | |
| | Terrain | 4.0 | 3 | 12.00 | |
| | Distance to Network | 10.0 | 2 | 20.00 | |
| | Potential for Expansion | 10.0 | 1 | 10.00 | |
| | | | | | |
| | | | | **Total** | 107 |
| **Operational** | | | | | |
| | Backup Capacity | 10.0 | 5 | 50.00 | |
| | Forecasting | 0.0 | 4 | 0.00 | |
| | Distribution of Windfarms | 4.0 | 3 | 12.00 | |
| | | | | | |
| | | | | **Total** | 62 |
| **Ethical** | | | | | |
| | Greenhouse Gas Reductions | 3.6 | 1 | 3.60 | |
| | Regional Development | 3.6 | 1 | 3.60 | |
| | | | | | |
| | | | | **Total** | 7 |
| | | | | | |
| | | | | **Total Score for Windfarm** | 176 |

## 5.2 Summary of Sites Analysis

Table 16 below is the summary of the results for all of the sites analysed with the spreadsheet. The highest scoring site was Coomagearlahy Phase 3 with a score of 221, followed by a score of 217 for Knockanore Phase 1. The third placed windfarm was Flughland windfarm at 198 and the lowest scoring sites were was Kilmashogue with 169 and Knocktopher with a score of 163. The following section compares the metric values for the sites as illustrated in Figure 17.

Table 16 Summary of Analysis of Windfarm Sites using Spreadsheet

| Item | Facility Name | Unit Name | Maximum Generator Capacity (MW) | County | Score |
|---|---|---|---|---|---|
| 1 | GU_400731 | Coomagearlahy Phase 3 | 30 | Kerry | 221 |
| 2 | GU_400800 | Flughland Phase 1 | 9.2 | Donegal | 198 |
| 3 | GU_400840 | Lisheen Phase 1 | 55 | Tipperary | 176 |
| 4 | N/A | Knocktopher Phase 1 | 40 | Kilkenny | 163 |
| 5 | N/A | Kilmashogue Phase 1 | 20 | Dublin | 169 |
| 6 | N/A | Knockanore Phase 1 | 100 | Kerry | 217 |

The chart in Figure 17 compares the scores obtained by the sites for each metric on the spreadsheet. Note the possible maximum scores for each metric are different so each metric score should not be compared to one another. The scores within each metric however can be compared as they differ due to the different characteristics of the each site.

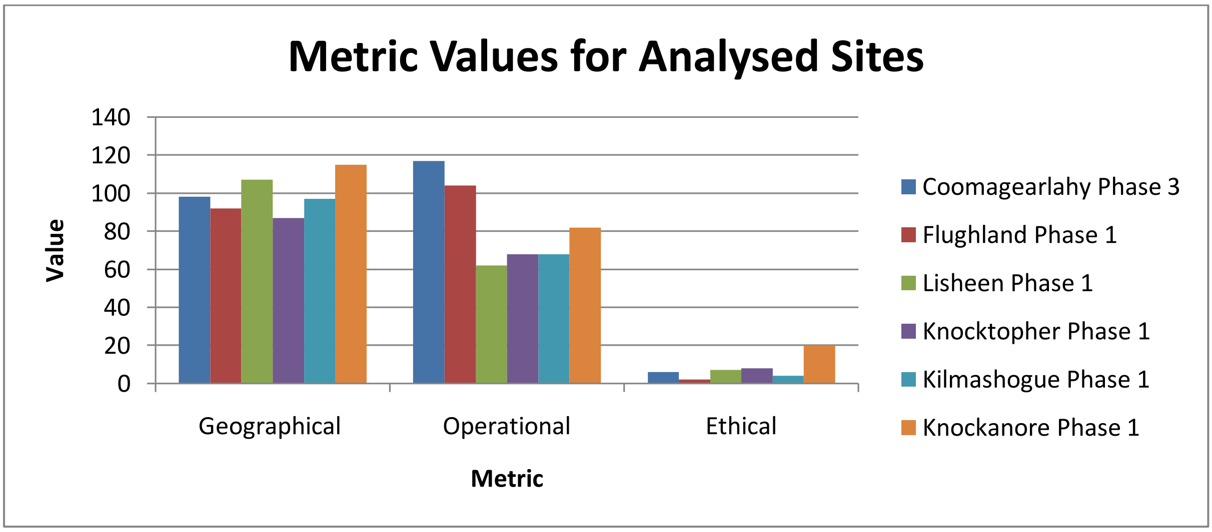



Figure 17 Metric Values for Analysed Sites

### *Geographical Metric*

The range of values scored by the sites for this metric was close, ranging from 87 to 115 for Knocktopher and Knockanore sites respectively. The Knocktopher site was chosen as the area did not have a good wind resource and even though it is located close to the network it scored poorly in this metric. Knockanore windfarm had the best wind resource of the sites and this is shown with the highest scoring geographic metric.

### *Operational Metric*

Coomagearlahy and Flughland outscored the other sites by a noticeable amount due to the fact that they are located on the perimeter of the country and a number of large windfarms are located close to them. This supports the hypothesis from Chapter 3 regarding the total wind capacity range and the importance of wind power forecasting. Note the Backup Capacity factor could not be examined in detail, as all of the sites were analysed based on the wind power levels in 2009 and 2010 and received a value of 10. This factor examines the level of wind against the targets set out in the National Renewable Energy Action Plan, and should targets in other areas not be met the factor will expose this. It will only become effective in the future when the wind levels rise to 2020 target levels.

### *Ethical Metric*

As expected the largest windfarm, Knockanore, scored the highest values for this metric as it offsets a larger amount of carbon and creates more local employment due to economy of scale.

## 5.3 Optimum Site Location

To perform a critical analysis of the spreadsheet, the optimum site for a windfarm must be considered. The optimum site location would be a location which obtains the maximum possible values for each factor. As mentioned earlier it is impossible to get the maximum score for all factors as there are a number which contradict each other in some form. An example of this is the wind speed and distance to the network. The highest wind speeds are achieved in the highest, most remote parts of the country and unless a windfarm has been developed close to these sites previously there is no network close by. The optimum windfarm site will possess the following features:

1. High wind speeds of 11 m/s or greater to score at least a value of 8 for this factor. The highest value for this factor is achieved on Slievemore in Achill Island of the coast of Mayo which has an average wind speed of 13.75 m/s on its peak.

2. Turbines facing southeast to the prevailing wind. This is not related to the site but the design of the turbine layout.

3. The area surrounding the windfarm has little resistance to the wind, caused by buildings, trees and hedges. The highest value for this factor is given to an offshore location.

3. A transmission station to be located within 10 Km which reduces line losses and simplifies connection to the network. The transmission network is shown in Figure 11.

4. Excellent Expansion potential. This indicated there are no planning or access issues with extending the site development in the future.

5. There is a good level of supply from other renewable technologies, interconnector, OCGT and energy storage. This factor will obtain high values should the proportion of wind remain manageable by the system operator.

6. There is a large amount of wind power generation in the area surrounding the site which would ensure inexpensive operating costs due to group forecasting and a small forecasting error.

7. The windfarm is located close to the coast of the country, over 180 Km from the centre, which would decrease the amount of reserve required and hence operating costs.

8. The windfarm has a large output of 100 MW or above, which would offset up to 30 MW of fossil fuel plant and would assist in developing the local area.

The features described above do not carry equal importance in the spreadsheet due to the weighting system, so emphasis must be placed on the factors with the highest weighting when locating the optimum site. The optimum site is one which scores high on all factors as shown in the example sites analysed.

## 5.4 Limitations of Spreadsheet

The spreadsheet contains a number of limitations due to its original scope, the assumptions made, and the weightings of the factors, all which may have lead to bias results. In examining the results obtained earlier in the chapter, a number of limitations of the spreadsheet were observed. Below is description of a number of these:

### 5.4.1 Scope of the Spreadsheet

To get a complete overview of a proposed windfarm site every variable which is likely to affect the outcome of the development must be examined. There are a large number of stakeholders involved in a windfarm and many of them are listed below (not in order of importance):

Land owners, windfarm owners, developers, designers, project managers, contractors, financers, operation companies, local residents associations, electrical network operator, electrical network owner, electrical market operator, government including departments, local authorities, environmental stakeholders, conservationists, energy companies, meteorologists, the public, fuel importers and turbine manufactures.

Many of the stakeholders have no input into the spreadsheet but do have an influence on the windfarm. Every stakeholder has their own agenda and many of the groups have enough influence to obstruct or even prevent the development from taking place. One major limitation of the spreadsheet is that it does not represent all stakeholders. Including all stakeholders into the process would involve analysis in the areas of finance, government policy, economics, public attitude, impacts of development and technology, to name a few. These areas were excluded from the scope of the project as there was insufficient time to examine them.

The scope of the spreadsheet was also limited to the data availability. The SEMO and Met Éireann data analysed in Chapter 3 did not contain information regarding the issues of finance, policies, attitudes and impacts. Additional data would have to be obtained through primary or secondary sources for further analysis. It should also be noted the tests carried out in Chapter 3 consisted of limited data from 2008 and 2009 which only represents a sample of the possible recorded data.

The software may also have limitations, although there were none discovered in this project. The software was developed for financial analysis such data mining a customers buying habits in supermarkets. The software was not presented for use in scientific research which may query its use in this research.

### 5.4.3 Assumptions made on Spreadsheet

There were a number of assumptions made to estimate values within the spreadsheet. The first assumption made was the orientation of the windfarm. Test 6 gave the wind direction as a key influencer to the power output of a windfarm. It was assumed this result was caused by the optimum direction the turbines were designed towards and this was compared to the prevailing wind directions to value the factor.

For the factor regarding the distribution of the windfarms, the value of the factor is determined by measuring the distance of the windfarm from the centre of Ireland. One assumption is that Athlone is the centre of the country. Athlone is not the exact centre of the country but the fact the ranges of distance from Athlone, as per Table 11, are in space of 20 Km this reduces this error. This factor does not take into account the prevailing wind which should influence the distribution of windfarms throughout the country.

### 5.4.2 Weighting Factors in the Spreadsheet

The weightings of the factors create a natural bias on the spreadsheet results. They favour particular factors such as wind speed of a site and backup capacity of the network, and devalue factors such as greenhouse gas reductions and regional development. The influences of the factors were determined using the conclusions from the papers examined in Chapter 2 and the tests performed in Chapter 3. With the inclusion of many more metrics the weighting factors could be recalculated, perhaps on the basis of the influence on the stakeholder.

## 5.5 Additional Metrics to Consider

To increase the scope of the spreadsheet to include more stakeholders, additional metrics could be developed for the spreadsheet. The following is a description of some of the metrics that could be included to increase the involvement in the spreadsheet:

### *Finance*

This metric would look the whole financing of a development including the land, construction and operational costs, and the cost of the capital finance. It could compare these costs to power purchase agreements, government tariffs and carbon credits over the lifetime of the development. This metric would be the basis for any assessment a commercial company will complete during the investigation of a potential windfarm development.

### *Attitudes*

This metric does not seem important but the attitudes of local residents and even the majority of the citizens in the country can influence policy makers, from local to central government. The SEAI complete a survey in people's attitudes towards the development of wind farms in Ireland (SEI, 2003) and concluded that although in general people were positively disposed towards wind farms they had many concerns with them. This metric could be combined with the Ethical metric as it can consider peoples values, including their opinion on issues such as greenhouse gas reductions and regional development.

### *Technology*

Wind power is considered mature technology as wind turbines have been designed to generate electricity since Charles Brush's 12 KW wind turbine built in 1888. As discussed in Chapter 1 there are issues surrounding the integration of wind power to the grid due to wind turbines supplying incorrect frequency and power factor. These problems are increased when high levels of wind power are connected to the grid. Selection of turbine for the windfarm could be considered to examine the characteristics of the turbine with respect to minimising these issues.

The above metrics could be included in the existing metrics or become their own entities. Creating the factors including values and weightings would require further research which is discussed in the concluding chapter.

## 5.4 Summary

The spreadsheet completed for Lisheen Windfarm Phase 1 was displayed at the start of this chapter and each metric concerning the site was discussed. Lisheen scored a value of 176 which was a mediocre score when compared to the others. The site competed favourably in some aspects but failed to score highly in factors such as wind speed, terrain, distribution of windfarms and forecasting. The reasons for the first 3 items were due to the location of the windfarm and the wind resource available, the landscape of the locality and the central location in the country. The forecasting factor scored poorly due to its isolation from other windfarms. The other sites which were analysed using the spreadsheet were then summarised and the metric scores were compared. Coomagearlahy Phase 3 produced the highest score which places it as the most suitable site to develop a windfarm. Following this, the characteristics of the optimum site are considered from the perspective of each factor. This section leads into the limitations of the spreadsheet and the causes of them. The scope and assumptions of the spreadsheet were discussed and the weighting factors were assessed. The chapter terminated with a look at further metrics that could be included in the spreadsheet and the research required allowing them to participate.

# 6. Summary and Conclusions

## 6.1 Goals Achieved

This paper set out to investigate the issues surrounding wind power and the operation of the Irish electrical system with large levels of the intermittent power. The goals as stated in Chapter 1 are reviewed below and the work completed in achieving these goals is explained.

***Goal 1: To research and analyse the key fundamental factors which influence power output from wind farms in Ireland*.**

The factors which influence power output from windfarms were discussed in Chapter 2, firstly by splitting up the equation which defined the power output that can be extracted from the wind, and secondly describing the conditions which affect each of these variables. The variables contained in the equation are wind speed, air density, rotor area, power co-efficient of the rotor and drive train efficiency. The latter 3 variables were dismissed as they are defined by the technology of the turbine, which was not within the scope of the project. The remaining variables are dependent on weather conditions so data was requested from Met Éireann on the weather recordings for a number of weather stations throughout the country. Data was also requested from the SEMO on the power supplied to the SEM by all generation facilities over a two year period. Using the Table Tool Analysis software the key influencers on the output of windfarms were determined. The results of these tests supported the previous chapters' conclusions and also lead to other variables influencing the windfarm output such as wind direction.

***Goal 2: To accurately classify, compare and distinguish each of the following combinations of energy production with that of wind generation to increase reliability, availability and efficiency of wind power on the grid against the patterns for national consumption:***

I. ***Mixing with other renewable technologies.***

II. ***Combining with the interconnector.***

III. ***Using Fossil Fuel as capacity backup.***

IV. ***Stabilising with Energy storage***

Chapter 2 briefly discussed the generation methods listed above, their relationship with wind power and their current levels of generation in Ireland. Renewable technologies which convert energy directly from the resource are intermittent and cannot fully replace conventional generation. A measure of the capacity of each technology called the Degree of Utilization is used to quantify the amount of conventional generation which can be offset by the renewable facilities.

The interconnectors between the Irish and UK grids were identified and the import and export power capacities that can be transferred between them were discussed. Recent studies carried out, examining the roll of the interconnector with large levels of wind power on the Irish grid, suggest a limit on the amount of power the Irish grid can import before the system becomes unstable. The roll of conventional generation to act as capacity backup for the network with high penetrations of intermittent power was examined. Open Cycle Gas Turbines were studied in detail as this is the best possible option to offer this service. The different available methods of energy storage were described including the existing facilities in Ireland and possible future developments that could become necessary.

***Goal 3. To develop an effective tool, system or technique, incorporating the key influencing metrics that could be used for balancing high levels of wind power generation onto the national grid.***

Using the conclusions of the research in Chapter 2 and the tests carried out in Chapter 3, a tool was developed which contained the key influencers that could be used to balance a network with high penetrations of wind power. The tool is structured as a spreadsheet to analyse a potential site that could be developed as a windfarm. It includes geographical, operational and ethical metrics which examines the suitability of the site and network for a windfarm development. The geographical metric investigates the environmental and physical features of the site. The operational metric evaluates the site with regard to the operation of the network and the ethical metric considers the consequences of the windfarm on the local region and environment. Each metric is divided into a number of factors which have weightings depending on the influence on the metric. The values for each factor are calculated from the physical aspects of the site, windfarm and network. This information is obtained from a number of existing resources that are available to access online and are free of charge to use. The output is achieved by analysing the factors and inputting values into the spreadsheet, which automatically calculates a score for the windfarm based on the weightings of the factors. The output is a score which can be compared to existing or rival windfarm sites.

***Goal 4. To evaluate and appraise the developed tool, system or techniques' ability to accurately, effectively and successfully integrate high levels of wind power generation onto the national grid, by using available stored data from existing sites and modelling scenarios.***

In Chapter 4 a number of sites, including existing and fictitious windfarms, were described and analysed using the spreadsheet. The results were presented and evaluated in Chapter 5 including a comparison of the site scores. Following this, a thorough examination was carried out on the spreadsheet, exploring its optimum site location and its limitations. These limitations included issues surrounding the scope of the spreadsheet, the assumptions made and the weighting method used. Additional metrics were discussed which could possibly give a better overall analysis of the sites although many of these areas were outside the scope of the project.

## 6.2 Conclusions of Research

This dissertation has successfully created a spreadsheet which can analyse a potential windfarm site for comparison with existing and other prospective sites. The geographical, operational and ethical issues are examined and a score is given for the suitability of the site as a potential windfarm development. This score can then be compared to other sites to locate the most suitable for development. The tool was developed through an extensive literature review followed by detailed analysis carried out on recorded data received from government agencies.

The paper provided the background for wind power, the existing levels and 2020 targets for the Irish network and the issues surrounding wind power. The key issue surrounding wind power is the intermittency and the causes of this occurrence were comprehensively researched. Following this the relationship of wind power with other technologies and the network were examined, and the effect it has on the operation of the system. It was realised that the stability of the system with high levels of wind penetration was dependent on having a diverse amount of generation technologies such as other renewable technologies, interconnection to other systems, conventional generators such as OCGT and energy storage.

Data received from the SEMO and Met Éireann over a two year period was examined with Table Tool Analysis software using Microsoft Excel and SQL Server. It was proven using these analysis systems that the wind speed is the key influencing factor on the output of a windfarm. Further analysis on the key influencers established wind direction as the second most influential factor on the output of a windfarm and the prevailing wind direction for the data received is southwest. The outcome for analysing the relationship between capacity values of windfarms concluded that the windfarms located close to each other produced similar capacity values. It was also shown that windfarms located in the centre of the country gave similar capacity values to the combined capacity value of wind power at any given time. This concluded that the location of a windfarm influences the range of capacity value for wind power, which varied between 0% and 92% for the data analysed.

The spreadsheet was developed using the conclusions of the analysis tests and the research of the previous chapters to include three metrics: geographical, operational and ethical. A number of existing and fictitious sites were examined using the spreadsheet and the results gave a clear indication of the more suitable locations for windfarm development. Critical analysis of the spreadsheet concluded that as it did not represent all stakeholders it is not a comprehensive analysis tool for a windfarm site. The limitations of the tool were due to the scope, assumptions made and the weighting dynamics used throughout the development of the spreadsheet. The following section discusses additional research which could improve the tool in the future.

The spreadsheet can be used by a number of stakeholders when assessing a windfarm. The System Operators can rank windfarm sites in order of suitability when there is a large amount of windfarms seeking a network connection. Windfarm developers can use it to locate the optimum windfarm site when assessing a number of potential sites for windfarm development. Local Planning authorities can use the tool to establish areas of good windfarm potential to include in their County Development Plan.

## 6.3 Future Research

As the level of wind power penetration increases on the Irish network in the coming years the extent of the issues discussed throughout this paper will be realised. Load control in real time is the single biggest issue with the intermittent power, although if emphasis were placed on user scheduling combined to wind forecasting, this may be effortlessly controlled. As the project developed, some of the tests provided interesting results which could have been investigated further if not for the time limit and scope of the project. Below are a number of topics which could warrant further study in the future.

***1. Addition of new Metrics into the Spreadsheet:*** A comprehensive study to include all stakeholders of a windfarm can be completed and any additional metrics that would be produced from this study could be added to the spreadsheet. Metrics that include the subjects of finance, attitudes and technology, which were outside the scope of this project, could be included in a more comprehensive spreadsheet. The weightings of the factors could be examined and should be less biased due to the additional stakeholders.

***2. Simulate Strategies using 2020 Targets:*** Further research in the strategies that may be used by the System Operators in balancing high levels of intermittent wind could be examined. Simulations using the 2020 targets and grid constraints could be performed to discover the approaches that may be required to keep the system stable.

***3. Examine the Influence of Wind Direction on a Windfarm:*** Test 6 gave results which concluded that each windfarm was influenced by wind from a certain direction, such as Arklow Banks Windfarm (168°-222° from North) and Tursillagh Phase 1 (70°-155° from North). As discussed earlier these results could be due to a number of reasons. Further research would involve the examination of the orientations of the windfarms to try and understand the reason for this. The local geographic conditions, terrain and the windfarm turbine layout could be studied in each case and comparison of windfarms may establish whether a relationship exists or it's a coincidence.

***4. Consumer Scheduling:*** One section of the electrical system which has not been discussed in detail in this paper is the consumer and their relationship with wind generation. Consumer usage patterns and intermittent power is an area in which there is potential to explore as this could minimise the issues surrounded with power intermittency. Prabhu (Prabhu, 2010) discusses the approach in which load control in real time can be distributed between generation, storage and the consumer. Within the manufacturing industry in Ireland there are opportunities to vary the load demands with the use of short term storage, as discussed in Section 2.5, and smart manufacturing control.

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# Appendix 1: Tests performed on Data

## Test 1: Calculate the Capacity Values of Windfarms including the Capacity Value of Wind Power.

### Aim

This test was performed to calculate the capacity factor for each windfarm for the sample of SEMO data for the period 2008-2009. The capacity value of wind power was then calculated using the weighted capacity values of the windfarms.

### Apparatus

Microsoft Excel software was used on a laptop computer.

### Method

1. The power output values for the 22 no. windfarms for each 30 minute interval in 2008 and 2009 were copied into an Excel spreadsheet from the SEMO Access files.

2. The output values were multiplied by a factor of 2 to adapt the units from MWH to MW.

3. These values were divided by the maximum generator capacity [MGC] values for each windfarm as given in the SEMO Mapping Spreadsheet Excel file. This gave the capacity value for the windfarm for each interval over the time period as a percentage of the MGC. The average capacity factor was then calculated for each windfarm.

4. The MGC were totalled for each windfarm and a weighting given to each windfarm. The capacity value for each interval was multiplied by the weighting factor and the sum total of the resulting figures was calculated. This is the capacity value of wind power given by the 22 no. windfarms over the 2 year period.

### Results

Table 17 below show the results of the calculations.

### Analysis

The capacity values of the windfarms ranged between 17.75% for GU_400400 (Raheen Bar) to 39.68% for GU_400560 (Tursillagh Phase 2). The majority of the windfarms gave capacity values in the region of 25-30%. The weighted average capacity for the windfarms is 29.42%.

**Table 17 Windfarm Capacity Values and Weighted Average Capacity Value**

| Facility Name | Capacity Value | Max Generator Capacity (MW) | Weighting factor | Weighted Capacity |
|---|---|---|---|---|
| GU_400020 | 28.73% | 25 | 0.042364983 | 1.22% |
| GU_400030 | 34.30% | 11.88 | 0.02013184 | 0.69% |
| GU_400041 | 31.15% | 10.5 | 0.017793293 | 0.55% |
| GU_400050 | 29.56% | 48 | 0.081340767 | 2.40% |
| GU_400060 | 30.02% | 32.4 | 0.054905018 | 1.65% |
| GU_400070 | 31.65% | 72.4 | 0.12268899 | 3.88% |
| GU_400080 | 33.84% | 27 | 0.045754181 | 1.55% |
| GU_400110 | 27.89% | 25.6 | 0.043381742 | 1.21% |
| GU_400130 | 26.44% | 42 | 0.071173171 | 1.88% |
| GU_400380 | 32.57% | 14 | 0.02372439 | 0.77% |
| GU_400390 | 32.86% | 12.6 | 0.021351951 | 0.70% |
| GU_400400 | 17.75% | 18.7 | 0.031689007 | 0.56% |
| GU_400410 | 29.92% | 25.3 | 0.042873363 | 1.28% |
| GU_400420 | 25.63% | 19.45 | 0.032959957 | 0.84% |
| GU_400430 | 28.97% | 42.5 | 0.072020471 | 2.09% |
| GU_400440 | 26.76% | 60 | 0.101675959 | 2.72% |
| GU_400450 | 30.99% | 15 | 0.02541899 | 0.79% |
| GU_400460 | 31.17% | 15 | 0.02541899 | 0.79% |
| GU_400470 | 38.31% | 11.9 | 0.020165732 | 0.77% |
| GU_400490 | 32.18% | 15.18 | 0.025724018 | 0.83% |
| GU_400550 | 26.84% | 38.9 | 0.065919913 | 1.77% |
| GU_400560 | 39.68% | 6.8 | 0.011523275 | 0.46% |
| | | | | |
| **Total** | **30.33%** | **590.11** | **1** | **29.42%** |

## Conclusion

The capacity values above are indicative of the expected values for an intermittent power resource such as wind.

# Test 2 Calculate the Range of Wind Speeds and Air Density for the Weather Station Data.

## Aim

From Equation 2.1 in Section 2.1 the wind speeds and air density have an influence on the power output of a wind turbine. This test was carried out to calculate the range of wind speeds and air density recorded in the weather stations over the 2 year period.

## Apparatus

Microsoft Excel software was used on a laptop computer.

## Method

1. The wind speed was multiplied by a factor of 0.5144 to adapt from Knots/s to m/s. The Air Density was calculated for each weather station and interval using Equation 2.2, Equation 2.3 and Equation 2.4 in Section 2.1, and the data in the Met Éireann Microsoft Excel file.

2. Each weather station variable was then copied to a single worksheet containing the 60 minute intervals. The variables on the columns were temperature, relative humidity, MSL (mean sea level ) pressure, wind direction from North, wind speed and air density for each weather station.

3. Using the Table Format tool the range of values for the wind speeds and air density are recorded.

## Results

**Table 18 Range of Wind Speeds and Air Density recorded in Weather Stations**

| Variable/Weather Station | Malin Head | Belmullet | Valentia | Johnstown Castle | Gurteen/Birr |
|---|---|---|---|---|---|
| Min Wind Speed (m/s) | 0 | 0 | 0 | 0 | 0 |
| Max Wind Speed (m/s) | 31.89 | 25.72 | 22.12 | 14.4 | 18 |
| Mean Wind Speed (m/s) | 7.66 | 6.13 | 4.88 | 3.52 | 4.04 |
| Min Air Density (kg/m³) | 1.18 | 1.17 | 1.17 | 1.17 | 1.17 |
| Max Air Density (kg/m³) | 1.32 | 1.33 | 1.33 | 1.33 | 1.35 |
| Mean Air Density (kg/m³) | 1.24 | 1.24 | 1.24 | 1.24 | 1.24 |

## Analysis

The wind speeds range from 0 m/s in each weather station up to 31.89 /s at Malin head. The average wind speeds range from 3.52 m/s at Johnstown Castle to an impressive 7.66 at Malin Head.

The air density range from 1.17 kg/m³ to 1.35 kg/m³ recorded in Gurteen/Birr. The average air density was calculated as 1.24 kg/m³ for each weather station.

## Conclusion

The average wind speeds appear to be similar to the SEAI Wind Map readings with averages between 3.5 m/s and 7.5 m/s. The range of wind speeds is vast and helps explain the intermittent nature of wind power. The air density does not vary much among the weather stations over the 2 years recorded, with an average of 1.24 kg/m³. Traditionally an average of 1.25 kg/m³ is used as an approximate value for air density in simple calculations.

## Test 3 Find prevalent wind direction for weather station data

### Aim

This test set out to find the most common or prevalent wind direction using the Met Éireann data.

### Apparatus

Microsoft Excel software was used on a laptop computer.

### Method

1. The wind directions for the 5 no. weather stations for each interval were copied into a new spreadsheet from the Met Éireann file. The wind directions were measured at 10° spacing's from North for each interval.

2. The Using a Pivot Table the angle of each interval was counted and a table was prepared with wind direction and a count. The sum total of the counts was calculated and the percentage duration for each angle was determined.

3. The percentage count was plotted against the 36 no. angles using a radar chart.

### Results

Below are the table of count of wind direction for the data and the subsequent Wind Rose, Figure 18.

### Analysis

The wind blows from every direction over the course of the period analysed. The most common direction is 230° from North, from where the wind blows up to 6% of the time. The South and West directions gave larger proportions than any other directions. The least likely wind direction is between North and East

### Conclusion

The prevailing wind direction for the data recorded is southwest. This indicated when designing the layout of wind turbines on a windfarm consideration should be taken to the southwest direction as the wind blows from this direction for longer periods than any other direction.

**Table 19 Count of Wind Direction for Met Éireann data**

| Wind Direction (° from North) | Count | Wind Direction (°from North) | Count |
|---|---|---|---|
| 0 | 1197 | 180 | 3505 |
| 10 | 1699 | 190 | 3966 |
| 20 | 1200 | 200 | 3835 |
| 30 | 1315 | 210 | 4311 |
| 40 | 1167 | 220 | 4321 |
| 50 | 1335 | 230 | 5253 |
| 60 | 1414 | 240 | 4076 |
| 70 | 1438 | 250 | 3455 |
| 80 | 1454 | 260 | 3724 |
| 90 | 1359 | 270 | 3408 |
| 100 | 1182 | 280 | 2855 |
| 110 | 1226 | 290 | 2386 |
| 120 | 1385 | 300 | 1885 |
| 130 | 1800 | 310 | 1661 |
| 140 | 1937 | 320 | 1844 |
| 150 | 2124 | 330 | 1840 |
| 160 | 2231 | 340 | 1728 |
| 170 | 3175 | 350 | 1681 |

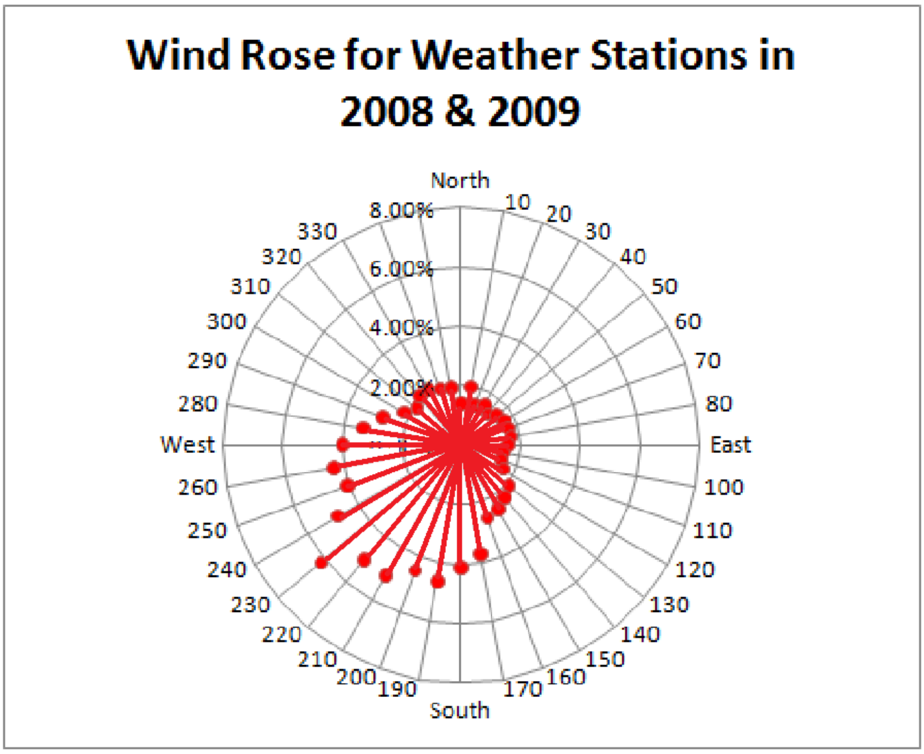


**Figure 18 Wind Rose for Met Éireann data**

## Test 4: Relationship between Windfarms Capacity Values

### Aim

This test was performed to examine the relationship between the capacity values of a sample of windfarms and all other 21 no. windfarms from the SEMO data. The details of Windfarms analysed are shown in Table 20. It is expected that the windfarms in close proximity to the analysed windfarms will have the strongest relationship.

**Table 20 List of Windfarms Analysed in Test 4**

| Item | Facility Name | Windfarm Name | County | Max Generator Capacity (MW) |
|---|---|---|---|---|
| 1 | GU_400020 | Kingsmountain windfarm phase 1 | Sligo | 25 |
| 8 | GU_400110 | Arklow Banks Windfarm | Wicklow | 25.6 |
| 18 | GU_400460 | Cark Windfarm | Donegal | 15 |
| 20 | GU_400490 | Tursillagh Windfarm Phase 1 | Kerry | 15.18 |

### Apparatus

Microsoft Excel software was used on a laptop computer. The test used the Analyze Key Influencers tool in the Table Tool Analysis in Microsoft Excel.

### Method

1. The power output values for the windfarms for each 30 minute interval in 2008 and 2009 were copied into an Excel spreadsheet from the SEMO Access files. This gave 35,088 intervals for the two years.

2. The output values were multiplied by a factor of 2 to convert from MWH to MW.

3. These values were divided by the MGC values for each windfarm as given in the SEMO Mapping Spreadsheet Excel file. This gave the capacity value for the windfarm for each interval over the time period as a percentage of the MGC.

4. This data was formatted into a table with intervals on the rows and Windfarm capacity values on the columns.

5. The Analyze Key Influencers tool was then run to compare the values of Tursillagh Windfarm Phase 1 using all other 21 no. windfarms.

6. This procedure was repeated on Kingsmountain Windfarm Phase 1, Arklow Banks Windfarm and Cark Windfarm.

## Results

The results for Tursillagh Windfarm Phase 1 are shown in Table 21 note this table has been filtered to show relative impacts of 30% and greater. The capacity value has been broken up into 5 different sections chosen randomly by the analysis tool: less than 10.7%, between 10.7% and 30%, between 30% and 54%, between 54% and 77.2% and greater than 77.2%. The first column identifies the influencer. The second column lists the range at which the influencer was examined against the third column, the range of the variable being analysed. The fourth column gives the impact of the influencer compared to the strongest relationship (100%). For example the influencer GU_400560, Tursillagh Phase 2, at relative impact of 100%, has an output capacity value of less than 16.79% when the tested facilities capacity value is less than 10.76%. This indicates Tursillagh Phase 2 has the strongest relationship with Tursillagh Phase 1 and this happens as Phase 2 has a capacity value of less than 16.79% and Phase 1 has a capacity value of less than 10.76%. The second most influencing unit is GU_400430 (Coomagearlahy), followed by GU_400060 (Midas) and GU_400420 (Booltiagh).

Table 22 is a summary of the results for the analysed windfarms as listed in Table 20.

## Analysis

From Table 22 it can be seen that for Arklow Banks, Cark and Tursillagh Phase 1, the windfarms located in the same region are the most influential. In particular for Tursillagh Phase 1, Phase 2 of that project gave the strongest influence on the capacity of the windfarm than any of the others.

Kingsmountain Phase 1 however gave mixed results which may be because there are no windfarms located close it. The closest windfarm to Kingsmountain Phase 1, Raheen Bar in Mayo, did not appear as a key influencer which could mean different wind directions give different capacity outputs for the windfarms.

## Conclusion

Windfarms located close to each other give similar levels of capacity values for the same time intervals. This indicates that when positioning a windfarm close to an existing windfarm, the capacity values of the existing windfarm may be used to explore the possible output of the potential windfarm. This can also be used for Regional Up-scaling in windfarm power forecasting.

Table 21 Key Influencers for Tursillagh Windfarm Phase 1

| Key Influencers Report for Tursillagh Windfarm Phase 1 | | | |
|---|---|---|---|
| Key Influencers and their impact over the values of 'GU_400490' | | | |
| **Column** | **Value** | **Capacity Value** | **Relative Impact** |
| GU_400560 | < 0.1679729242 | < 0.107645937425 | |
| GU_400430 | < 0.116193841275 | < 0.107645937425 | |
| GU_400060 | < 0.113101876225 | < 0.107645937425 | |
| GU_400420 | < 0.131748684575 | < 0.107645937425 | |
| GU_400410 | < 0.1122506149375 | < 0.107645937425 | |
| GU_400440 | < 0.1108228174375 | < 0.107645937425 | |
| GU_400560 | 0.1679729242 - 0.42677324525 | 0.107645937425 - 0.30091860885 | |
| GU_400560 | 0.42677324525 - 0.7616002013 | 0.30091860885 - 0.5400613671 | |
| GU_400560 | 0.7616002013 - 0.8912988761 | 0.5400613671 - 0.772913433 | |
| GU_400560 | >= 0.8912988761 | >= 0.772913433 | |
| GU_400410 | >= 0.7539417643 | >= 0.772913433 | |
| GU_400390 | >= 0.8171450235 | >= 0.772913433 | |
| GU_400060 | >= 0.719851299 | >= 0.772913433 | |
| GU_400440 | >= 0.68580519 | >= 0.772913433 | |
| GU_400430 | >= 0.7678947468 | >= 0.772913433 | |

Table 22 Summary of Test 4 Results

| Item | Facility Name | Windfarm Name | Key Influencers |
|---|---|---|---|
| 1 | GU_400020 | Kingsmountain windfarm phase 1 | Cark (Donegal) |
| | | (Sligo) | Derrybrien (Galway) |
| | | | Cuillagh (Donegal) |
| | | | Booltiagh (Clare) |
| | | | Tursillagh (Kerry) |
| 8 | GU_400110 | Arklow Banks Windfarm | Ballywater (Wexford) |
| | | (Wicklow) | Carnsore (Wexford) |
| | | | Richfield (Wexford) |
| 18 | GU_400460 | Cark Windfarm | Cuillagh (Donegal) |
| | | (Donegal) | Meentycat (Donegal) |
| | | | Sorne Hill (Donegal) |
| | | | Beam Hill (Donegal) |
| | | | Barnesmore (Donegal) |
| 20 | GU_400490 | Tursillagh Windfarm Phase 1 | Tursillagh Phase 2 (Kerry) |
| | | (Kerry) | Coomagearlahy (Kerry) |
| | | | Taurbeg (Cork) |
| | | | Moanmore (Clare) |
| | | | Midas (Kerry) |

## Test 5: Relationship between Windfarm Power Output and Weather Conditions

### Aim

This test compared the power outputs of the Windfarms to the weather conditions recorded in nearby weather stations as detailed in Table 23, to determine which weather variables have the strongest influence. The weather variables within the data are temperature, relative humidity, pressure, wind direction, wind speed and air density.

**Table 23 List of Weather Stations and Windfarms Analysed in Test 5 and Test 6**

| Station Ref | Station | County | Windfarm Ref | Windfarm | County |
|---|---|---|---|---|---|
| A | Malin Head | Donegal | 18 | Cark | Donegal |
| B | Belmullet | Mayo | 1 | Kingsmountain phase 1 | Sligo |
| C | Valentia | Kerry | 20 | Tursillagh Phase 1 | Kerry |
| D | Johnstown Castle | Wexford | 8 | Arklow Banks | Wicklow |

### Apparatus

Microsoft Excel software was used on a laptop computer. The test used the Analyze Key Influencers tool in the Table Tool Analysis in Microsoft Excel.

### Method

1. The power output values for the 4 windfarms for each 30 minute interval in 2008 and 2009 were copied into an Excel spreadsheet from the SEMO Access files. This gave 35,088 intervals for the two years. The hourly values were then calculated by adding the half hourly values. This gave 17,544 intervals.

2. The recorded weather data received from Met Éireann was copied into the excel spreadsheet and formatted to hourly intervals on the rows and weather variables on the columns for each station. The wind speed was multiplied by a factor of 0.5144 to adapt from Knots/s to m/s. The air density was calculated as per Test 2.

3. The formatted weather data for Malin Head and power output data for Cark Windfarm were copied onto a new Excel spreadsheet with the interval on the rows and temperature, relative humidity, pressure, wind direction, wind speed, air density and power output on the columns.

4. The Analyze Key Influencers tool was then run to compare the power output of Cark Windfarm using the weather variables on each column.

5. This procedure was repeated on Kingsmountain Phase 1 and Belmullet recordings, Tursillagh Phase 1 and Valentia recordings, and Arklow Banks and Johnstown Castle recordings.

## Results

Table 24 below shows the results for the key weather condition influencers on the power output of Cark Windfarm. The wind speed is the key influencer for all output ranges of the windfarm. Note the wind direction has a strong influence at the higher power outputs for the windfarm. The results for other 3 tests carried out had the wind speed as the most influential factor in the power output of the windfarms.

**Table 24 Results for Key Influencers for Cark Windfarm using Malin Head Recordings**

**Key Influencers Report for 'Cark Wind Farm Output _MW_'**

**Key Influencers and their impact over the values of 'Cark Wind Farm Output _MW_'**

| Column | Value | Favors | Relative Impact |
|---|---|---|---|
| Wind Speed _m_s_ | < 4.8778680088 | < 1.7317179794 | |
| Wind Speed _m_s_ | 4.8778680088 - 7.98550596 | 1.7317179794 - 4.8518821192 | |
| Wind Speed _m_s_ | 7.98550596 - 11.3128286656 | 4.8518821192 - 7.3929198344 | |
| Wind Speed _m_s_ | 11.3128286656 - 15.6058952544 | 7.3929198344 - 10.6096838576 | |
| Wind Speed _m_s_ | 7.98550596 - 11.3128286656 | 7.3929198344 - 10.6096838576 | |
| Wind Speed _m_s_ | 11.3128286656 - 15.6058952544 | >= 10.6096838576 | |
| Wind Speed _m_s_ | >= 15.6058952544 | >= 10.6096838576 | |
| Direction __from N_ | 215 - 280 | >= 10.6096838576 | |

## Analysis

The most influential factor for each of the windfarms was wind speed. This supports Equation 2.1 in which states the wind speed is a variable which is directly related to the power. The reason the wind speed may be the main influencer as the in Equation 2.1 the wind speed is multiplied to the power of 3, which increases its affect in the output.

## Conclusion

The Table Tool Analysis software concludes that the wind speed has the largest influence of weather variables in the power output from a windfarm.

## Test 6 Relationship between Windfarm Power Output and Weather Conditions Excluding Wind Speed

### Aim

This test set out to discover the second most influential factor in the power output of windfarms. The test was identical to Test 6 except for the wind speed variable was removed. The weather station data and windfarms in Table 23 were analysed in same manner as before.

### Apparatus

Microsoft Excel software was used on a laptop computer. The test used the Analyze Key Influencers tool in the Table Tool Analysis in Microsoft Excel.

### Method

1. The power output values for the 4 windfarms for each 30 minute interval in 2008 and 2009 were copied into an Excel spreadsheet from the SEMO Access files. This gave 35,088 intervals for the two years. The hourly values were then calculated by adding the half hourly values. This gave 17,544 intervals.

2. The recorded weather data received from Met Éireann was copied into the excel spreadsheet and formatted to hourly intervals on the rows and weather variables on the columns for each station. The wind speed was removed for each interval. The air density was calculated as per Test 2.

3. The formatted weather data for Malin Head and power output data for Cark Windfarm were copied onto a new Excel spreadsheet with the interval on the rows and temperature, relative humidity, pressure, wind direction, air density and power output on the columns.

4. The Analyze Key Influencers tool was then run to compare the power output of Cark Windfarm using the weather variables on each column.

5. This procedure was repeated on Kingsmountain Phase 1 and Belmullet recordings, Tursillagh Phase 1 and Valentia recordings, and Arklow Banks and Johnstown Castle recordings.

### Results

The Table 25 below gives a summary of the results recorded. Note the range of the windfarm outputs were chosen randomly by the software.

**Table 25 Summary of Key Influencers on Windfarm Outputs for Test 6**

| **Analysis** | **Range of Windfarm Power Output (MW) and *key Influencer*** | | | | |
|---|---|---|---|---|---|
| Cark Output | 0-1.7 | 1.7-4.8 | 4.8-7.4 | 7.4-10.6 | 10.6-15 |
| Malin Head | *Pressure >1022.7 Pa* | *83-154°* | *Relative Humidity 80-88%* | *215-280°* | *215-280°* |
| | | | | | |
| Kingsmountain Phase 1 Output | 0-3 | 3-7.35 | 7.35-12.5 | 12.5-18 | 18-35 |
| Belmullet | *0-72°* | *222-275°* | *222-275°* | *156-222°* | *156-222°* |
| | | | | | |
| Tursillagh Phase 1 Output | 0-1.78 | 1.78-5.15 | 5.15-8.45 | 8.45-12.19 | 12.19-15.28 |
| Valentia | *0-70°* | *281-360°* | *Air Density <1.21 Kg/m³* | *Relative Humidity <60%* | *70-155°* |
| | | | | | |
| Arklow Banks Output | 0-2.7 | 2.7-7.15 | 7.15-11.8 | 11.8-17.25 | 17.25-25.6 |
| Johnstown Castle | *pressure >1024 Pa* | *222-269°* | *168-222°* | *168-222°* | *168-222°* |

**Note: Wind Direction is measured from North**

## Analysis

It can be observed from the results that there is no unanimous influencer on the output of the windfarms however, the wind direction is cited the majority of the time. Wind direction is the key influencer at high output levels from the windfarms and is the key influencer 70% of the time. It should also be noted the wind direction does varies direction between the output ranges of the windfarms.

## Conclusion

It can be concluded that wind direction is a key influencer on the output of a windfarm however the direction of the wind is different for each windfarm. The reason why wind direction has the influence is unclear; it may be due to turbine layout, local terrain, local geography or a coincidence.

## Test 7 Relationship between the Capacity Value of Wind Power and all other Generation Technologies

### Aim

This test investigated the pattern between the outputs of all the generation facilities in the SEMO and the capacity value of wind power. The test should reveal any relationships between the wind power and any other generation system, and any strategy in place for wind intermittency by the System Operator.

### Apparatus

Microsoft Excel software was used on a laptop computer. The test used the Analyze Key Influencers tool in the Table Tool Analysis in Microsoft Excel.

### Method

1. Using the SEMO data, the output of all generation facilities operational during 2008 and 2009 were copied onto an Excel spreadsheet. The windfarm participants were removed and the 55 SEMO participants remained are detailed in Table 26.

2. The power outputs of the 55 units were multiplied by 2 to adapt the units to MW. The capacity value of each unit for each interval calculated using the unit's MGC.

3. The power output values for the 22 no. windfarms for each 30 minute interval in 2008 and 2009 were copied into an Excel spreadsheet from the SEMO Access files.

4. The output values were multiplied by a factor of 2 to adapt the units from MWH to MW.

5. The windfarm values were totalled for each interval and divided by the sum of the MGC. This gave the capacity value of wind power for each interval.

6. The capacity value of wind power is copied into the spreadsheet with the 55 SEMO participants.

7. The Analyze Key Influencers tool was then run to compare the capacity value of wind power for key factors using the SEMO participants.

**Table 26 List of Participants used in Test 7**

| Item | FACILITY NAME | UNIT NAME | FUEL TYPE | Maximum Generator Capacity (MW) |
|---|---|---|---|---|
| 1 | GU_400120 | Sealrock 3 (Aughinish CHP) | MULTI | 83 |
| 2 | GU_400121 | Sealrock 4 (Aughinish CHP) | MULTI | 83 |
| 3 | GU_400140 | Edenderry unit 1 | PEAT | 117.57 |
| 4 | GU_400181 | Aghada CT Unit 1 | MULTI | 95 |
| 5 | GU_400182 | Aghada CT Unit 2 | MULTI | 95 |
| 6 | GU_400183 | Aghada CT Unit 4 | MULTI | 95 |
| 7 | GU_400190 | Aghada Peaking Unit | DISTL | 52 |
| 8 | GU_400200 | Ardnacrusha Unit 1 | HYDRO | 21 |
| 9 | GU_400201 | Ardnacrusha Unit 2 | HYDRO | 22 |
| 10 | GU_400202 | Ardnacrusha Unit 3 | HYDRO | 19 |
| 11 | GU_400203 | Ardnacrusha Unit 4 | HYDRO | 24 |
| 12 | GU_400210 | Erne Unit 1 | HYDRO | 10 |
| 13 | GU_400211 | Erne Unit 2 | HYDRO | 10 |
| 14 | GU_400220 | Erne Unit 3 | HYDRO | 22.5 |
| 15 | GU_400221 | Erne Unit 4 | HYDRO | 22.5 |
| 16 | GU_400230 | Great Island Unit 1 | OIL | 54 |
| 17 | GU_400231 | Great Island Unit 2 | OIL | 49 |
| 18 | GU_400232 | Great Island Unit 3 | OIL | 101 |
| 19 | GU_400240 | LOUGH REE UNIT 1 | PEAT | 91 |
| 20 | GU_400250 | Liffey Unit 1 | HYDRO | 15 |
| 21 | GU_400251 | Liffey Unit 2 | HYDRO | 15 |
| 22 | GU_400252 | Liffey Unit 4 | HYDRO | 4 |
| 23 | GU_400260 | Liffey Unit 5 | HYDRO | 4 |
| 24 | GU_400270 | Moneypoint Unit 1 | COAL | 287.5 |
| 25 | GU_400272 | Moneypoint Unit 3 | COAL | 287.5 |
| 26 | GU_400280 | Lee Unit 1 | HYDRO | 15 |
| 27 | GU_400281 | Lee Unit 2 | HYDRO | 4 |
| 28 | GU_400290 | Lee Unit 3 | HYDRO | 8 |
| 29 | GU_400300 | Marina CC | MULTI | 112 |
| 30 | GU_400310 | Northwall Unit 4 | MULTI | 163 |
| 31 | GU_400311 | Northwall Unit 5 | MULTI | 104 |
| 32 | GU_400320 | Poolbeg Unit 1 | MULTI | 114.5 |
| 33 | GU_400321 | Poolbeg Unit 2 | MULTI | 114.5 |
| 34 | GU_400322 | Poolbeg Unit 3 | MULTI | 242 |
| 35 | GU_400323 | Poolbeg Combined Cycle | MULTI | 463 |
| 36 | GU_400330 | Rhode Unit 1 | DISTL | 52 |
| 37 | GU_400331 | Rhode Unit 2 | DISTL | 52 |
| 38 | GU_400340 | Tarbert Unit 1 | OIL | 54 |
| 39 | GU_400341 | Tarbert Unit 2 | OIL | 54 |
| 40 | GU_400342 | Tarbert Unit 3 | OIL | 240.7 |
| 41 | GU_400343 | Tarbert Unit 4 | OIL | 240.7 |
| 42 | GU_400350 | Tawnaghmore | DISTL | 52 |
| 43 | GU_400351 | Tawnaghmore | DISTL | 52 |
| 44 | GU_400370 | WEST OFFALY UNIT 1 | PEAT | 137 |
| 45 | GU_400480 | Huntstown | GAS | 352 |
| 46 | GU_400500 | Dublin Bay Power | MULTI | 415 |
| 47 | GU_400530 | Tynagh | GAS | 404 |
| 48 | GU_400540 | Huntstown Phase II | GAS | 412 |
| 49 | GU_400570 | Arthurstown Phase2 (ESB) | BIO | 4.239 |
| 50 | GU_400571 | Arthurstown Phase3 (ESB) | BIO | 1.25 |
| 51 | GU_400580 | Arthurstown Phase1 and Phase 4 | BIO | 8.652 |
| 52 | GU_400360 | Turlough Hill Unit 1 | PUMP | 73 |
| 53 | GU_400361 | Turlough Hill Unit 2 | PUMP | 73 |
| 54 | GU_400362 | Turlough Hill Unit 3 | PUMP | 73 |
| 55 | GU_400363 | Turlough Hill Unit 4 | PUMP | 73 |

## Results

The results of the test are shown below in Table 27.

**Table 27 Key Influencers on Total Windfarm Capacity Values in Test 7**

| Key Influencers Report for 'Total Wind Capacity' | | | |
|---|---|---|---|
| Key Influencers and their impact over the values of 'Total Wind Capacity' | | | |
| **Column** | **Value** | **Favors** | **Relative Impact** |
| GU_400290 | < 0.02958984375 | < 0.1487856522 | |
| GU_400281 | < 0.173029848725 | < 0.1487856522 | |
| GU_400310 | >= 0.3781151037 | < 0.1487856522 | |
| GU_400480 | >= 0.43805711865 | < 0.1487856522 | |
| GU_400280 | < 2.69926925234375E-03 | < 0.1487856522 | |
| GU_400211 | >= 0.45484601445 | 0.2997360365 - 0.47239516085 | |
| GU_400280 | >= 0.5088010356 | 0.2997360365 - 0.47239516085 | |
| GU_400210 | >= 0.4693022113 | 0.2997360365 - 0.47239516085 | |
| GU_400281 | 0.5121332518 - 0.6405180341 | 0.2997360365 - 0.47239516085 | |
| GU_400140 | < 0.01036501985625 | 0.2997360365 - 0.47239516085 | |
| GU_400310 | < 0.00368449429375 | 0.2997360365 - 0.47239516085 | |
| GU_400290 | >= 0.4043945312 | 0.47239516085 - 0.6563898785 | |
| GU_400320 | < 0.013678174178125 | >= 0.6563898785 | |
| GU_400203 | 0.29749348955 - 0.39143880205 | >= 0.6563898785 | |
| GU_400140 | >= 0.4606548539 | >= 0.6563898785 | |

## Analysis

From the table above it can be observed there are no unique influencers on the capacity value of wind power. This suggests there is no relationship between the wind capacity and any other generation facility such as hydro, open cycle gas turbines, pumped hydro storage and interconnector. It also suggests there is no strategy used by the System Operator on the wind.

## Conclusion

These results are not surprising as no natural relationship is known to exist between wind power and other types of commercial generation. In relation to the strategy, the penetration of wind power on the system for 2008 and 2009 was very little and would be managed easily by the operation reserve, not requiring a strategy of its own.

## Test 8: Comparison of the Capacity Value of each Windfarm to the Capacity Value of Wind Power

### Aim

This test was performed to see any relationship between the capacity value of wind power and each windfarm. The test would advise what windfarms, if any, would give a capacity value close to the capacity value of wind power.

### Apparatus

Microsoft Excel software was used on a laptop computer. The test used the Analyze Key Influencers tool in the Table Tool Analysis in Microsoft Excel.

### Method

1. The power output values for the 22 no. windfarms for each 30 minute interval in 2008 and 2009 were copied into an Excel spreadsheet from the SEMO Access files.

2. The output values were multiplied by a factor of 2 to adapt the units from MWH to MW.

3. These values were divided by the MGC values for each windfarm as given in the SEMO Mapping Spreadsheet Excel file. This gave the combined capacity value of wind power for each interval over the time period as a percentage of the MGC.

4. The capacity value of wind power for each interval was copied from Test 7 and placed into the spreadsheet.

5. The Analyze Key Influencers tool was then run to compare the capacity value of wind power for key factors using the capacity values for each individual windfarm.

### Results

The results are shown in Table 28.

**Table 28 Key Influencers for Total Windfarm Capacity Values for Test 8**

Key Influencers Report for 'Total'

Key Influencers and their impact over the values of 'Total'

| Column | Value | Favors | Relative Impact |
|---|---|---|---|
| GU_400440 | < 0.106914563725 | < 0.129939041925 | |
| GU_400420 | < 0.1111586430875 | < 0.129939041925 | |
| GU_400050 | < 0.140356313775 | < 0.129939041925 | |
| GU_400030 | < 0.1104155819 | < 0.129939041925 | |
| GU_400440 | 0.106914563725 - 0.25014467925 | 0.129939041925 - 0.2873618743 | |
| GU_400041 | 0.1112086526 - 0.2803244078 | 0.129939041925 - 0.2873618743 | |
| GU_400410 | 0.116854869925 - 0.30492406415 | 0.129939041925 - 0.2873618743 | |
| GU_400420 | 0.1111586430875 - 0.2900383892 | 0.129939041925 - 0.2873618743 | |
| GU_400440 | 0.25014467925 - 0.45961417385 | 0.2873618743 - 0.43566016545 | |
| GU_400041 | 0.2803244078 - 0.49654773515 | 0.2873618743 - 0.43566016545 | |
| GU_400050 | 0.32087144085 - 0.5458280587 | 0.2873618743 - 0.43566016545 | |
| GU_400041 | 0.49654773515 - 0.7619456313 | 0.43566016545 - 0.6315774595 | |
| GU_400440 | 0.45961417385 - 0.659039692 | 0.43566016545 - 0.6315774595 | |
| GU_400050 | 0.5458280587 - 0.7524358987 | 0.43566016545 - 0.6315774595 | |
| GU_400440 | >= 0.659039692 | >= 0.6315774595 | |
| GU_400041 | >= 0.7619456313 | >= 0.6315774595 | |
| GU_400030 | >= 0.7965515363 | >= 0.6315774595 | |
| GU_400050 | >= 0.7524358987 | >= 0.6315774595 | |

## Analysis

The key influencing windfarms for the capacity value of wind power are units GU_400440 (Derrybrien), GU_400041 (Gartnaneane) and GU_400420 (Booltiagh), which are located in Co. Galway, Co. Cavan and Co. Clare respectively. These windfarms are located close to the centre of the country which suggests the windfarms located close to the centre of the country have a similar capacity value as the capacity value of wind power.

## Conclusion

The windfarms that are located in the centre of the country give a capacity value similar to that of the capacity value of wind power. This can lead to a large range for the capacity value of wind power which in turn requires a large amount of operational reserve. Locating windfarms away from the centre of the country can lead to a reduced range of overall wind power capacity value which requires less reserve.

# Appendix 2: Spreadsheets for Sites Analysed

**Table 29 Spreadsheet for Coomagearlahy Windfarm Phase 3**

| | | | | | |
|---|---|---|---|---|---|
| **Wind Farm Name** | Coomagearlahy Windfarm Phase 3 | | | | |
| **Location** | Derrynasaggart Mountain Co. Kerry | | | | |
| **Capacity** | 30 MW | | | | |
| | | | | | |
| | | | | | |
| **Metric** | **Factor** | **Factor Value (1-10)** | **Weighting (1-5)** | **Score (1-50)** | **Total Metric Score** |
| | | | | | |
| **Geographical** | | | | | |
| | Wind Speed | 5.90 | 5 | 29.50 | |
| | Orientation of Windfarm | 7.30 | 4 | 29.20 | |
| | Terrain | 3.00 | 3 | 9.00 | |
| | Distance to Network | 10.00 | 2 | 20.00 | |
| | Potential for Expansion | 10.00 | 1 | 10.00 | |
| | | | | | |
| | | | | **Total** | 98 |
| **Operational** | | | | | |
| | Backup Capacity | 10.00 | 5 | 50.00 | |
| | Forecasting | 10.00 | 4 | 40.00 | |
| | Distribution of Windfarms | 9.00 | 3 | 27.00 | |
| | | | | | |
| | | | | **Total** | 117 |
| **Ethical** | | | | | |
| | Greenhouse Gas Reductions | 3.00 | 1 | 3.00 | |
| | Regional Development | 3.00 | 1 | 3.00 | |
| | | | | | |
| | | | | **Total** | 6 |
| | | | | | |
| | | | | **Total Score for Windfarm** | 221 |

**Table 30 Spreadsheet for Flughland Windfarm Phase 1**

| | | | | | |
|---|---|---|---|---|---|
| **Wind Farm Name** | Flughland Windfarm Phase 1 | | | | |
| **Location** | Sorne Hill Co. Donegal | | | | |
| **Capacity** | 9.2 MW | | | | |
| | | | | | |
| | | | | | |
| **Metric** | **Factor** | **Factor Value (1-10)** | **Weighting (1-5)** | **Score (1-50)** | **Total Metric Score** |
| | | | | | |
| **Geographical** | | | | | |
| | Wind Speed | 5.20 | 5 | 26.00 | |
| | Orientation of Windfarm | 7.10 | 4 | 28.40 | |
| | Terrain | 4.00 | 3 | 12.00 | |
| | Distance to Network | 8.00 | 2 | 16.00 | |
| | Potential for Expansion | 10.00 | 1 | 10.00 | |
| | | | | | |
| | | | | **Total** | 92 |
| **Operational** | | | | | |
| | Backup Capacity | 10.00 | 5 | 50.00 | |
| | Forecasting | 6.00 | 4 | 24.00 | |
| | Distribution of Windfarms | 10.00 | 3 | 30.00 | |
| | | | | | |
| | | | | **Total** | 104 |
| **Ethical** | | | | | |
| | Greenhouse Gas Reductions | 1.00 | 1 | 1.00 | |
| | Regional Development | 1.00 | 1 | 1.00 | |
| | | | | | |
| | | | | **Total** | 2 |
| | | | | | |
| | | | | **Total Score for Windfarm** | 198 |

**Table 31 Spreadsheet for Knocktopher Windfarm Phase 1**

| | | | | | |
|---|---|---|---|---|---|
| **Wind Farm Name** | Knocktopher Windfarm Phase 1 | | | | |
| **Location** | Co. Kilkenny | | | | |
| **Capacity** | 40 MW | | | | |
| | | | | | |
| **Metric** | **Factor** | **Factor Value (1-10)** | **Weighting (1-5)** | **Score (1-50)** | **Total Metric Score** |
| **Geographical** | | | | | |
| | Wind Speed | 4.60 | 5 | 23.00 | |
| | Orientation of Windfarm | 7.30 | 4 | 29.20 | |
| | Terrain | 3.00 | 3 | 9.00 | |
| | Distance to Network | 8.00 | 2 | 16.00 | |
| | Potential for Expansion | 10.00 | 1 | 10.00 | |
| | | | | **Total** | 87 |
| **Operational** | | | | | |
| | Backup Capacity | 10.00 | 5 | 50.00 | |
| | Forecasting | 0.00 | 4 | 0.00 | |
| | Distribution of Windfarms | 6.00 | 3 | 18.00 | |
| | | | | **Total** | 68 |
| **Ethical** | | | | | |
| | Greenhouse Gas Reductions | 4.00 | 1 | 4.00 | |
| | Regional Development | 4.00 | 1 | 4.00 | |
| | | | | **Total** | 8 |
| | | | | **Total Score for Windfarm** | 163 |

**Table 32 Spreadsheet for Kilmashogue Windfarm Phase 1**

| | | | | | |
|---|---|---|---|---|---|
| **Wind Farm Name** | Kilmashogue Windfarm Phase 1 | | | | |
| **Location** | Dublin 16 | | | | |
| **Capacity** | 20 MW | | | | |
| | | | | | |
| | | | | | |
| **Metric** | **Factor** | **Factor Value (1-10)** | **Weighting (1-5)** | **Score (1-50)** | **Total Metric Score** |
| | | | | | |
| **Geographical** | | | | | |
| | Wind Speed | 6.40 | 5 | 32.00 | |
| | Orientation of Windfarm | 7.30 | 4 | 29.20 | |
| | Terrain | 2.00 | 3 | 6.00 | |
| | Distance to Network | 10.00 | 2 | 20.00 | |
| | Potential for Expansion | 10.00 | 1 | 10.00 | |
| | | | | | |
| | | | | **Total** | 97 |
| **Operational** | | | | | |
| | Backup Capacity | 10.00 | 5 | 50.00 | |
| | Forecasting | 0.00 | 4 | 0.00 | |
| | Distribution of Windfarms | 6.00 | 3 | 18.00 | |
| | | | | | |
| | | | | **Total** | 68 |
| **Ethical** | | | | | |
| | Greenhouse Gas Reductions | 2.00 | 1 | 2.00 | |
| | Regional Development | 2.00 | 1 | 2.00 | |
| | | | | | |
| | | | | **Total** | 4 |
| | | | | | |
| | | | | **Total Score for Windfarm** | 169 |

**Table 33 Spreadsheet for Knockanore Windfarm Phase 1**

| | | | | | |
|---|---|---|---|---|---|
| **Wind Farm Name** | Knockanore Windfarm Phase 1 | | | | |
| **Location** | Knockanore Mountain Co. Kerry | | | | |
| **Capacity** | 100 MW | | | | |
| | | | | | |
| **Metric** | **Factor** | **Factor Value (1-10)** | **Weighting (1-5)** | **Score (1-50)** | **Total Metric Score** |
| **Geographical** | | | | | |
| | Wind Speed | 7.30 | 5 | 36.50 | |
| | Orientation of Windfarm | 10.00 | 4 | 40.00 | |
| | Terrain | 4.00 | 3 | 12.00 | |
| | Distance to Network | 8.00 | 2 | 16.00 | |
| | Potential for Expansion | 10.00 | 1 | 10.00 | |
| | | | | **Total** | 115 |
| **Operational** | | | | | |
| | Backup Capacity | 10.00 | 5 | 50.00 | |
| | Forecasting | 2.00 | 4 | 8.00 | |
| | Distribution of Windfarms | 8.00 | 3 | 24.00 | |
| | | | | **Total** | 82 |
| **Ethical** | | | | | |
| | Greenhouse Gas Reductions | 10.00 | 1 | 10.00 | |
| | Regional Development | 10.00 | 1 | 10.00 | |
| | | | | **Total** | 20 |
| | | | | **Total Score for Windfarm** | 217 |