Department of Mechanical and Aerospace Engineering

Testing the Power System Feasibility of Scotland's Renewable Energy Targets

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Abstract

This project endeavoured to model the new Scottish renewable energy targets, as set out in the Electrical Generation Policy Statement (EGPS), and accompanying report by consultants Sinclair Knight Mertz (SKM). Modelling was completed in ANTARES, a sequential Monte-Carlo simulator developed by RTE. The model included the whole of Great Britain, and key interconnectors with Ireland and with Europe, so to appropriately model the UK national grid and proposed transmission 'bootstraps' between Scotland and the north of England and Wales.

Various improvements were made to previous models used in the department, including a more detailed model of the wind power with more sites of wind speed data and also a single simplified tidal stream time series.

Key objectives were to model the SKM scenario 1, as detailed in their report, and to investigate the feasibility of this suggested scenario regarding the resultant spilled energy and potential transmission curtailment. The relationship between installed capacity and spilled wind was thus examined and the sensitivity of these results to the presence of the transmission 'bootstraps' detailed in the EGPS was also investigated.

It was found that wind energy was only 'spilled' after a certain amount of installed wind capacity, which varied between 9-10GW depending on the transmission setup. Expected values over 200 Monte Carlo years showed that very little energy would be unsupplied or spilled, provided the proposed transmission bootstraps were in place in time. It was also found that with both transmission bootstraps, the transmission capacity would be enough in more than 68% of cases, but with less transmission capability curtailment would happen more frequently.

The overall conclusion was reached that the feasibility of the proposed scenario would be highly dependent on the installed transmission capacity.

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List of Abbreviations

ANTARES	- A New Tool for Adequacy Reporting of Electric Systems
AC	- Alternating Current
BMRS	- Balancing Mechanism Reporting System
CCGT	- Closed Cycle Gas Turbine
CCS	- Carbon Capture and Storage
CHP	- Combined Heat and Power
DECC	- Department of Energy and Climate Change
DTI	- Department for Trade and Industry
DUKES	- Digest of United Kingdom Energy Statistics
EGPS	- Electrical Generation Policy Statement
ELSI	- Electricity Scenario Illustrator
EU	- European Union
HVDC	- High Voltage Direct Current
OCGT	- Open Cycle Gas Turbine
ROCs	- Renewables Obligation Certificates
RTE	- Reseau de Transport d’Electricite (French transmission system operator)
SHETL	- Scottish Hydro Electric Transmission Limited
SKM	- Sinclair Knight Mertz
SPT	- Scottish Power Transmission
SSE	- Scottish and Southern Energy
UK	- United Kingdom

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Introduction

1.1. Background

Scotland is a country with extensive renewable resources, particularly wind, tidal and wave energy. Scotland has a quarter of the European offshore resources of wind energy and tidal energy, and 10% of the European offshore resources of wave energy [1]. Currently 31% of electricity generation in Scotland comes from renewable sources, mostly from wind and hydro power [2].

Exploiting this renewable energy has many advantages; reducing emissions, no fuel needing to be purchased (reducing costs and increasing security of supply) and increased sustainability. There are also several disadvantages, particularly regarding energy generation relying heavily on certain weather patterns such as wind, solar and wave power. These are less predictable than other forms of energy generation, which could result in shortages of supply. Also renewable sources such as wind, hydro and marine energy are dependent on specific geographical conditions, and thus these sources of energy are more geographically dispersed than traditional thermal power sources. This entails a whole new set of issues with the transmission of renewable power, most notably with connecting such sites to the grid and upgrading transmission networks.

The Scottish Government have recently set an ambitious target for 100% of the Scottish electricity consumption in 2020 to come from renewable energy, as part of a wider electricity mix. To this end, an Electricity Generation Policy Statement (EGPS) has been produced, outlining how these targets can be met [1]. This involves an estimated 14-16GW of installed renewable capacity required, almost four times as much as is currently installed. This additional installed capacity will most likely be made up of a very high proportion of wind energy (approx 13GW), which introduces various new complications due to its stochastic nature.

Critics of these targets argue that Scotland does not have the necessary infrastructure, technology, skills or funding for such an ambitious project [3]. Also, the project does not meet the Institute of Mechanical Engineers sustainability policy regarding energy, which specifies that energy demand reduction and improved energy efficiency should be prioritised before introducing increasing amounts of generation capability [3].

As part of their report, the Scottish Government commissioned consultants Sinclair Knight Mertz (SKM) to produce a study on the possible scenarios of generation mix to meet this target and the resulting power flows. From this study they consider the target of 100% electricity generation from renewables to be 'technically feasible', provided that additional transmission capacity would be installed by 2020 to support the increased requirements for electrical import and export. Without this additional transmission capacity, generation would have to be curtailed by 2020. See section 2.1.2 for further detail on the SKM report.

The main barriers to this project seem to be connection issues between renewables and the grid, transmission issues limiting the amount of power that can be exported from Scotland and economic issues involving the cost of such a large scale project [1]. This report focuses on investigating some of the issues that could occur by 2020 due to significantly higher electricity generation from renewables.

1.2. Project Objectives

This project would aim to undertake a similar analysis to that of SKM, modelling the possible future scenarios as closely as possible. The resulting installed capacity, spilled wind, unsupplied energy and transmission power flows will be compared to explore the issues related with such high generation levels of renewable energy.

The key objectives are:

1. To model the SKM scenario 1 in RTE tool ANTARES
2. To conduct a simulation study with different levels of installed wind power in Scotland, to investigate the relationship between installed capacity and spilled wind
3. To conduct a simulation study with and without the transmission ‘bootstraps’ providing additional capacity to the Scotland-England link

1.3. Project Scope

This project focuses specifically on the electrical generation within Scotland and so does not explore issues such as energy used in transportation and heating. Although focusing on Scotland, the modelling undertaken is of the entire UK, to get as realistic as possible a simulation of the UK electrical grid.

It is logical to focus mostly on changes regarding wind power, as the predicted installed capacity mix by 2020 will be made up of more than 50% wind power. This will be discussed in greater detail in later sections.

The year 2020 was chosen as the year to model due to the significant targets set for this date by the Scottish Government and many other governing bodies.

1.4. Methods

Objective 1

Use the RTE ANTARES tool to model possible generation scenarios

This involves creating equivalent models of electrical systems, to simplify interconnected power systems into 'nodes'. Each node in the model will represent the electrical demand and supply present in that area. The tool uses Monte Carlo simulation to model variations such as weather changes and outages of the system.

The general methodology of this modelling involves several steps:

> -Defining the generation in each area using the SKM report as a general guide and conducting further research as to the planned renewable energy developments by 2020.
>
> -Where no current planning or scoping processes exist and yet the SKM scenario suggests an installed capacity of renewables, using research and educated guesses to place this capacity to an area of the model.
>
> -Research parts of the model such as transmission capacities, links, load and economics to build up a logical and defendable model of the UK electrical grid by 2020.

-Editing the existing ANTARES models available and creating new parts to adequately fit the SKM scenarios and model the UK transmission system of 2020.

-Run simulations using these models in ANTARES to meet the further objectives.

Objective 2

Conduct a simulation study with different levels of installed wind power in Scotland, to investigate the relationship between installed capacity and spilled wind

Using the model built up in ANTARES, simulations will be undertaken with different levels of installed wind power, and the resultant spilled wind for each scenario noted. A graph will be drawn up to view any resulting relationship between installed capacity and spilled wind.

It is postulated that spilled wind and installed capacity could be linearly related, so that an increase in installed capacity also results in an increase in spilled wind (figure 1.4-1, below). However this relationship may be found to be more complex, and there could in fact be a point where an increase in installed capacity results in a very large increase in spilled wind (figure 1.4-2, below), signifying a point where the investment for additional installed capacity is unwise.

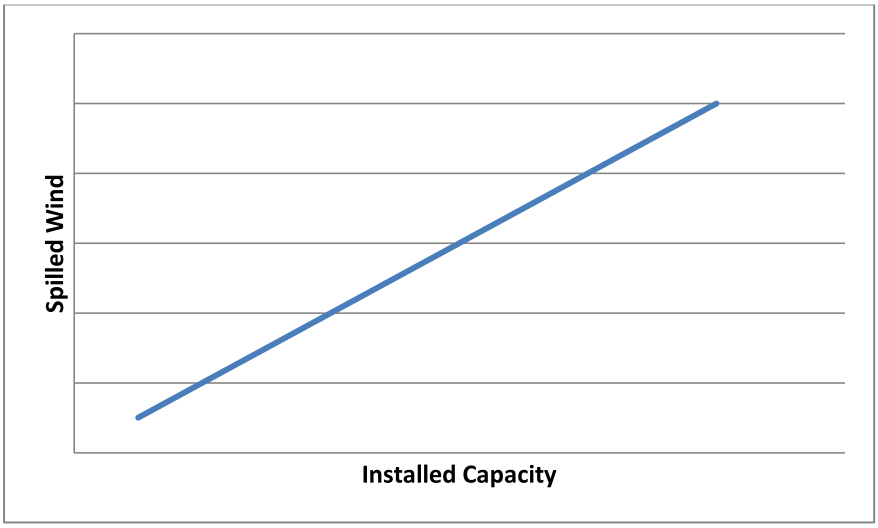


Figure 1.4-1. Illustrating a direct linear relationship between installed capacity and spilled wind

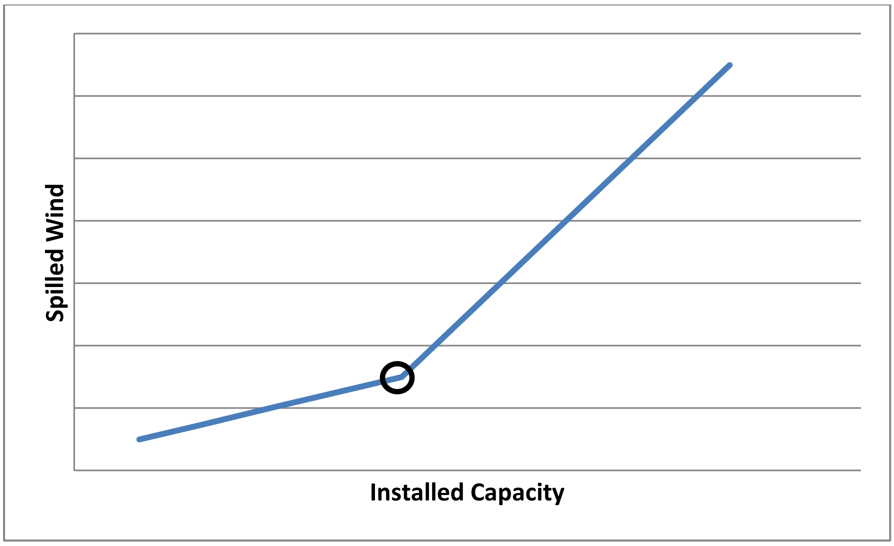


Figure 1.4-2. Illustrating a point of change in the relationship between installed capacity and spilled wind

Objective 3

Conduct a simulation study with and without the transmission ‘bootstraps’ providing additional capacity to the Scotland-England link

An additional point to investigate would be the sensitivity of the spilled wind results to the transmission capacity between Scotland and England. In particular the two key transmission bootstraps under construction, the East and West HVDC links. In theory, these will be completed by 2020, but if the East link is delayed at the construction phase, or the West link is delayed due to issues concerning planning permission, then it is possible one or both links may not yet be completed by this date.

This would be investigated by creating similar graphs as in the previous section, with one or both links missing.

2. Key Concepts

2.1. Government Targets and Renewable Energy

2.1.1. Energy and Emissions Targets

For the past two decades we have seen an increase in governmental targets regarding climate change and emissions, the most recognisable being the Kyoto agreement in 1997. Emissions of carbon dioxide in particular have been targeted to be reduced, as a major greenhouse gas. Since the majority of emissions are a result of the processes required by the energy sector, solutions such as reducing energy consumption and increasing the overall usage of renewable energy sources have been suggested.

Recently, 2020 has been chosen as a key year for climate change and renewable energy targets. The EU in particular have been noted for their Renewable Energy Directive, involving various targets for member states to reach their overall target of 20% energy coming from renewable sources by 2020 [4]. It also has targets of 20% reduction in emissions compared to 1990 levels, and 20% reduction in energy usage due to energy efficiency measures. These targets are known as the ’20-20-20’ targets [5]. Due to the heating and transport sectors mainly using fossil fuels such as gas and oil, and conversions to renewable sources of this energy being very costly, many countries have focused on electrical energy as the main provider of these targets.

The EU directive requires that the UK has a target of 15% energy from renewable sources by 2020. This has led to the target that 30% of electricity from the UK is to be from renewable sources by 2020, a vast increase from 6.7% in 2011 [6].

2.1.2. Scottish Government Targets

In 2011, The Scottish Government set a target to produce 100% of the Scottish electricity demand equivalent from renewable sources. Since then they have produced various reports on the plans and progress for such an ambitious target.

The 2020 Routemap for Renewable Energy in Scotland [7] was created by the Scottish Government in 2011 as an update to their previous Renewables Action Plan, based on the new renewables targets. In this report they discuss various issues such as costs, planning and infrastructure, as well as going through each type of renewable energy and stating the applicable ambitions and targets. They conclude that various steps need to be taken to simplify the processes for developers and communities, increase transmission capacity quickly and encourage the research and development of technologies such as hydrogen systems, geothermal energy, wave energy and tidal energy.

The Electrical Generation Policy Statement [1] was originally produced in 2010 but updated for the new renewable targets in 2012. It describes these new targets in detail, not only the 100% electrical demand from renewables target but also targets for community ownership of renewables, lowering energy consumption and introducing carbon capture and storage at a large scale. It features an appendix summarising the modelling completed by SKM.

The key targets from the Scottish Governments electricity generation policy statement [1] are:

> “ *- delivering the equivalent of at least 100% of gross electricity consumption from renewables by 2020 as part of a wider, balanced electricity mix, with thermal generation playing an important role through a minimum of 2.5GW of thermal generation progressively fitted with Carbon Capture and Storage (CCS);*
>
> *- enabling local and community ownership of at least 500MW of renewable energy by 2020;*
>
> *- lowering final energy consumption in Scotland by 12%;*
>
> *- demonstrating carbon capture and storage (CCS) a commercial scale in Scotland by 2020, with a full retrofit across conventional power stations thereafter by 2025-30;*
>
> *- seeking increased interconnection and transmission upgrades capable of supporting projected growth in renewable energy.* ”

The Scottish Generation Scenarios and Power Flows report [8] was compiled by the consultants Sinclair Knight Mertz (SKM) for the Scottish Government in 2012. They detail two scenarios produced to describe possible generation in Scotland in 2020, Scenario 1 meets the 2020 targets exactly, and is largely based on renewables already in planning and development, Scenario 2 is as they describe ‘more ambitious’ and could generate twice Scotland’s electricity requirements by 2020.

Key assumptions for Scenario 1 include:

> “ • *Scottish installed generation capacity almost doubles over the 10 year period to 2020 – with most growth in onshore and offshore wind. Onshore wind increases to 8 GW by 2020 and offshore to 5 GW. This growth rate represents a significant challenge*
>
> • *Some additional renewables also grow, including marine generation and, to a lesser extent, small scale biomass. The growth rate in marine generation also represents a significant challenge*
>
> • *It is assumed that Hunterston B does not extend its life beyond 2016*
>
> • *One unit of thermal plant with carbon capture and storage is installed*” p6 [8]

Key assumptions for Scenario 2 include:

> “ • *Scottish installed generation capacity more than doubles over the 10 year period to 2020 – from around 12 GW to 26 GW*
>
> • *The increase in total capacity is driven by renewables, particularly onshore and offshore wind. Onshore wind increases to 9.5 GW by 2020 and offshore to 7 GW. The implied growth rate from current installed capacity of around 2.5 GW represents an enormous investment challenge*
>
> • *Some additional renewables also grow, including marine generation and, to a lesser extent, small scale biomass. The growth rate in marine generation also represents a significant challenge*
>
> • *Hunterston B receives an additional life extension to 2021*
>
> • *One thermal unit with carbon capture and storage is installed by 2020*
>
> • *In order to maintain Scotland’s aspiration of generating twice its gross electricity requirements three thermal power stations with CCS are required by 2030 as older thermal plant retires*
>
> • *No new nuclear plant construction is assumed* ”p7 [8]

The key results from the modelling in this report state that with such scenarios more transmission capability than currently planned will be required between Scotland and England by 2020. This includes the assumption that both the East and West HVDC links will be available by 2020. In addition to transmission capability, the other major potential constraint to these targets will be availability of investments in renewable systems. It is estimated that the total investment to reach these targets would be £35bn, mostly in wind power and additional transmission [8].

2.2. Current State of Energy in the UK

2.2.1. Current Resources and Planning

The pie chart below (figure 2.2.1-1) shows the breakdown of electricity generation in the UK and in Scotland 2010. It can be seen that whilst the majority of generation in the UK is from gas, in Scotland the generation has a more even split between nuclear, coal, renewables and gas.

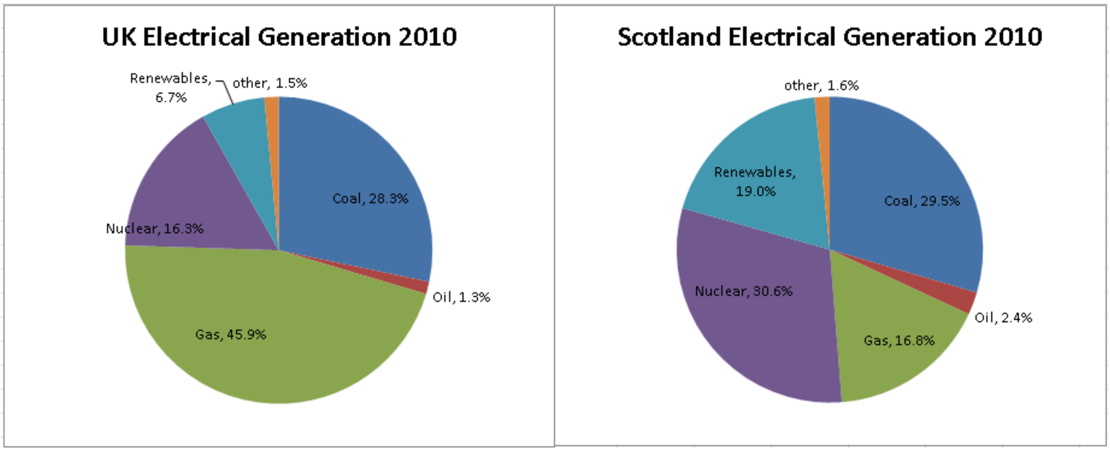


Figure 2.2.1-1 Electricity generation in the UK and Scotland in 2010. Data from DUKES [9]

Installed capacity of renewable energy in the UK has increased greatly over the past decade, particularly wind and bioenergy sources. This is illustrated in figure 2.2.1-2 below.

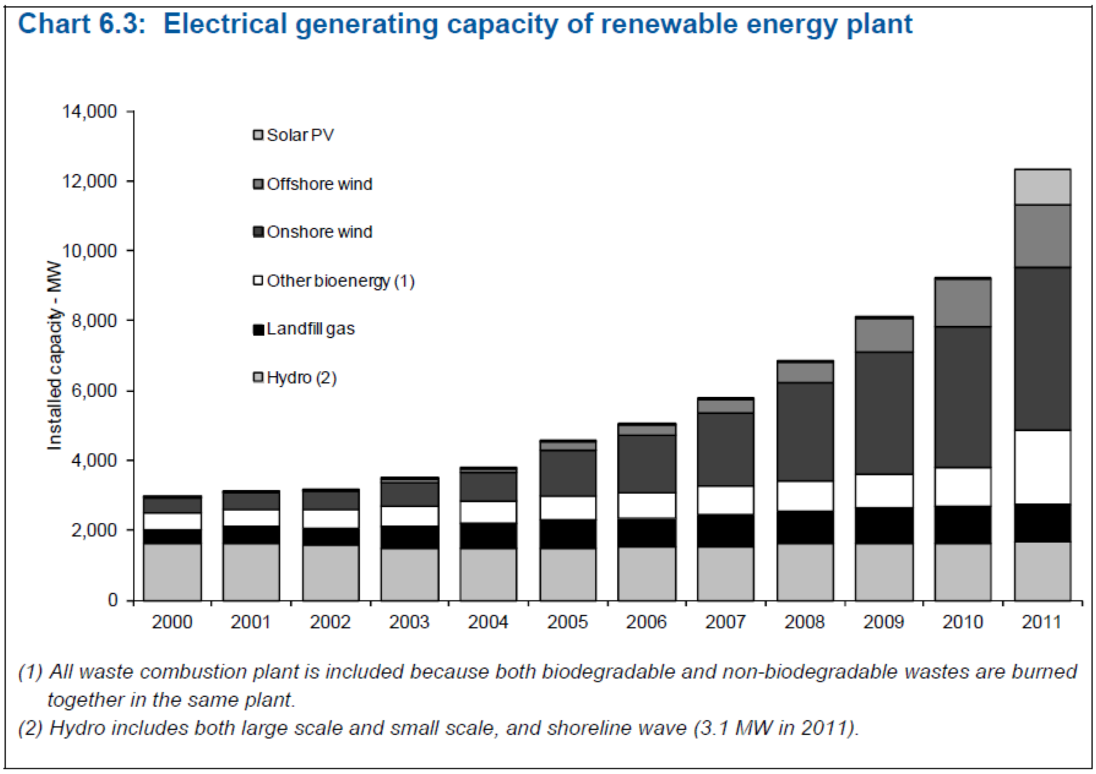


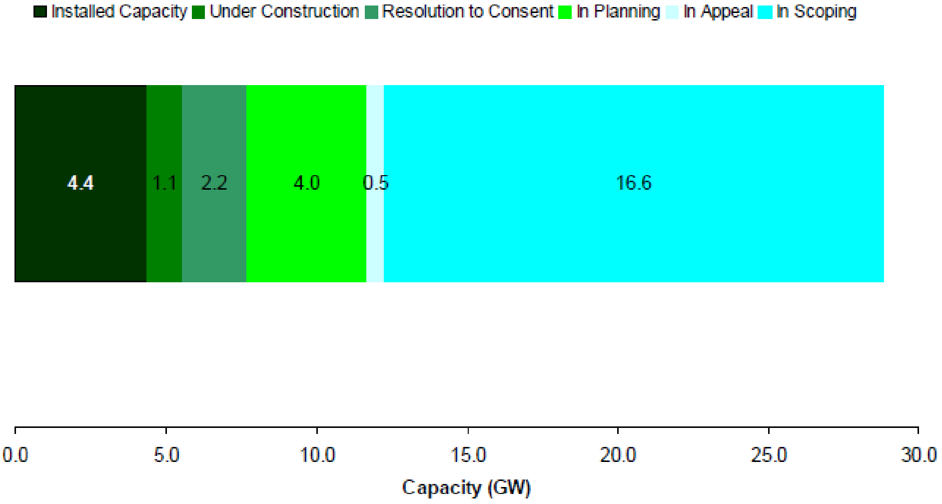
Chart 6.3: Electrical generating capacity of renewable energy plant

(1) All waste combustion plant is included because both biodegradable and non-biodegradable wastes are burned together in the same plant.

(2) Hydro includes both large scale and small scale, and shoreline wave (3.1 MW in 2011).

Figure 2.2.1-2 Installed capacity of renewable electrical generation from 2000-2011, taken from DUKES [9].

In Scotland in particular, a high number of renewable energy projects are in the scoping and planning stages. Figure 2.2.1-3 below illustrates the potential capacity of renewable energy projects in various stages of development.

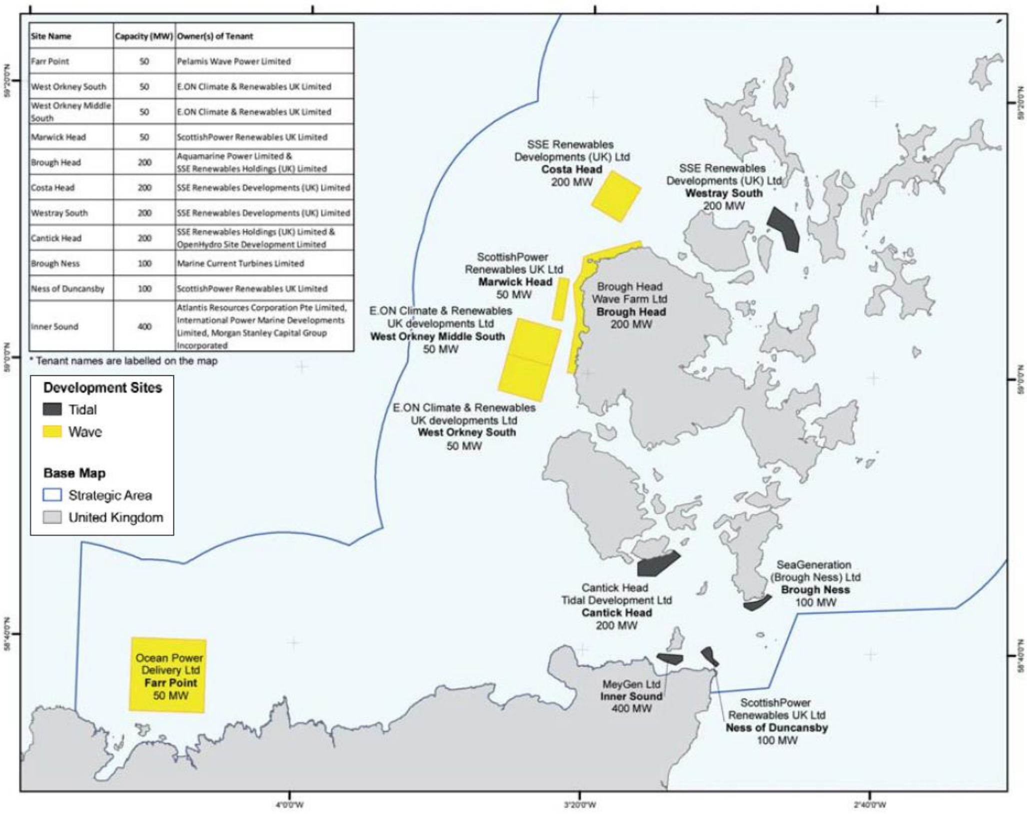


Note: Not all projects in scoping will proceed to planning/consent

Source: Scottish Renewables (21st December 2011)

Figure 2.2.1-3 Scottish Renewable Capacity, taken from Scottish Government EGPS [1].

Specific upcoming projects include various leasing sites by the Crown Estate for marine renewables. In particular of note is the new Marine Energy Park development in the Pentland Firth and Orkney waters, a wave and tidal development that could have an installed capacity of up to 1,600MW. Figure 2.2.1-4 below illustrates the developments occurring in this area.



Site Name	Capacity (MW)	Owner(s) of Tenant
Farr Point	50	Pelamis Wave Power Limited
West Orkney South	50	E.ON Climate & Renewables UK Limited
West Orkney Middle South	50	E.ON Climate & Renewables UK Limited
Marwick Head	50	ScottishPower Renewables UK Limited
Brough Head	200	Aquamarine Power Limited & SSE Renewables Holdings (UK) Limited
Costa Head	200	SSE Renewables Developments (UK) Limited
Westray South	200	SSE Renewables Developments (UK) Limited
Cantick Head	200	SSE Renewables Holdings (UK) Limited & OpenHydro Site Development Limited
Brough Ness	100	Marine Current Turbines Limited
Ness of Duncansby	100	ScottishPower Renewables UK Limited
Inner Sound	400	Atlantis Resources Corporation Pte Limited, International Power Marine Developments Limited, Morgan Stanley Capital Group Incorporated

* Tenant names are labelled on the map

Figure 2.2.1-4 Round 1 developments in Pentland Firth and Orkney waters. From [10].

This development will face many challenges however. Research and development of such technologies still need to be completed. Also there is no established supply chain for wave or tidal devices and there will be difficulties with connection and transmission of power from the very top of Scotland to where it is required [10].

Other leased sites for renewable energy in Scottish waters are shown below in figure 2.2.1-5.

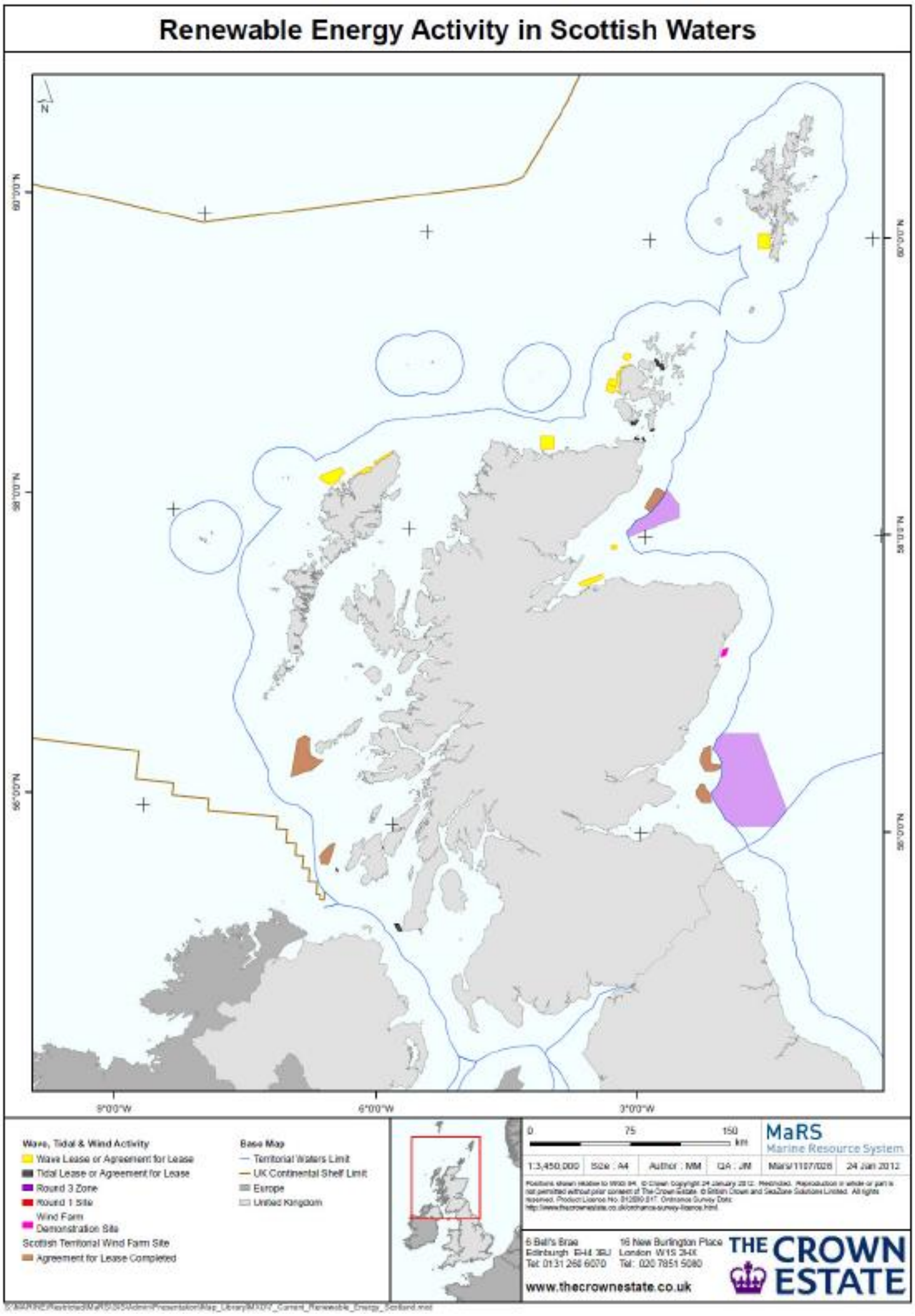


Figure 2.2.1-5 Offshore Renewables Sites, taken from Scottish Government EGPS [1]

Other projects include SSE’s Choire Ghlais pumped storage development in Lochaber [11], the Viking onshore wind development in Shetland [12], new wind farms such as

Dorenell and Dumnaglass and extensions to existing wind farms such as Harestanes and Blackcraig [13].

2.2.2. Transmission Setup

The electrical transmission setup in the UK comprises a complex grid of high voltage overhead lines, linked with the lower voltage underground distribution network. A map of the transmission network in Scotland is shown in the figure below.

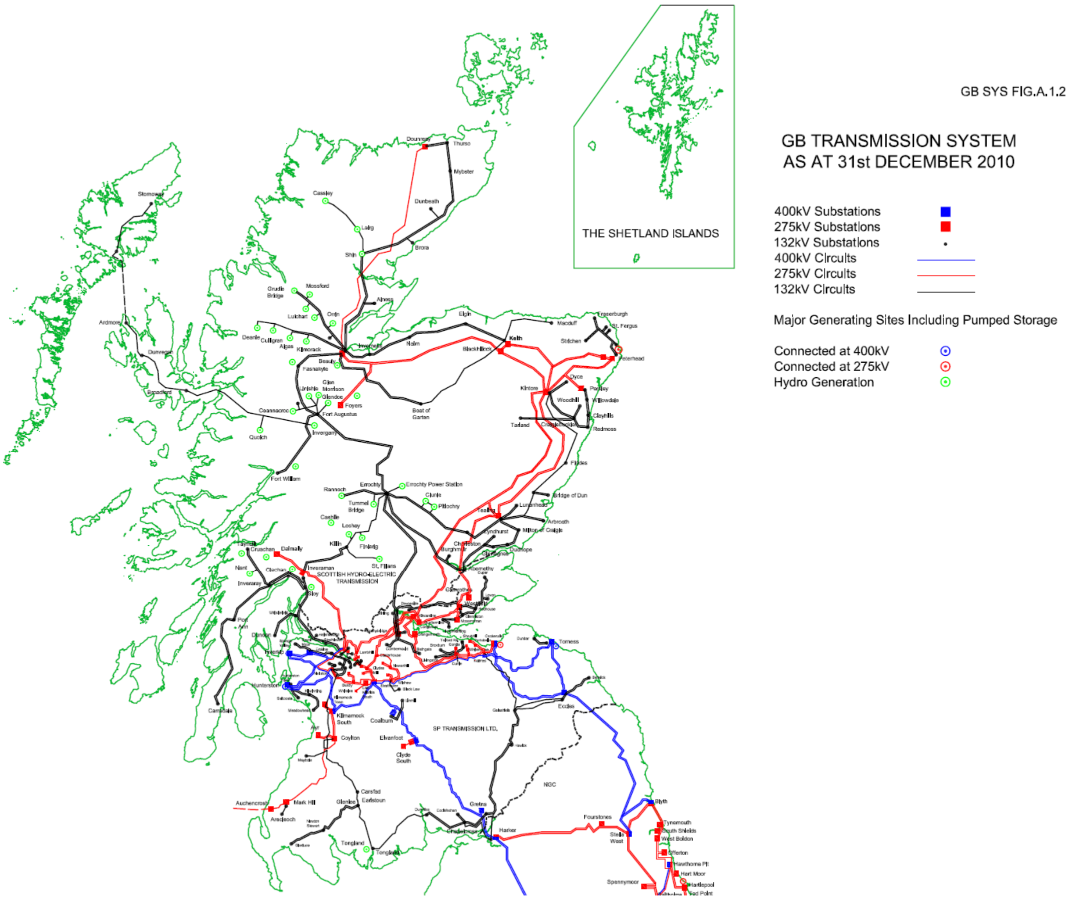


Figure 2.2.2-1. Map of transmission network in Scotland. Taken from NG Seven Year Statement [14].

This existing network in Scotland uses alternating current (AC). Many proposed transmission links are High Voltage Direct Current (HVDC). This has advantages over the AC transmission network in the UK due to reduced losses (loss being proportional to the square of the current). Normally, these HVDC links are proposed when over large distances due to considerable improvements in losses.

To continue effective transmission in the future, various additions to this transmission grid are underway. Two subsea interconnectors between Scotland and England are currently in development, as illustrated in figure 2.2.2-2 below. These will have a transmission capacity of 1.8GW. Also a proposed 600MW HVDC link will connect Caithness to Moray to allow the transmission of energy from various offshore developments in the pentland firth [15].

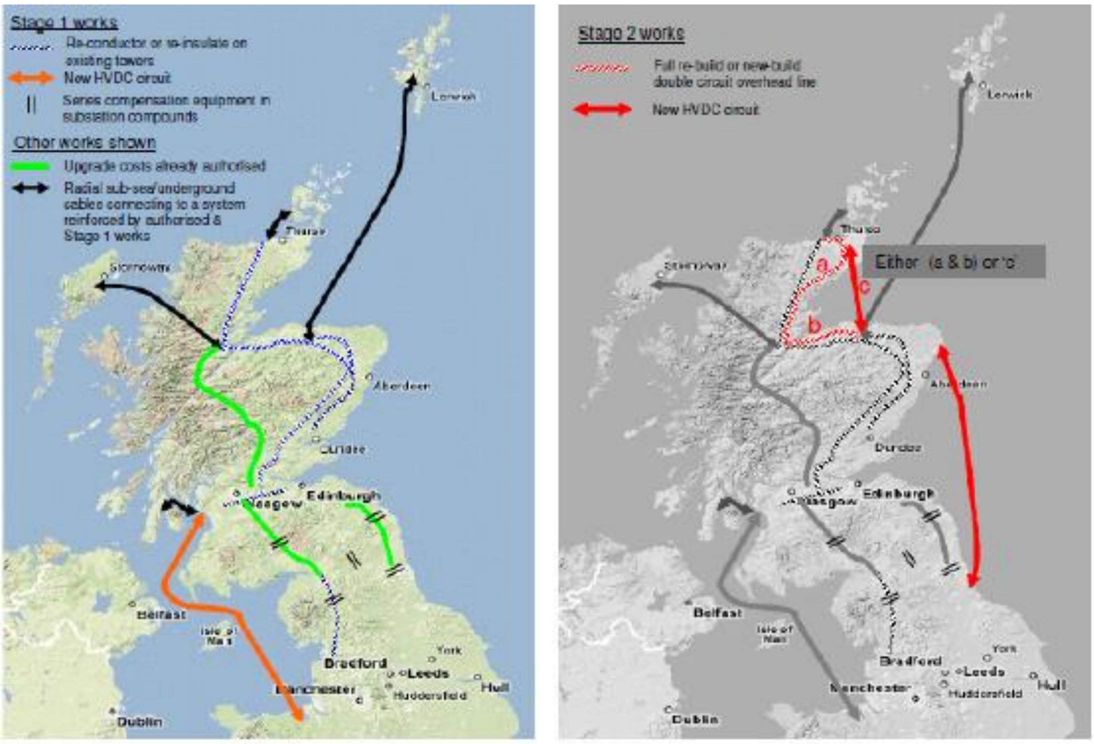


Figure 2.2.2-2 Stage 1 and 2 Transmission reinforcements. From the EGPS [1]

In addition to the UK grid there are various existing HVDC interconnectors between the UK and Ireland and Europe. These are illustrated below in Figure 2.2.2-3.

Figure 2.2.2-3. Interconnectors between UK and Europe, colour coded as existing, in progress and proposed. From Guardian article [16].

The key interconnectors affecting transmission in and out of the UK by 2020 are described below:

Moyle - between south-west Scotland and Northern Ireland. Owned by Mutual Energy, this link originally had 500MW transmission capacity. However it became out of service late in 2011, and following repairs is now operating at 450MW [17].

East-West - between the Republic of Ireland and Wales, with a transmission capacity of 500MW. East-West is currently under construction by eirgrid, and is due to be in operation by the end of 2012 [18].

Anglo-French - between south-east England and north-east France. Built in the 1980’s it has a transmission capacity of 2000MW and is jointly owned and operated by NGC and RTE [19].

BritNed - between south-east England and the Netherlands has a transmission capacity of 1000MW. It is operated by BritNed Development Ltd, a joint company owned by National Grid and TenneT [20].

2.2.3. Network Limits

It has already been mentioned that ambitious renewable energy targets such as those introduced by the UK and EU involving a higher proportion of renewable energy can result in issues with transmission. A key conclusion of the Scottish government EGPS was that transmission constraints would be a significant factor in ensuring that the renewable energy produced is properly utilised [1].

This report focuses on a scenario with a high proportion of installed wind power. Wind power in particular with its unpredictability and variability can cause issues with distribution systems, such both slow and fast variations in voltage, resulting in voltage ‘flicker’ [21].

One key issue when considering network limits is the sensitivity of the network to temperature. Losses cause heating in electrical lines, and to maintain thermal limits the transmission capacities can reduce at higher ambient temperatures in warmer seasons. Quite simply, this can be modelled by reducing the transmission capacity during warmer seasons [22].

Another issue is maintaining the frequency of an AC power system. Within the UK grid this frequency is 50Hz. This figure is very sensitive to any changes in the load-generation balance; if the real power generated is less than the load required the frequency falls and if the generation is greater than the load then the frequency will increase [21]. Essentially, to maintain a steady AC frequency electrical demand must be met by generation and this becomes progressively more challenging when dealing with unpredictable sources of energy.

2.2.4. Electricity Trading

The system of electricity trading in the UK exists to ensure that electricity supply meets demand within transmission limits. Generation units may be committed to producing electricity depending on their availability. Factors such as minimum down time, minimum up time, ramping rates and fuel constraints will affect this availability, specifically for thermal generation with higher minimum up/down times such as nuclear and coal power [23].

The 24 hour day is split into 48 half-hourly settlement periods. Trading for each settlement period ends an hour before the settlement period begins, and generators and suppliers must agree on the amount of energy to be traded by this time. Any inconsistencies in supply and demand are dealt with by National Grid by means of bids (generators offering to reduce generation, suppliers offering to increase demand) or offers (generators offering to increase generation, suppliers offering to reduce demand) [24]. A certain amount of spinning reserve is kept to deal with emergencies such as outages.

2.3.Renewable Energy Systems

2.3.1. Wind Power

Electricity generation from wind is very different to traditional thermal generation. Thermal generation occurs mostly at full capacity, once up and running. Wind power on the other hand is entirely dependent on the wind speed at any given time. The annual variation of wind speeds tends to follow a Weibull distribution, illustrated below in figure 2.3.1-1.

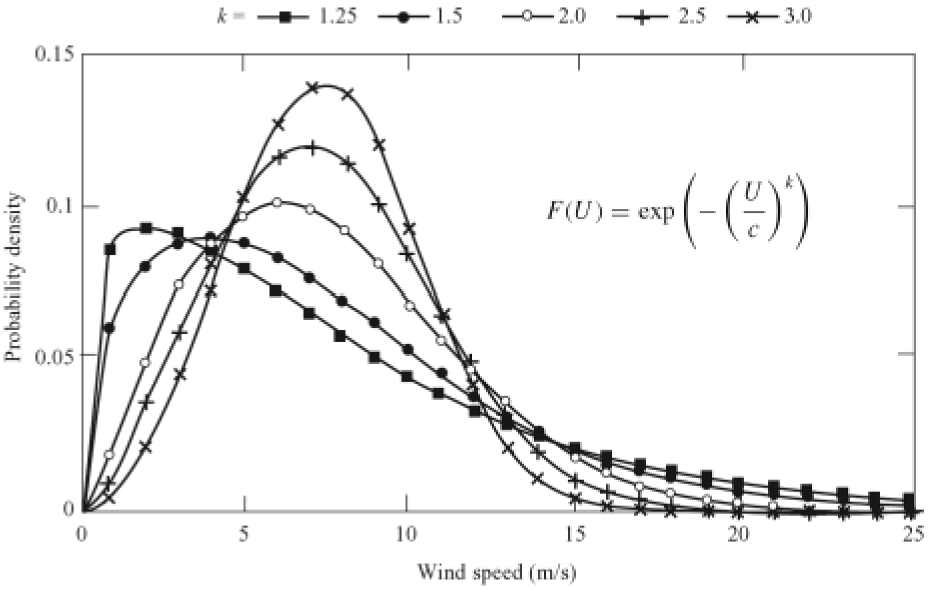


Figure 2.3.1-1 Some examples of Weibull distributions, taken from Fig2.2, p13 Wind Energy Handbook [21].

Power generated from a wind turbine is proportional to the cube of the wind speed, and can be calculated by the following equation:

$$P = \frac{1}{2} C_p \rho A V^3 \qquad \text{(equation 1) [21]}$$

where P is power produced (W), Cp is the power coefficient of the device (%) , ρ is the density of air (kg/m^3), A is the swept area of the blades of the device (m^2) and V is the wind speed (m/s).

Cut-in and Cut-out wind speeds are typically around 3m/s and 28m/s, meaning that generation can only occur when the wind speed is between these values. Rated speeds are typically around 15m/s, after which power generation is at full capacity for the device. For a single turbine the power curve rises steeply until the rated value for generation, and falls back to zero at the cut out speed. For a wind farm the curve rises to a maximum less than 100% and then falls steadily at a value less than the cut out speed. These power curves are shown below.

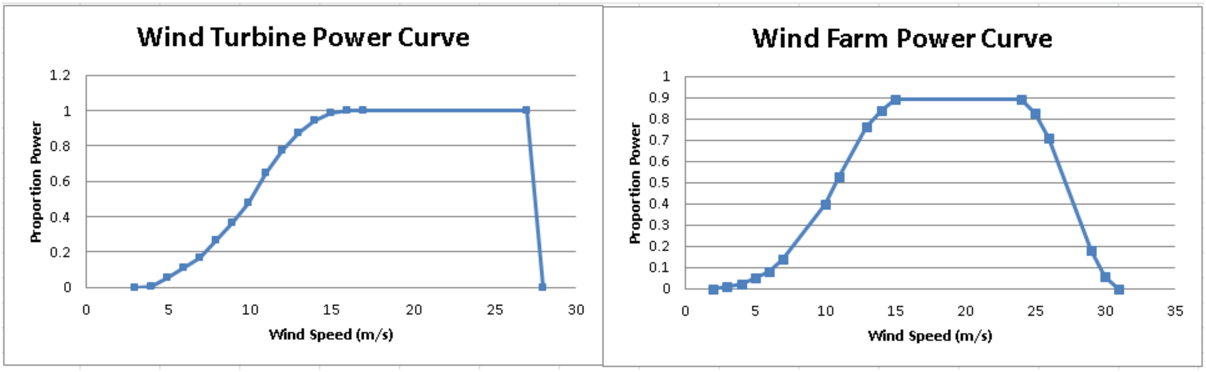


Figure 2.3.1-2 Wind Turbine and Wind Farm power curves, respectively. Supplied by Garrad Hassan to the University of Strathclyde.

An important metric used in this study to describe wind power is the capacity factor. The capacity factor is defined by Adaramola et al [25] as *"the fraction of the total energy produced over a period of time divided by the maximum energy that could have been produced if the turbine was to operate at designed rated power over the entire period"* It can be used to describe all kinds of power generation, not only wind.

Wind power has several advantages and disadvantages. The main advantages are that it is an environmentally clean (once installed), well developed technology that has been used for hundreds of years in one form or another. The main disadvantages, regarding onshore wind power in particular, are that there is often a very public opposition to any new development. Planning processes include environmental assessments and public consultations and tend to last a long time and often delay the progress of such ventures. Another key disadvantage of wind power is its unpredictability; lulls of several days can be relatively common [26].

The first offshore wind farm was installed in 1991 at Vindeby, since then various developments have taken place, particularly by Denmark but also by the UK, Belgium, the Netherlands and China. The advantages and disadvantages of offshore wind are less social and more technical than those discussed previously of onshore wind. Advantages include; less planning permission issues, larger turbines and thus more energy captured per turbine, high average wind speeds and low turbulence. Disadvantages include higher capital costs and challenges with connection to developments that are not 'near shore'. In addition the sea is an extremely corrosive environment, and introduces difficulties with the renewable energy systems and with the transmission of the electricity. In Horns Reef in Denmark, a large dismantling and repair effort had to take place just 18months after the wind farm had been installed, due to the corrosive effects of the sea air [26].

2.3.2. Spilled Energy

Spilled energy is a term describing the energy that is generated, but cannot be used in the current system setup, due to low demand or lack of transmission capacity. All generated energy can be 'spilled', but this study focuses especially on 'spilled wind'. No renewable energy in this study is curtailed, and so all energy not used is recorded as spilled.

2.3.3. Tidal Power

Tidal behaviour is caused by the gravitational effect of the moon and the sun on the seas, as well as the rotation of the earth. The moon has a much stronger influence, even though much smaller than the sun, due to it being considerably closer. Tides in the UK and other countries on the Atlantic coastline are semidiurnal, occurring twice a lunar day. This means we get two maxima and minima of tidal height every 24hours and 50minutes. Spring tides occur when the moon is full or new (in line with the sun), and are considerably stronger than neap tides, which occur in between. Neap tides are weaker due to the partial cancellation of the forces from the sun and the moon. Seasonal variations also occur due to the relative position of the sun to the moon and the earth, and take an annual pattern [27].

Tidal power can be harnessed using tidal lagoons, tidal barrages and tidal streams. This project focuses only on tidal stream power, and in particular at the recent Pentland Firth development. Tidal streams are created by water flowing between positions of high and low tide. This occurs mostly in areas where straits between land masses mean that the stream is in effect constrained, and then allowed to flow. Horizontal axis tidal stream turbines work in much the same way as wind turbines, only using the tidal stream to turn the turbine instead of the wind.

The main advantage of tidal power is its reliability. From year to year there is less than a 5% difference in tidal behaviour [27]. Other advantages include the possibility of storage in lagoons, the higher power density of the medium, no visual impact and the sustainability of the power source [26]. The major disadvantage is again the corrosive powers of the sea, introducing frequent maintenance which is expensive. In addition, tidal turbines are a relatively new technology, especially compared to wind turbines, and much research and development work still has to be completed.

3. Modelling the UK National Grid

3.1. ANTARES Software

ANTARES (A New Tool for Adequacy Reporting of Electric Systems) is a Monte-Carlo simulator used to model interconnected power systems, and has been used for various studies [28], [29]. Developed by RTE in France, simulations minimise costs of transmission and generation by modelling hourly system performance over various Monte-Carlo years.

ANTARES is specifically a sequential Monte-Carlo simulator, which considers each hour over each 8760 hour Monte-Carlo year to be dependent on those previous, differing from non-sequential Monte-Carlo simulators, which treat each hour independently. This has the advantage that outage and spin-up/spin-down rates for generators can be accounted for; to give an example a coal-fired generator taking several hours to spin-up is able to be modelled correctly [30].

Also the ANTARES software in particular allows spatially connected areas to have spatially dependant variables by introducing special coefficients, for example similar sites of wind data or rainfall data will have similar wind and hydro power results. By running simulations over many (typically hundreds) of Monte-Carlo years, expected values for more stochastic energy sources such as wind power can be achieved, as well as minima and maxima to account for unusual years of factors such as weather patterns, generation or load.

The model built up in ANTARES for this study is relatively simple; 9 nodes across the UK describe the generation, transmission connections and load for each area. It was based on a model constructed by a previous student and altered to suit this study. The model is shown below in figure 3.1-1

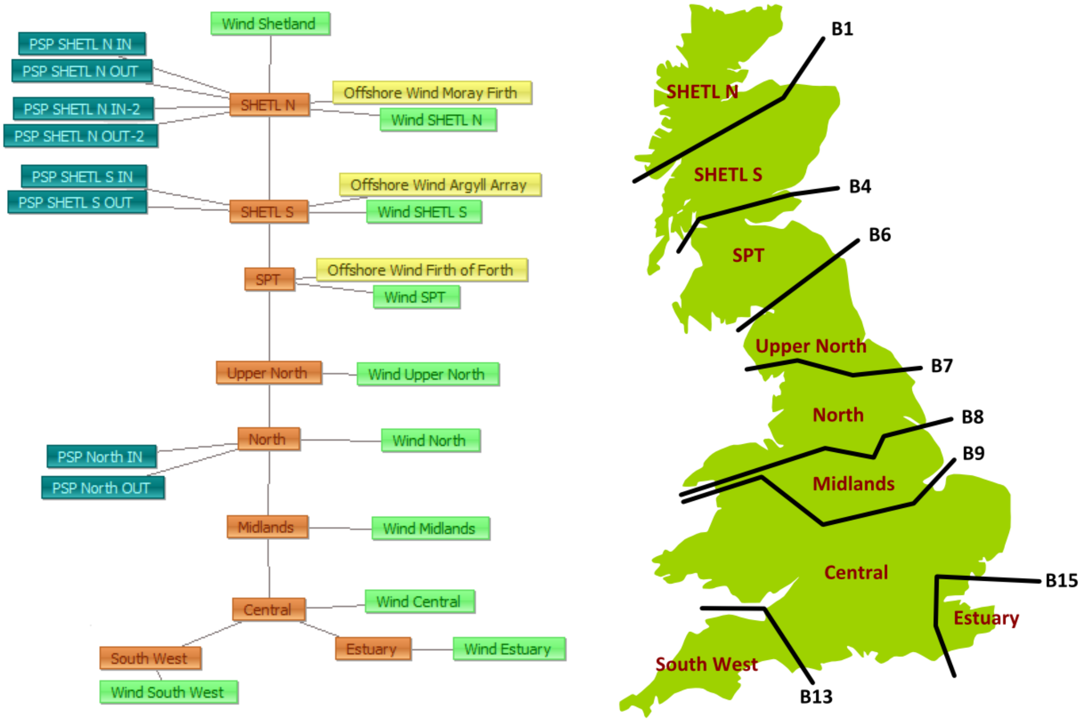


Figure 3.1-1 ANTARES model, alongside display of boundaries on UK map, taken from [31]. PSP regions correspond to pumped hydro.

The model could have been adapted to be more complex and model more areas, but due to the extent of assumptions and uncertainties already involved in future predictions and simplified models this would most probably increase the uncertainties rather than improving the accuracy of the model [29].

3.2. Transmission

Each scenario model contains various ‘nodes’ describing different areas of the UK, shown in figure 3.1-1 above. These nodes are connected by transmission ‘links’ set to the maximum transmission capacity between them, simulating a heavily simplified equivalent electrical network.

There are seasonal variations in the modelled transmission capacity, to account for generally higher temperatures in the summer months affecting the thermal limits of transmission. This has been simplified to a higher transmission capacity for the winter months (December to February), a 10% lower transmission capacity for spring and autumn (March to May and September to November) and a 20% lower transmission capacity for summer (June to August).

Transmission capacities between each area were updated in the model using the inputs from the ELSI tool by National Grid [32]. These are shown below:

Link	**Transmission Capacity (Direct)** *Winter/Spring-Autumn/Summer*	**Transmission Capacity (Indirect)** *Winter/Spring-Autumn/Summer*
B1-SHETL N/SHETL S	3189MW/2870MW/2551MW	221MW/206MW/187MW
B4-SHETL S/SPT	4705MW/4235MW/3764MW	726MW/666MW/605MW
B6-SPT/Upper North	4300MW/3870MW/3440MW	1662MW/1524MW/1385MW
B7a-Upper North/North	5800MW/5220MW/4640MW	1927MW/1767MW/1606MW
B8-North/Midlands	13700MW/12330MW/10960MW	2410MW/2209MW/2008MW
B9-Midlands/Central	13900MW/12510MW/11120MW	1842MW/1689MW/1535MW
B13-Central/South West	1396MW/1279MW/1163MW	4800MW/4320MW/3840MW
B15-Central/Estuary	2298MW/2107MW/1915MW	6400MW/5760MW/5120MW

Table 3.2-1 Transmission Capacities throughout the year

3.3. Thermal Generation

Thermal generation is described in ANTARES as clusters of plants with the same performance characteristics (e.g. efficiency, size, fuel). Time series of generation available for dispatch are generated from each of these clusters. Outages, both planned and unplanned, are dealt with using probabilities of occurrence and associated downtime for these cases.

Minimum up/down times were altered due to a new version of the software being available that allowed inputs of any integer value (rather than previously 1hr, 24hr or 168hr). Open cycle gas (OCGT) was kept at 1hr, closed cycle gas (CCGT) was changed from 24 hours to 8 hours, coal was changed from 24 hours to 12 hours and nuclear was kept at 168 hours. This was decided due to various quoted figures in the literature [33] [34], and also from ELEXON's balancing mechanism reporting system (BMRS) [35].

The minimum stable power was already set in the model to 40% of the average generating unit for each type of generation. For OCGT this was 25MW, CCGT 100MW, coal 100MW and nuclear 200MW.

While thermal generation for Scotland was altered to SKM scenario 1, for England it was kept as in National Grids 'Gone Green' scenario, taken from the ELSI tool online [32]. Generation capacities for the model are summarised in table A3.3 in the appendix.

3.4. Hydro Generation

Hydro generation is heavily weather dependant, and so is modelled using historical rainfall data. The yearly to monthly scales are most heavily dependent on this weather data, and are modelled with spatial correlations to ensure that nearby sites with similar weather patterns will also have similar hydro outputs [30].

The simulation maintains the following statistical properties whilst generating time series:

“ (1) For each area and for each month, the distribution of the monthly energies throughout all the Monte-Carlo years follows a Log-Normal fitting of the historical data

(2) For each area, the auto-correlation of the successive monthly hydro-energies follows an exponential fitting of the historical data

(3)The yearly energies of the different area are correlated in the same way as are the yearly rainfalls in the different areas ” p6 [30]

Pumped storage is modelled as separate nodes in this model (seen in blue). This is so energy used in pumping and energy produced by the hydro turbine can both be accounted for. It is assumed to have an overall efficiency of 72%, set up using binding constraints within the model.

3.5. Wind Generation

Wind generation is also heavily weather dependant, and historical wind speed data (adjusted for a hub height of 80m) is used in building the model. ANTARES has a ‘time series analyser’ which analyses historical wind speed data and generates distribution coefficients and calculates the spatial relationship between sites of data. The time series generators then produce time series of wind generation using this adjusted wind speed data, using seasonal coefficients to describe month-to-month relationships in wind speed behaviour and wind farm generation power curves to calculate the produced wind energy from forecasted wind speeds.

The modelling of wind generation was of particular focus in this project. It was found by a previous student that the method of modelling each node using a single source of weather data was not representative of the entire area. This was unsurprising due to the large areas located to each node, for example the SPT area covers the west and east coasts of central and southern Scotland, as well as many different terrain types.

To make the model more representative of the true power generated by wind in Scotland, several points of weather data were included for each node, with the installed wind capacity of the node split and assigned to the nearest weather station. Further details of this can be found in section 4.1. Although each of the sites mentioned in section 4.1 were input to ANTARES for generation of time series, it was found that these could be combined (as the software does when in simulation) for each region, so only one additional node per area was included, with the exception of Shetland. This data could infact have been combined into the wind section of each area, but separate wind nodes allowed the separate ‘spilled wind’ results to be obtained, instead of the whole areas ‘spilled energy’.

Offshore wind generation was dealt with separately for Scotland, the focus of the model, using offshore weather data. English offshore wind generation was assumed to be near shore, with such wind farms being assigned to the nearest onshore coastal weather station.

Embedded wind generation was also included in this model, in both the wind generation and also added to the load to compensate.

3.6. Tidal Generation

Tidal generation is not modelled within ANTARES, which posed a problem due to a significant amount of tidal power forecasted in the modelled scenarios. The assumption is that SKM based their marine energy predictions on a Crown Estate report entitled “Wave and Tidal Energy in the Pentland Firth and Orkney Waters – How the Projects Could Be Built” [10]. This report includes various assumptions for 2020, which are possibly a little too optimistic, with only a leasing round having taken place, and no scoping or planning processes yet completed. As stated in the report:

“Wave and tidal stream energy projects and technologies are currently at early stages of development. While the Pentland Firth and Orkney waters schemes are very promising, no one has yet developed, constructed and operated a commercial wave or

tidal stream project (of multiple devices, operated over several years) and the industry is currently learning how to do this." p9 [10]

A simplified time series was developed for tidal power, using tidal stream velocities for the Pentland Firth, using tidal stream atlases [36] and a nautical almanac [37]. This process is detailed further in section 4.2.

3.7. Miscellaneous Generation

Miscellaneous generation in ANTARES includes Biomass, CHP, waste, geothermal, 'other' and an option for row balance. Biomass and 'other' values in the scenario modelled are included in this section, with a single time series of installed capacity included. This is possibly not the most realistic way to model each of these values, as operational costs cannot be input to this section of the model, and it is likely that these types of generation would in reality essentially be turned on or off when required. However these installed capacities are such low values that any attempt to model this more accurately could involve a great deal of time and effort and yield very little change to the final results.

The 'Row Balance' option did allow interconnectors to be modelled, using time series of historical data input to this area. Negative row balance indicated an import of power to the UK and positive row balance an export of power from the UK.

3.8. Reserve

The 'spinning reserve' of the system is the reserve power available at any moment in time due to generation already 'spinning' and immediately able to connect to the network. This is often a series of thermal power stations paid to run lower than maximum output. The amount of spinning reserve required is described by Wood and Wollenberg as:

"Typical rules specify that reserve must be a given percentage of forecasted peak demand, or that reserve must be capable of making up the loss of the most heavily loaded unit in a given period of time" p135 [23]

In this model the spinning reserve is modelled as coal and CCGT. To make up the reserve of 1320MW this was taken as a percentage of the total installed coal and CCGT and this percentage input into ANTARES as the total spinning reserve.

3.9. Load

Load time series were already loaded into the model and had been taken from averages between 2000-2009 and scaled up for a future demand of 365TWh for the UK [15].

Load split between regions is assumed to be:

SHETL N	0.5 %
SHETL S	2.3 %
SPT	6.6 %
Upper North	4.8 %
North	22.6 %
Midlands	12.7 %
Central	42.5 %
Estuary	3.5 %
South West	4.5 %

Table 3.9-1 Load split percentages, taken from users notes within model, based on data from [31].

Embedded generation from wind and hydro were also already combined into the load profiles for each region.

3.10. Economic Model

Operational costs of various power sources were built into the model by the previous student, including a calculation of carbon pricing of £15 a tonne. These are shown below:

Generation Costs				
	£/kWh	**CO2 kg/MWh (in)**	**Efficiency**	**CO2 kg/MWhe**
Coal	62.8	300.0	30%	1000.0
CCGT	24.9	198.0	45%	440.0
OCGT	31.4	198.0	35%	565.7
Nuclear	6.9	0.0	35%	0.0

Table 3.10-1 Generation Costs within model, both operational and carbon costing. Taken from table 3.2.1 [38]

The minimisation of operational costs in the transmission simulations completed allowed the software to maximise the utilisation of renewable energy. Having no operational costs, renewable energy was used first in load matching in the simulations run, with thermal sources making up the remainder (depending on spin up and spin down cycles and outages). Operational costs of renewables are not included in this model so that their curtailment is not possible, and instead a record can be made of the ‘spilled’ energy that is produced but not used.

Hurdle costs were also built into the model to allow the optimisation process to allow power from closer geographical regions to be used before that from further away. Hurdle costs were set at £0.01 for both directions of transmission for each link.

3.11. Simulations

ANTARES can simulate both system adequacy studies and transmission studies. This project focuses on the transmission studies as an economic optimisation of the power system. This optimisation minimises costs based on the minimum and maximum power able to be generated and the load requirements at each node, as well as the transmission capacity and any binding constraints between nodes.

ANTARES is a Monte-Carlo simulator, meaning each simulation occurs over a number of Monte-Carlo years in order to achieve statistical convergence. It has been suggested that for transmission studies, the simulation should occur over at least 200 Monte-Carlo years [30]. This figure was thus used for all simulations. The result for the model described is a simulation time of around 4 hours, generating over 7Gb of data.

The results generated by ANTARES give expected values, as well as the minimum, maximum and standard deviation for each measurement. Results are displayed as area related, such as operating costs, power generated, unsupplied energy and spilled energy, and link related, such as power flow and congestion frequency. Within ANTARES these can be viewed hourly, daily, weekly and annually. The key metrics used in this study are described below:

Spilled energy

The energy produced by various sources of generation, but not utilised. In this model, wind nodes were modelled separately and so spilled wind was able to be noted separately to other sources of spilled energy. Spilled energy was measured in MWh and totals over the whole year of expected values and minima and maxima were noted.

Unsupplied Energy

The energy required, but not delivered, due to problems either with generation or transmission. Unsupplied energy was measured in MWh and annual totals of expected values, standard deviations, minima and maxima were noted.

Power Flows

Power flowing from one area to another can be viewed as link related results. Expected values, standard deviations, minimum and maximum values were noted for hourly power flows between Scotland and England.

4. Model Improvements

4.1. Wind Power

A particular focus of this project was the improvement of how wind power was being modelled in ANTARES. The original model, inherited from Scott McLaren-Gow had the UK split into 9 sections, and each of these were represented by wind data from only one site within the area. Since his original work, he had considered the problems that could arise from each area only being represented by one site of weather data, and recommended further steps were taken to improve the reliability of the wind data.

Steps taken in this project included assigning more weather sites to the model to give more geographically distributed wind results, and a study of the capacity factors of the data, old and new.

Originally 50 sites of weather data were provided from the Met Office integrated data archival system [39]. This data contained large gaps and large proportions of zeros. Scott analysed the gaps in the data and cut the 50 sites to 26 using the following upper limits:

longest allowable contiguous section of missing data - 216 hours
maximum percentage of any month that could be missing data - 38%
maximum number of missing hours of data in the year – 800

with the following exceptions:

Saughall	2004	- missing hours in year 919
Rhyl	2003	- 1 month with error percentage of 45% - maximum error length of 403
Sennybridge	2000	- 1 month with error percentage of 60% - max error length 444
	2005	- max error length 309
Langdon Bay	2007	- 1 month with error percentage of 54% - max error length 607

Histograms were also generated to view the sites with high proportions of zeros in the data. Sites were labelled either ‘suspicious’, ‘kind of suspicious’ or ‘fine’ depending on these histograms. The 26 sites of data remaining were converted to a hub height of 80m and gaps were filled in using the Shepards method of inverse distance weighted averaging, with a weighting parameter of 2. All of this work was passed on by Scott and using his results decisions were made regarding which sites to include and which sites to discount.

From the 26 sites, six were discounted as suspicious (Rhyl, Culdrose, Holbeach, Coningsby, West Freugh and Altnaharra). The remaining suspicious sites (Aultbea, St Beeshead, Valley and Chivenor) were kept to allow a certain amount of geographical distribution of wind data within the regions.

On further examination of the data, the capacity factors of the generation data for each site were produced by ANTARES. This led to a further five sites being struck off due to yielding unacceptably low generation (less than 20%). The locations of these fifteen sites are shown in figure 4.1-1 below. Sites struck off due to low capacity factors were ChurchFenton, Nottingham, Wattisham, Sennybridge and Eskdalemuir.

A further verification stage was completed on the data once entered into ANTARES and analysed by the time-series analyser. It was important to check that the temporal coefficients generated had a maximum in winter (December/January) and a minimum in summer (June/July) to make sure that the time series generated had an annual pattern with these trends. The weather data had been passed on without an indication of the time and date of the first data point and so it was possible that the input data could have started in the summer, where wind speeds are typically less. This verification stage made sure that higher generation of wind power occurred in the winter months, in which the model also has a higher load and higher transmission capacities.

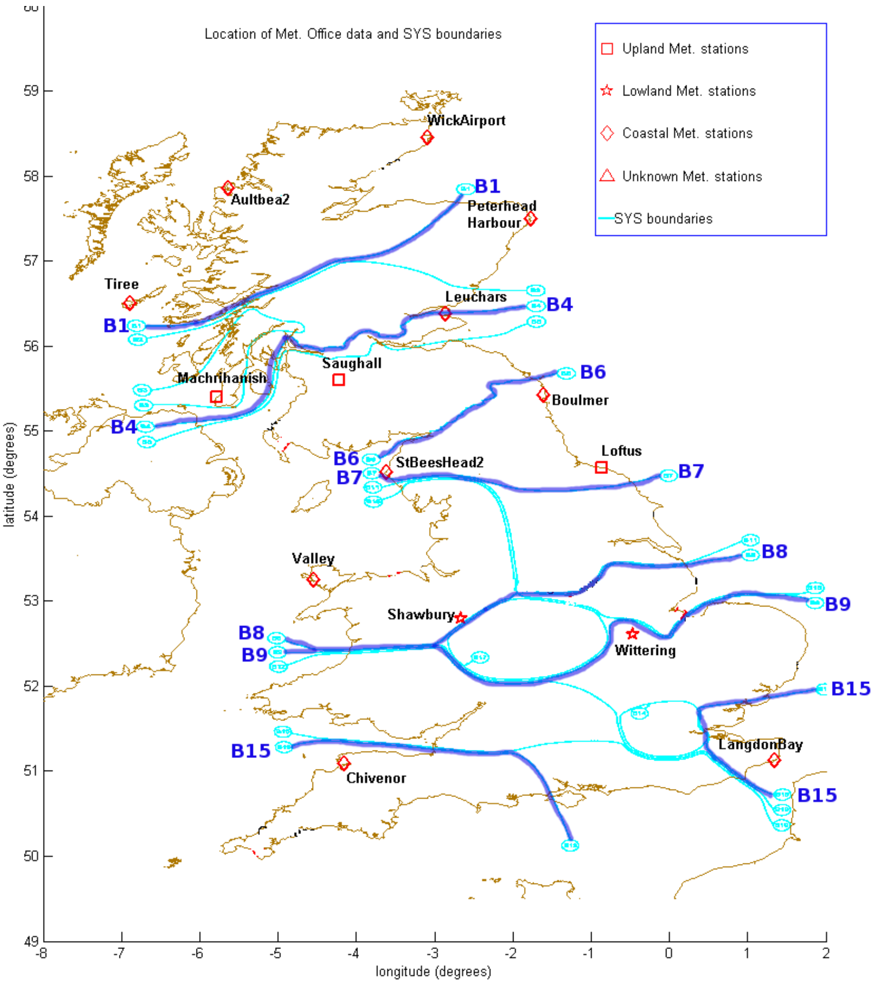


Figure 4.1-1 Weather data sites used, with region boundary lines shown.

To gain an insight as to the true capacity factors of each region, each separate site had to be assigned an installed capacity, based on the existing and predicted wind capacity for the UK in 2020.

For England and Wales, the installed capacity was determined by the ‘Gone Green’ scenario using the National Grid tool ELSI [32]. Offshore wind farms were assumed as near shore developments. Key wind farm developments in each area were assigned to a weather station, and the remainder was split evenly between the nearby weather stations for each region.

For Scotland, a more involved method was used to assign wind farms to the appropriate weather station. Wind Farm location and installed capacity data was accessed using the UK Wind Energy Database [13]. Each wind farm was plotted onto a map using google maps and assigned a weather station based on geographical position and terrain type (coastal, upland, lowland etc). The map is shown below in figure 4.2. The total installed wind capacity in Scotland was chosen to be equal to the SKM scenario1 (8000MW onshore).

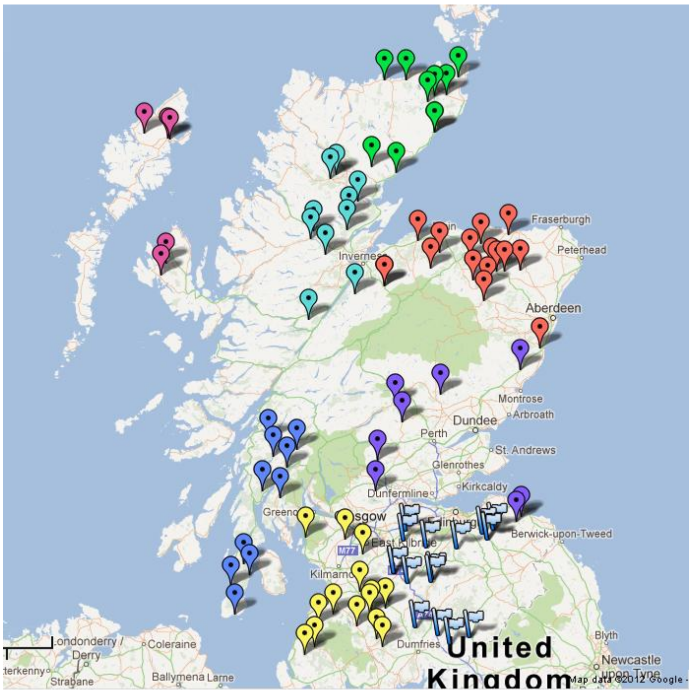


Figure 4.1-2 Google Map showing assigned wind farms to regions of wind data. Key is as follows: Pink – Tiree, Light Blue – Aultbea, Green – Wick, Red – Peterhead, Purple – Leuchars, Blue – Machrihanish, Yellow – Saughall, Flags – Eskdalemuir (later discounted due to low capacity factor and split between Saughall, Boulmer and St Beeshead).

Table 4.1-1 below displays the breakdown of installed capacity per assigned weather station.

Area	Region	Installed Capacity (MW)
Wick Airport	SHETL N	723.5
Aultbea 2	SHETL N	388
Tiree	SHETL N	479
Peterhead Harbour	SHETL N	354.5
Total	**SHETL N**	**1945**
Machrihanish	SHETL S	376
Peterhead Harbour	SHETL S	604
Leuchars	SHETL S	426
Aultbea 2	SHETL S	99
Total	**SHETL S**	**1505**
Leuchars	SPT	345.5
Saughall	SPT	2273.5
St Beeshead	SPT	637
Boulmer	SPT	637
Total	**SPT**	**3893**
Boulmer	Upper North	297

Loftus	Upper North	449
St Beeshead 2	Upper North	717
Total	**Upper North**	**1463**
Loftus	North	1366
Valley	North	1020.5
Shawbury	North	780.5
St Beeshead	North	2470
Total	**North**	**5637**
Wittering	Midlands	401
Shawbury	Midlands	258
Loftus	Midlands	1200
Total	**Midlands**	**1859**
Wittering	Central	1272
Wattisham	Central	990.5
Chivenor	Central	688
Langdon Bay	Central	1111.5
Total	**Central**	**4062**
Chivenor	South West	1138
Total	**South West**	**1138**
Langdon Bay	Estuary	1577
Total	**Estuary**	**1577**
Total	**All**	**23079**

Table 4.1-1 Installed Capacity assigned to each weather station in the UK, and thus each set of weather data. These figures include embedded generation.

For Scotland, offshore wind was assigned due to developments in the Moray Firth, Firth of Forth and Argyll array. Each of these areas was represented by offshore weather data, provided by Tom Houghton. Table 4.1-2 below shows the assigned capacities of each offshore region.

Wind Farm	Offshore Node	Installed Capacity
Beatrice	Moray Firth	1000MW
Moray Firth Offshore Wind Farm (stage 1)	Moray Firth	120MW
Moray Firth Offshore Wind Farm (stage 2)	Moray Firth	300MW
Total	**Moray Firth**	**1420MW**
Argyll Array (stage 1)	Argyll Array	400MW
Total	**Argyll Array**	**400MW**
Firth of Forth Offshore Wind Farm	Firth of Forth	1075MW
Firth of Forth Offshore Wind Farm	Firth of Forth	1825MW
Neart Na Gaoithe Offshore Wind Farm	Firth of Forth	450MW
Total	**Firth of Forth**	**3350MW**
Total:		**5170MW**

Table 4.1-2 Installed capacity assigned to offshore weather data.

Five year figures from the DUKES 2012 report [9] were used to give an indication of the typical capacity factor of onshore and offshore wind generation. Removing all of the sites with a capacity factor less than 20% gave an overall average capacity factor of 27% in Scotland for onshore wind and an overall UK average of 30% for onshore and offshore wind. These figures were found to be consistent with the DUKES figures. See table 4.1-3 below for a record of these individual and combined capacity factors.

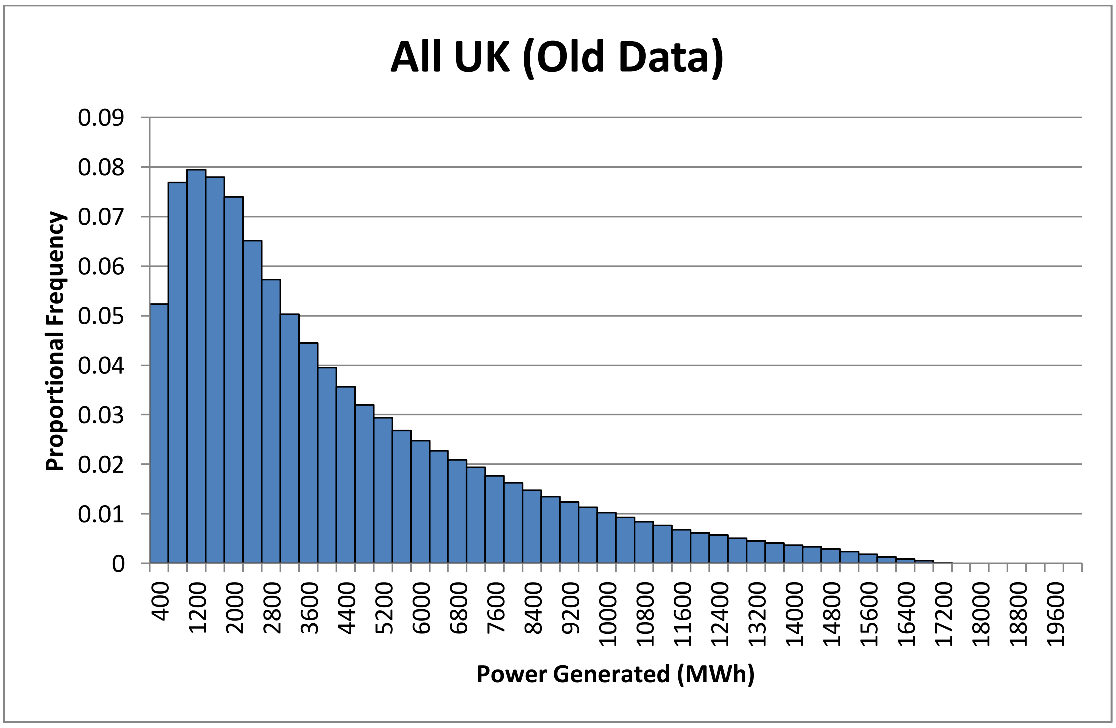
Region	Capacity Factor	Installed Capacity
ENGLAND & WALES		
Central	23.46%	4062MW
Estuary	35.58%	1577MW
Midlands	25.88%	1859MW
North	29.26%	5637MW
South West	24.90%	1138MW
Upper North	29.54%	1463MW
Totals:	**27.70%**	**15736MW**
SCOTLAND		
SHETL N	34.96%	1945MW
Offshore – Moray Firth	38.15%	1420MW
SHETL S	26.50%	1505MW
Offshore – Argyll Array	49.31%	400MW
SPT	22.41%	3895MW
Offshore – Firth of Forth	45.44%	3350MW
Totals Onshore:	**26.57%**	**7345MW**
Totals Offshore:	**43.73%**	**5170MW**
Totals Combined:	**33.66%**	**12515MW**
UK Totals:	**30.34%**	**28251MW**

Table 4.1-3 Capacity factors by region and weighted averages for Scotland, Rest of UK and overall UK, as well as total installed capacity for each region. Note Rest of UK figures include onshore and offshore figures, as offshore sites have been assumed as near shore. Shetland has been discounted from Scotland totals. DUKES figures give the load factors of 29.8% for the UK overall and 27.3% for onshore wind in 2011 [9].

A comparison of old and new capacity factors is shown below in table 4.1-4. It can be seen that the old data used has several very low capacity regions, and that the capacity factors from the new data give an average much closer to that already quoted from the DUKES report. Furthermore, histograms generated from the combined generation time series are shown below in figure 4.1-3. It can be seen from these that using the new data sites the resultant power generated resembles a clearer distribution.

Site	Old Data Capacity Factor	New Data Capacity Factor
Central	24.07%	23.46%
Estuary	36.74%	35.58%
Midlands	16.34%	25.88%
North	12.11%	29.26%
SHETL N	19.60%	34.96%
SHETL S	32.64%	26.50%
South West	25.49%	24.90%
SPT	24.07%	22.41%
Upper North	23.05%	29.54%
Weighted Average	**21.58%**	**27.34%**

Table 4.1-4 Comparison of old and new data capacity factors, based on wind generation time series generated by ANTARES. For fairness of comparison, both old and new data are weighted by new installed capacities as in table 4.1-3.



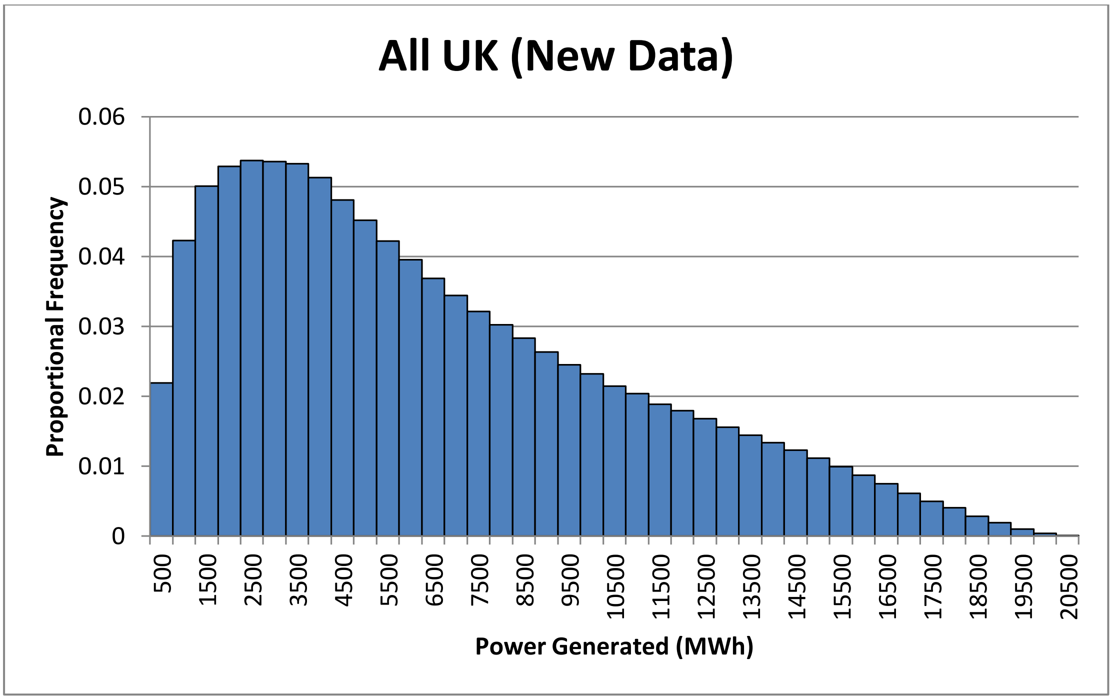


Figure 4.1-3 Histograms displaying proportional frequencies of various levels of generated power. Both old and new data again has been weighted by the same installed capacities per region.

One final problem when assigning installed capacities to regions was the Viking and North Nesting wind farms, currently in development in Shetland. Wind farms located on Shetland famously have a very high capacity factor [40] which could not be matched by the wind data discussed so far in this section. Eventually it was decided that one historical time series from Burradale would be scaled to the correct installed capacity. This time series has a capacity factor of 48.58%, close to the maximum values of 52% that have been reported in that area.

4.2. Tidal Power

It was decided that the SKM scenario 1 value of 500MW installed tidal power was too large to discount, despite the fact that ANTARES does not model tidal generation. Instead it was decided to create one simplified time series for the year and include it in the unused ‘solar’ section of the model.

Although this time series is by no means a perfect representation, it at least displays a regular daily, monthly and yearly pattern representative of tidal power, something which was not possible to model in ANTARES using the inbuilt wind or hydro time series generators.

Although only one simplified time series was input to the model to represent the Tidal power, in reality year to year the tidal behaviour does not change more than 5% [27]. Thus the only real variation in power generated would be due to maintenance of the turbines and connection to the grid.

All tidal power was assumed to come from the Pentland Firth marine energy park, currently having just completed the leasing stage by the crown estate, but predicted to be producing up to 500MW by 2020 in their report [10].

The creation of a time series involved two key stages; determining the tidal stream speeds throughout the year in the Pentland Firth, and the conversion of these tidal stream speeds to power using the tidal stream devices.

Stage 1. Determining Tidal Stream Speeds

To determine the hourly data for a year of tidal stream speeds, first average spring and neap speeds for a typical 12.5hour cycle in the Pentland Firth were taken from the Admirality Tidal Stream Atlases [36]. These were provided in knots and converted to m/s at a factor of 0.5144. The graph of these is shown in the figure below. It was assumed that whichever direction the tidal stream was moving in, the turbine would be able to generate equal amounts of power, so the direction of tidal stream movement has been ignored.

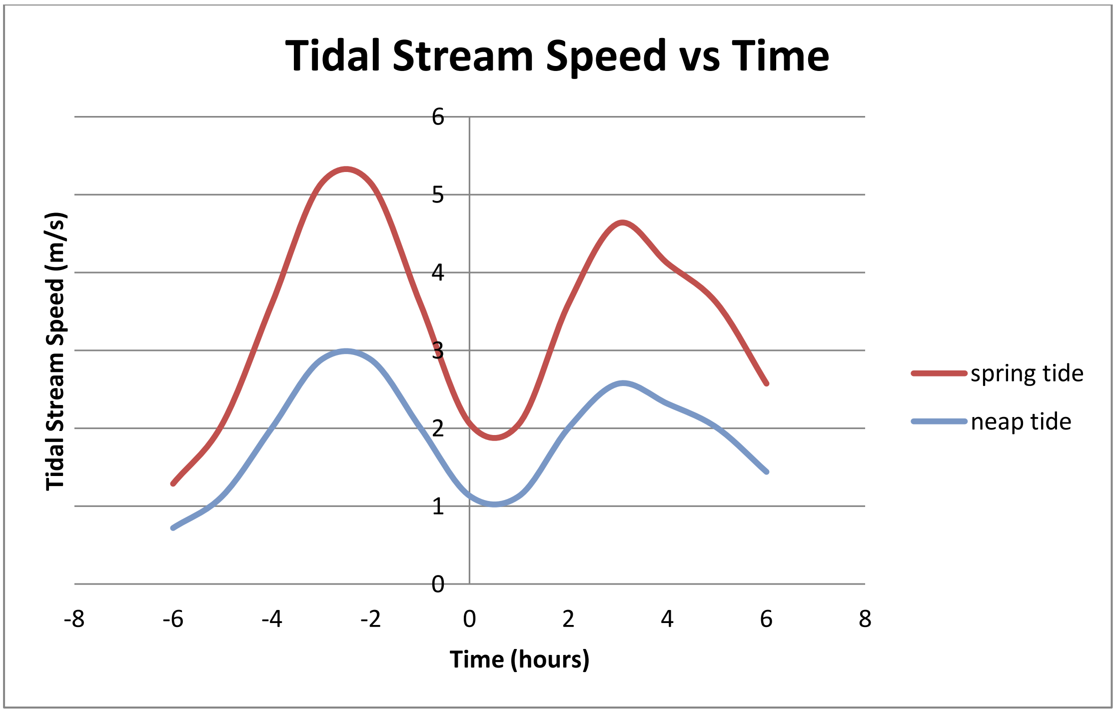


Figure 4.2-1 Average tidal stream speeds over the 12.5hour cycle, showing both spring and neap tides.

An overly simplified model of the tidal stream could have involved the repetition of these graphs throughout the year, alternating between spring and neap tides depending on the lunar conditions. This is shown below in figures 4.2-2 and 4.2-3.

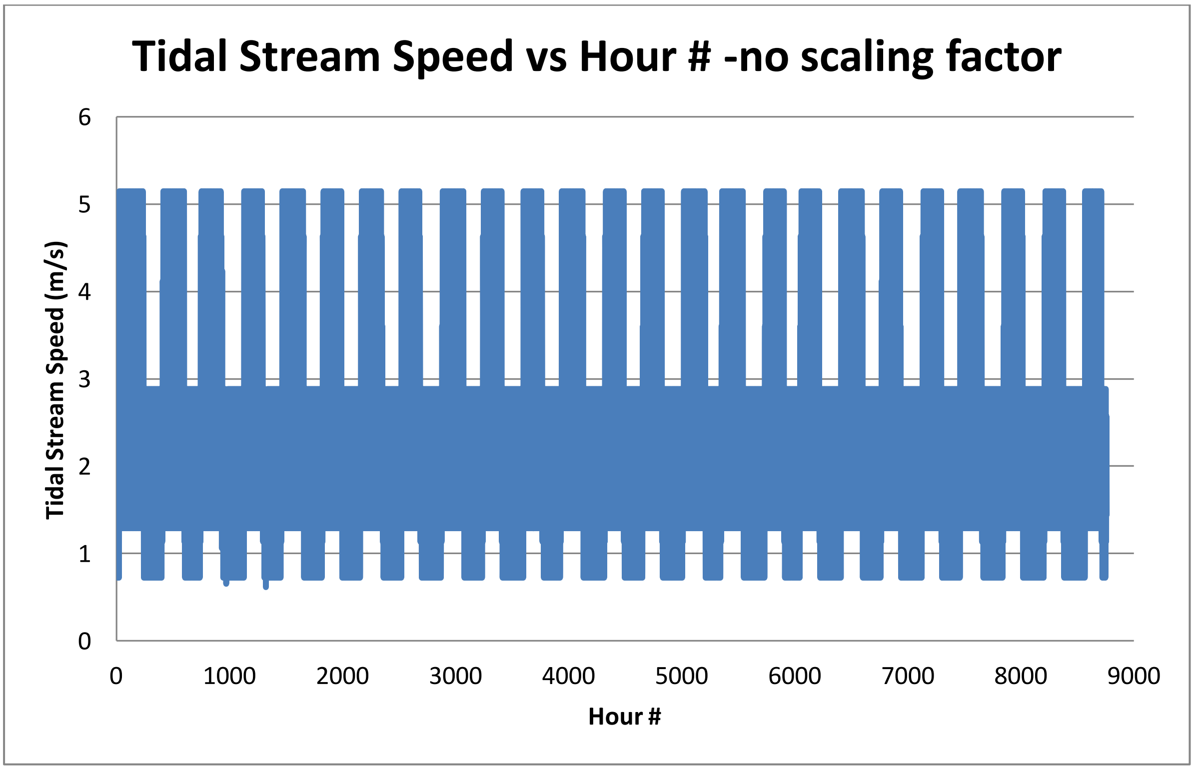


Figure 4.2-2 Tidal stream speed for one year, alternating between spring and neap tides depending on lunar behaviour. Times of spring and neap tides were taken from Reeds Nautical Almanac [37].

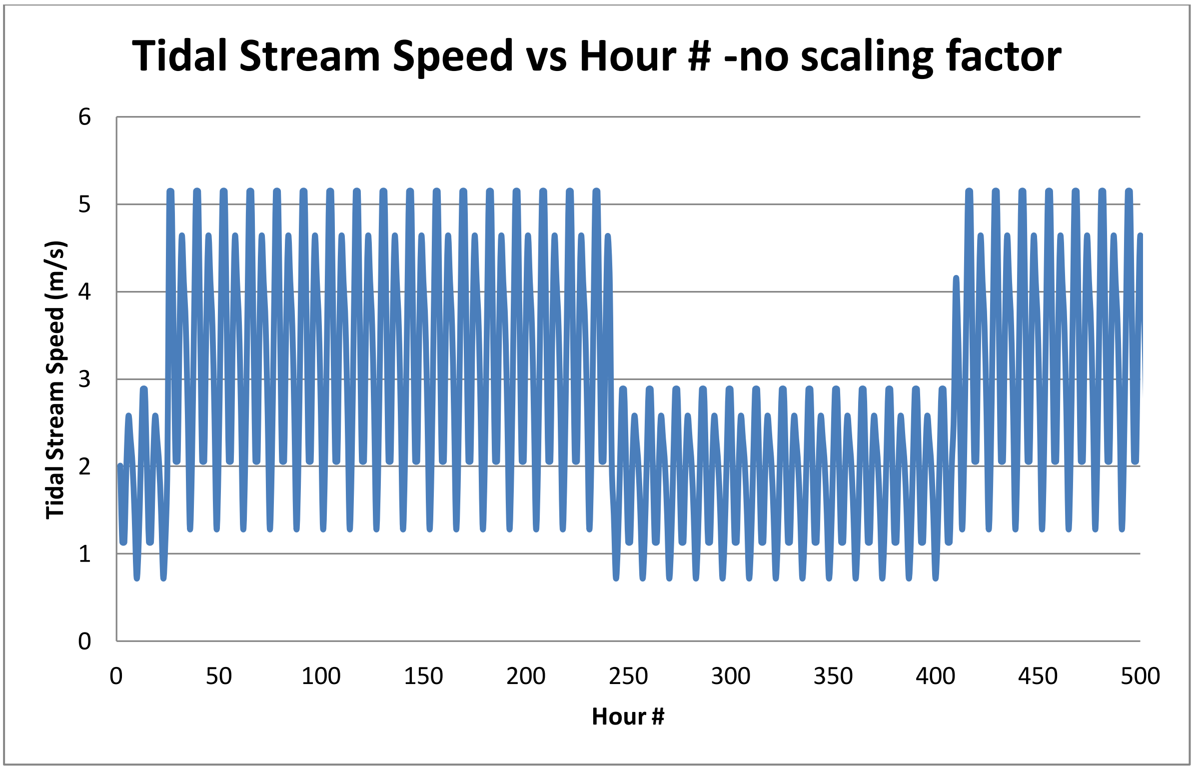


Figure 4.2-3 Tidal stream speed for each hour, as in 4.2-2, limited to the first 500 hours (~21days), to show the clear step-down between spring and neap tides.

To make the tidal stream speed time series more representative of temporal trends, it was decided that a scaling factor should be introduced. This allows the modelling of yearly trends in tidal behaviour, as well as monthly trends of spring and neap tides. Using the tidal tables available for Wick in the Reeds Nautical Almanac [37] (the closest available tidal table to the Pentland Firth) we can see these yearly trends in figure 4.2-4. As the tidal streams are caused by the difference between the maximum and minimum of tidal height it is this difference that has been graphed.

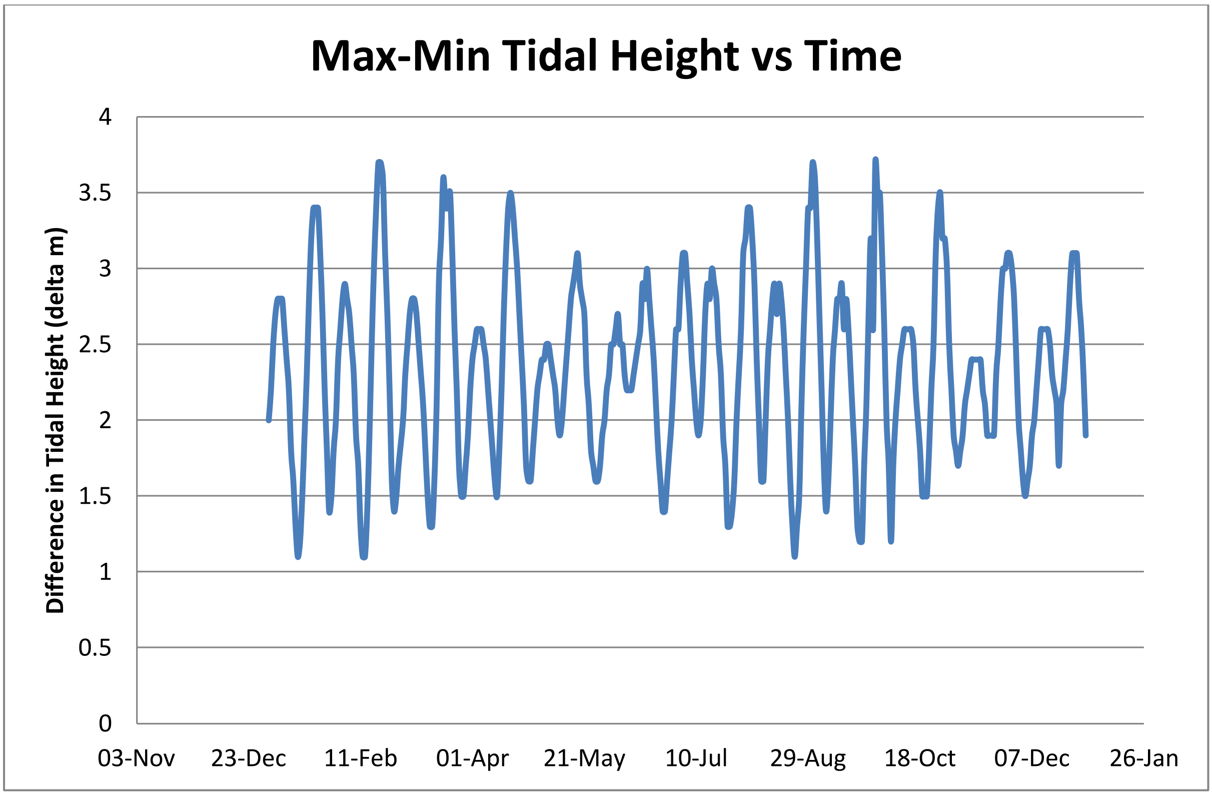


Figure 4.2-4. The difference between maximum and minimum tidal height for each day of the year. From this graph we can see a clear pattern of spring and neap tides as peaks and troughs, and also a clear yearly pattern followed by the graph.

To introduce this yearly pattern along with the already established spring and neap tide pattern, a scaling factor was introduced. Using the Reeds Nautical Almanac for times of spring and neap tides, the average difference in tidal height over one year was taken for both the spring periods and for the neap periods. The difference in tidal height for each hour was then calculated as a percentage of this average (either for spring or neap, depending on which it had been assigned by the Nautical Almanac), and these daily percentages were used to scale each hourly tidal stream figure. The results are shown in Figure 4.2-5 and Figure 4.2-6, and now show a gradual transition between spring and neap tides, as well as a yearly pattern.

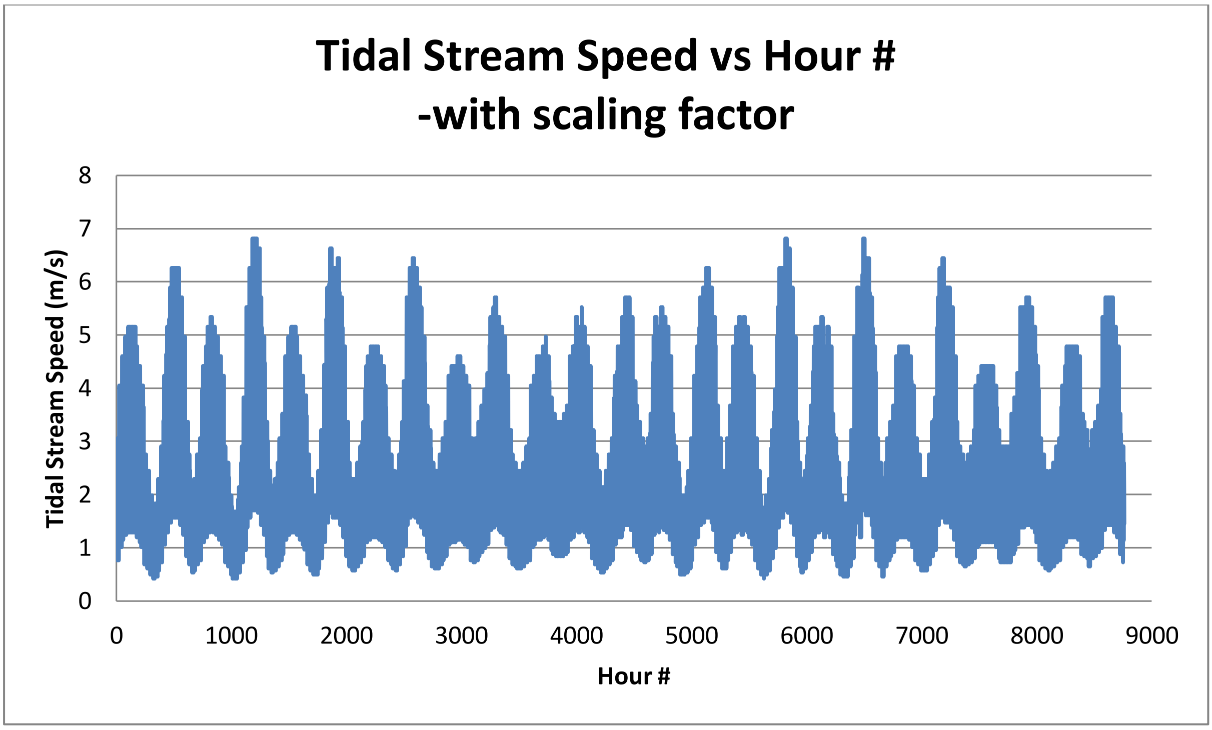


Figure 4.2-5. Tidal Stream speed over one year complete with scaling factor. Comparison with figures A2-2 and A2-4 shows a spring-neap tide pattern as in A2-2 but with a more representative yearly pattern as in A2-4.

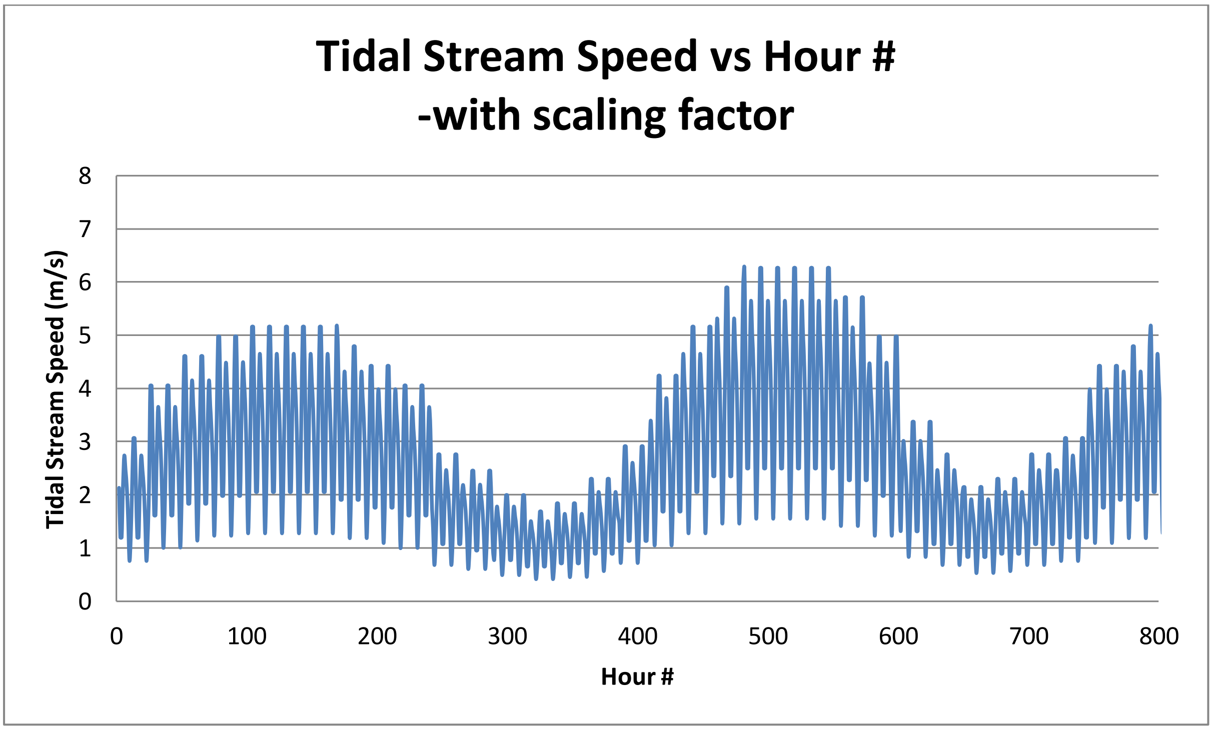


Figure 4.2-6. Tidal Stream speed over one year, as above but displaying the first 800 hours (~33days) of the year. Comparison with figure A2-3 shows a more gradual flow between spring and neap sections, much more representative of the reality of tidal behaviour.

Stage 2. Converting Tidal Stream Speed to Power

This second stage involves using the hourly tidal stream speed (in m/s) to the power produced by the tidal turbine. This was done assuming a horizontal axis tidal turbine, and so the formula used to do this conversion is:

$$P = \frac{1}{2} C_p \rho A V^3 \qquad \text{(equation 1) [21]}$$

As seen previously in section 2.3.1.

To calculate the power curve of the tidal turbine, a cut-in speed of 1m/s, rated speed of 2.5m/s and cut out speed of 5m/s was used. In addition a power coefficient of 0.23, a swept area using a rotor diameter of 10m and a fluid density of 1025kg/m^3 was used. These figures came from the DTI report “Economic Viability of a Simple Tidal Steam Energy Capture Device” [41]. Using these figures and equation 1 a power curve was generated, and scaled to a rated capacity of 500MW (as in scenario 1). This is shown below in Figure A2-7.

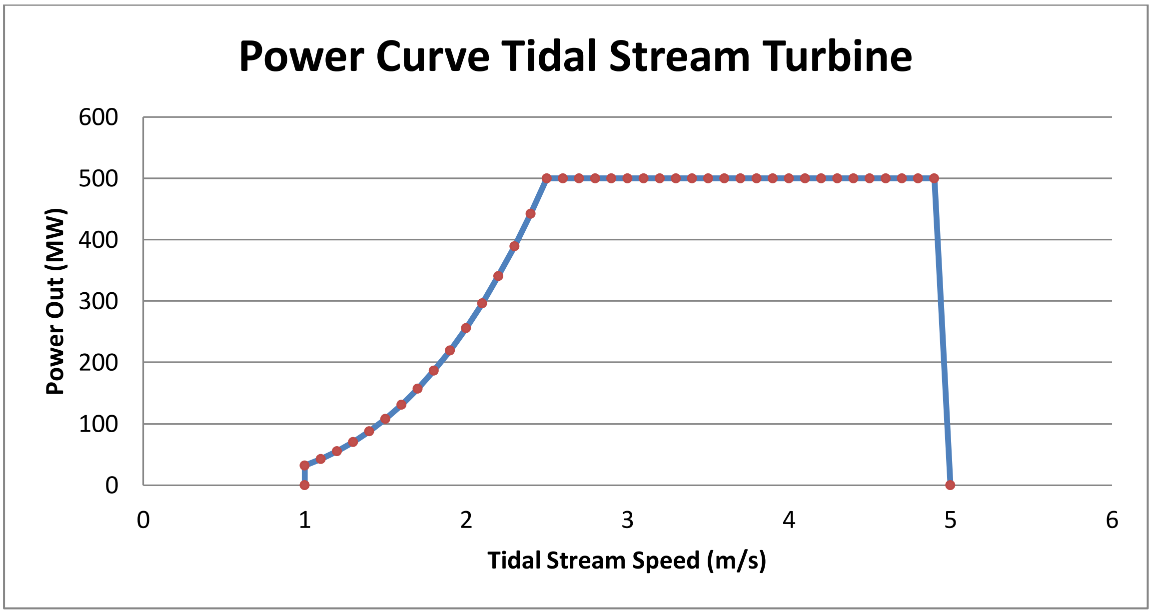


Figure 4.2-7. Power Curve Tidal Stream Turbine, displayed as power out versus the tidal stream speed.

From these values and the yearly time series of tidal stream speeds, a time series of power produced by the predicted tidal turbine farm was generated, and input into ANTARES in the SHETL N region. The capacity factor for this data was found to be 60.0%, which is consistent with the Seagen tidal turbine in Ireland which has achieved a capacity factor of 66% over 1000hours [42].

4.3. Interconnectors

Previous projects using this modelling software have modelled interconnectors as miscellaneous positive or negative generation, based on the historical trends of the usage of these links. As this project is concerning quite large amounts of additional renewable installed capacity, it was considered logical to improve this previous method. This involved modelling each interconnector as a node, with a transmission link and an equal load, and with some form of generation also. The details of each interconnector are shown in the table below:

Interconnector	Transmission Capacity	Load	Generation
MOYLE	450MW	450MW	-
BritNed	1000MW	1000MW	4*500MW Coal
Anglo France	2000MW	2000MW	4*500MW Nuclear, 4*500MW Coal
East West	500MW	500MW	1000MW Wind

Table 4.3 Interconnectors

Coal in continental Europe was priced as cheaper than in the UK. Hurdle costs were set as the same as links within the UK.

The results of this attempted model improvement were:

Moyle – 450MW load was always matched in full. This in reality does not happen currently, with a transmission of around 200MW on average from Scotland to Northern Ireland, from historical data.

BritNed – 1000MW was constantly being transmitted from the Netherlands to the UK. In reality this does not currently happen. Normally the power flow is from the Netherlands to the UK but not usually at full capacity, and around a quarter of the time the power flow is from the UK to the Netherlands [20].

Anglo-France – 2000MW or thereabouts was constantly being transmitted to the UK. Again in reality the historical data does not display a link being used to full capacity, and the transmission direction does sometimes change.

East West – A varying amount of energy (depending on that produced by installed wind) was constantly being transmitted to the UK. However due to the wind farm power curve always producing less than the installed capacity (with a maximum of

89%), in extremely windy hours the interconnector is still not often used to full capacity.

These interconnectors could have been made more representative of realistic behaviour by altering hurdle and operational costs, and in the case of East-West by increasing the installed capacity of wind power.

It was decided due to time constraints that these modelled nodes were not realistic enough and the previous method of using historical data was used in the final model. If time had been permitting more work would have gone in to developing more realistic model versions of these interconnectors.

5. Scenarios

For all scenarios only the Scottish model was adapted, with the rest of the UK remaining as National Grids ‘Gone Green’ scenario.

5.1. SKM Scenario 1

The generation capacity for Scotland from SKM Scenario 1 is shown in the table below and for 2020 as a pie chart underneath.

MW	2010	2015	2020	2030
Coal	3,386	2,284	1,713	0
Thermal with CCS	0	0	571	2,284
CCGT	1,322	1,322	1,322	120
Nuclear	2,289	2,289	1,215	0
Other thermal	173	50	50	39
Pumped Storage	740	740	1,040	1,340
Biomass	65	117	150	200
Hydro	1,308	1,364	1,500	1,700
Offshore Wind	10	500	5,000	7,000
Onshore Wind	2,373	5,500	8,000	9,500
Tidal	10	29	500	1,020
Wave	11	22	200	750
Other renewables	103	103	103	103
Total Capacity	11,790	14,321	21,365	24,057
Renewables as % total capacity	33%	53%	72%	84%

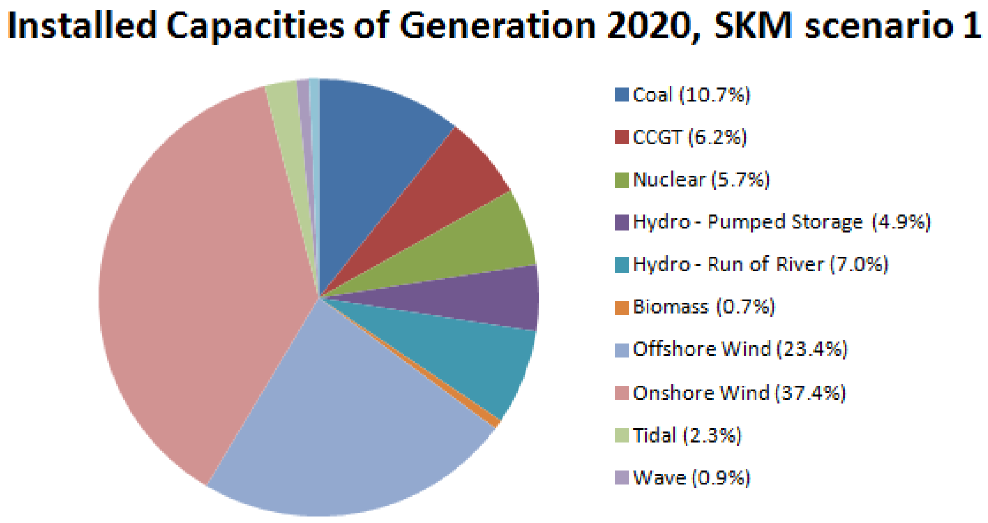


Figure 5.1-1. Table and pie chart of generation capacities for various years as per SKM Scenario 1.

The assumptions made for this scenario were discussed in section 2.1.2 previously. The model was adapted to match these generation capacities as discussed below:

Coal

With the closure of Cockenzie in 2016, all coal power will come from Longannet in SPT. This scenario also assumes that 571MW of the total 2284MW from Longannet will be fitted with CCS by 2020.

CCGT

All CCGT is assumed to be at Peterhead in SHETL S, though it is unclear where the figure of 1322MW installed capacity comes from, as most sources quote the CCGT capacity at 1180MW [32].

Nuclear

With Hunterston B assumed closed by 2016, all nuclear power comes from Torness in SPT.

Pumped Storage

The pumped storage capacity for Scotland is shown as 740MW for 2010 and 2015. This current capacity is made up of 440MW at Cruachan in SHETL S and 300MW at Foyers in SHETL N. It has been assumed that the rise of 300MW by 2020 up to a total of 1040MW installed capacity is due to the SSE Choire Ghlais development [11], and so this was added as a separate node of pumped storage to the SHETL N region.

Biomass

Biomass electricity generation currently in place or nearing completion includes 5MW at Balcas, Invergordon (SHETL N) [43], 44MW at Steven’s Croft, Lockerbie (SPT) [44], 50MW at UPM, Irvine (SPT) [45], 10MW at Westfield, Glenrothes (SPT) [46], 8MW at Greengairs (SPT) [47] and 10.5MW at Baldovie, Dundee (SHETL S) [48]. The remainder (15%) is assumed to be smaller projects in the SPT region and the 20MW Peel Energy project in Corpach (SHETL N) [49].

Hydro

In the supplied model, existing hydro has been distributed among the appropriate regions for which it is installed. Additional capacity as far as 2015 that is already in the planning and construction stages is well documented and so can be added to the appropriate regions [50] [51]. The small difference between 2015 and 2020 is divided up between regions due to the percentage of financially available power from the Scottish Hydropower Resource Study [52] (1.59% to SPT, 51.41% to SHETL S and 46.99% to SHETL N).

Offshore Wind

SKM scenario 1 specifies 5000MW installed capacity of offshore wind. The closest approximation to this with the planned installed wind farms comes to 5170MW. The breakdown of installed capacities was discussed in section 4.1

Onshore Wind

As covered in detail in section 4.1

Tidal

All tidal resources are assumed to be within SHETL N, at the Pentland Firth and Orkney waters area, as part of the marine renewable developments in that area. One simplified time series was included for tidal, as described in section 4.2.

Wave

All wave power by 2020 would have been assumed to be located in the Pentland Firth and Orkney waters area, as part of the marine renewable developments in that area. Due to time constraints however, and the inability for ANTARES to model wave power, all wave generation was ignored for this scenario.

Other

Other renewables and other thermal were both included in the scenario. These were input to the ‘other’ section in Misc Gen in ANTARES, divided by region in proportion to the load split as shown in section 2.

Final Scenario Breakdown – SKM Scenario 1 2020

The final scenario breakdown for SKM scenario 1 in 2020 is shown in the table below:

Installed Capacity (MW)	SPT	SHETL S	SHETL N	**Total**
Coal	1713	0	0	**1713**
Coal with CCS	571	0	0	**571**
CCGT	0	1322	0	**1322**
Nuclear	1215	0	0	**1215**
Other Thermal	35	12	3	**50**
Pumped Storage	0	440	600	**1040**
Biomass	114.5	10.5	25	**150**
Hydro	135	708	657	**1500**
Offshore Wind	3350	400	1420	**5170**
Onshore Wind	3893	1505	1917	**7315***
Tidal	0	0	500	**500**
Wave	0	0	0	**0**
Other Renewable	72	25	6	**103**
Total	**11098.5**	**4422.5**	**5128**	**20694**

*SKM Scenario 1 total of 8000 made up with additional onshore wind in Shetland.

Table 5.1-1 Breakdown of installed capacities for SKM scenario 1.

5.2. Scenario Changes Simulated

Initially, the model included the two transmission 'bootstraps' previously described in section 2.2.2. The Easterly bootstrap links the SHETL S region with the North region, and has a transmission capacity of 1800MW. The Westerly bootstrap links the SPT region with the North region and also has a transmission capacity of 1800MW. The group of simulations conducted with different installed wind capacities with this transmission setup will hereafter be referred to as the 'East and West' scenario.

To meet objective 3, and a very possible likelihood, it was suggested that perhaps one or both transmission bootstraps would not be present in the next eight years. In particular the East bootstrap was chosen to be discounted, due to its later finishing date and also due to its higher observed use in the first set of simulations. This would provide more of a worst case scenario when presuming one of the bootstraps would not be completed. Hereafter this group of simulations will be referred to as the 'West only' scenario.

Additionally to this, it was investigated what would happen if both transmission bootstraps were not present, due to either issues with planning permission, delays in construction or faults resulting in their unavailability. This group of simulations will be referred to as the ‘No Bootstraps’ scenario.

As an additional point to investigate, it was considered to be interesting to see if the proposed HVDC Caithness-Moray link would improve the ‘East and West’ results, as the spilled energy in these simulations occurred only in the SHETL N region, thus suggesting better connectivity between this region and the rest of the UK would be required. This additional 600MW HVDC link was included between the SHETL N and SHETL S regions. This group of simulations will be referred to as the ‘Additional East’ scenario.

6. Results

All results are for Scotland, as per the scope of this project, described in section 1.3. Installed capacity, spilled wind and unsupplied energy are the sums of all three Scottish regions (SPT, SHETL S, SHETL N) in the model.

6.1. Installed Capacity and Spilled Wind

From the project objectives in section 1.2, objective 2 was:
"To conduct a simulation study with different levels of installed wind power in Scotland, to investigate the relationship between installed capacity and spilled wind"

To complete this objective, various levels of total installed wind power in Scotland were used. These were ten equally spaced points between the current installed capacity and the installed capacity for 2020 (figures displayed in Figure 5.1-1 previously). A simulation was run at each of these installed capacities and the total expected spilled wind was recorded. The graph below shows the relationship between installed capacity and spilled wind.

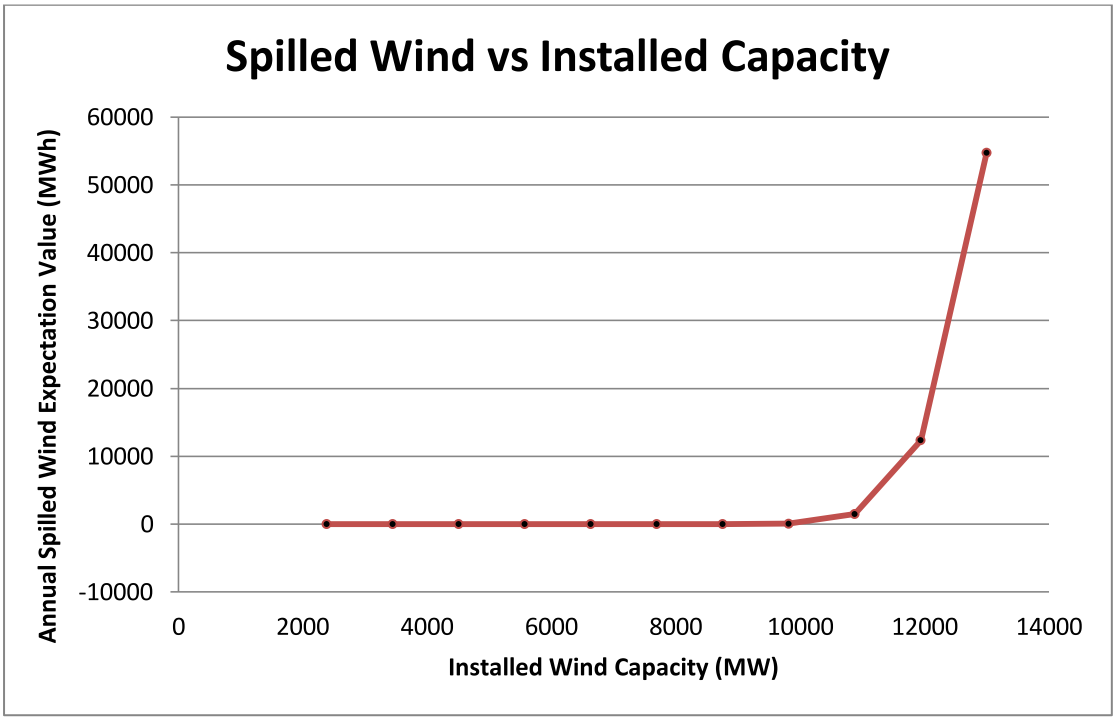


Figure 6.1-1 Graph of spilled wind against installed capacity, for SKM Scenario 1 in which both East and West transmission 'bootstraps' are included.

From this graph we can see that after around 10GW installed wind capacity we start to see wind power being 'spilled' and this rises steeply with increasing installed capacity. In the graph below we see the maximum and minimum values generated over the 200 Monte-Carlo years and also the expected value plus one standard deviation.

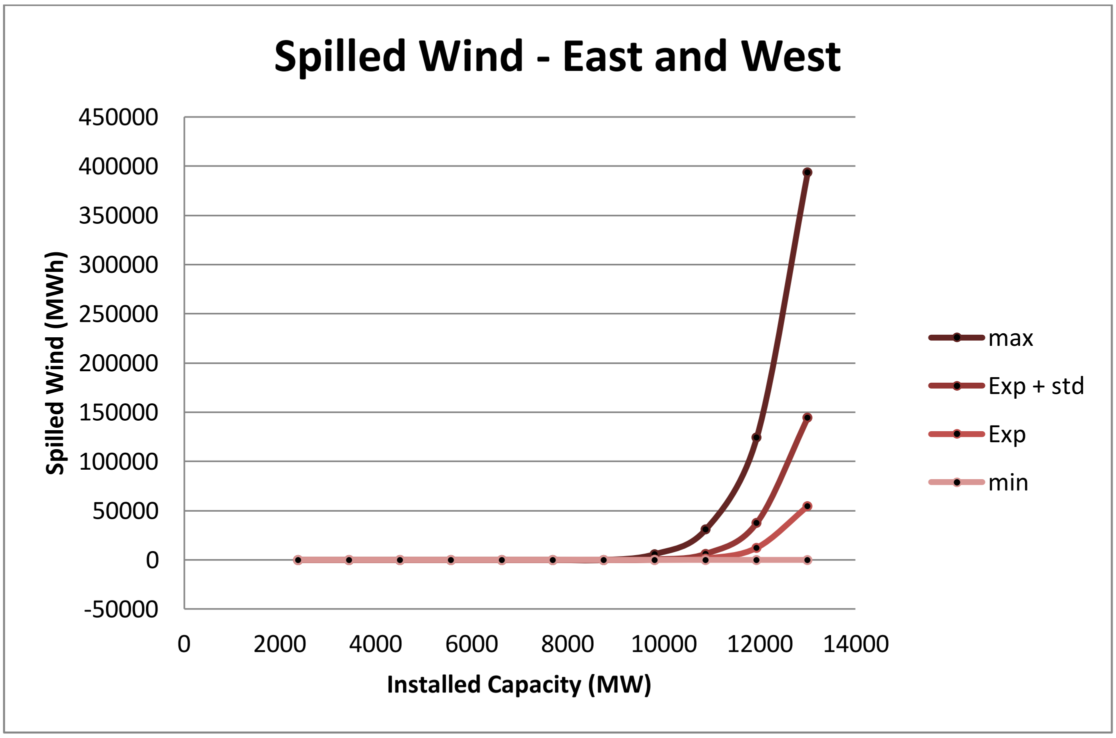


Figure 6.1-2. Graph of spilled wind against installed capacity for East and West scenario, with min, max and exp+std values for 200 Monte Carlo years.

From this graph we see that the maximum value is almost eight times greater than the expected value. The minimum value is always zero. Similar graphs to this for each of the scenarios can be found in Appendix 2 section 2.1.

A graph of all spilled energy for each installed wind capacity was also drawn. This can be seen below as figure 6.1-3. This graph shows the total spilled energy (including spilled wind) in green, with the same red line of the expected value of spilled wind as in the previous figures. It can be seen that the greater proportion of spilled energy comes from the spilled wind, and a lesser proportion from other sources. This is unsurprising due to the high proportions of installed capacity of wind power.

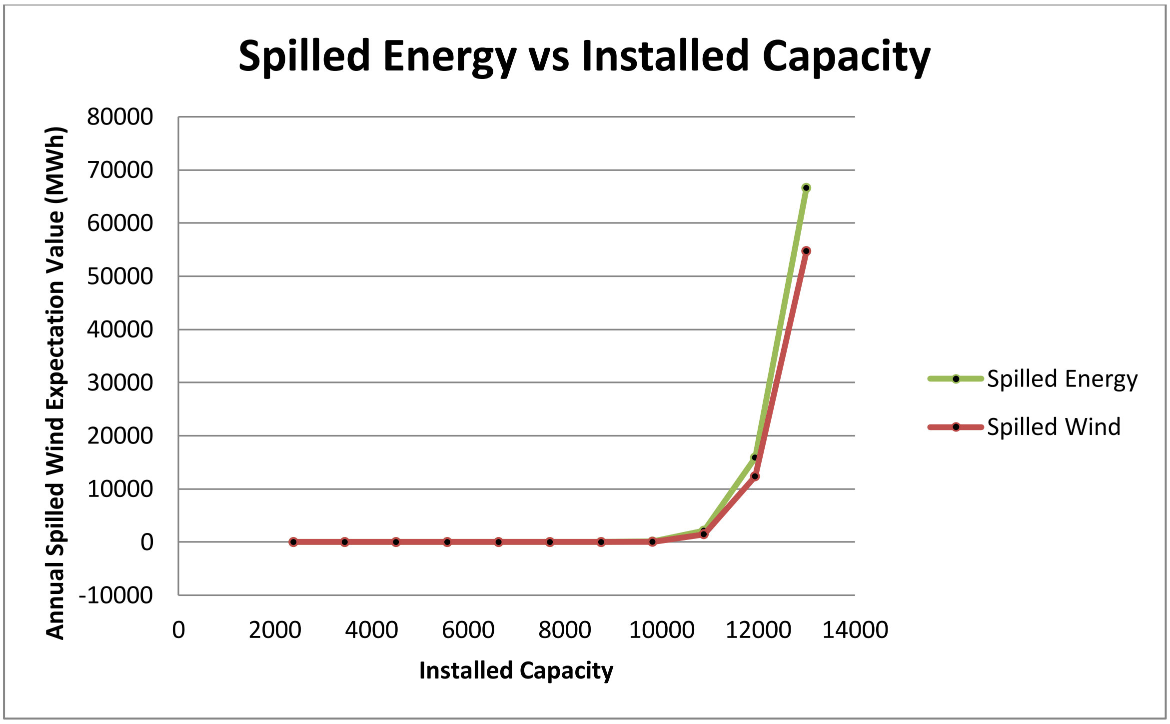


Figure 6.1-3. Graph of spilled energy against installed capacity, for SKM Scenario 1 in which both transmission 'bootstraps' are included.

Similar graphs for each scenario can be found in Appendix 2.2. These show very similar results to that displayed in the graph above, with a high proportion of spilled energy coming from spilled wind.

6.2. Sensitivity of Results to Transmission Bootstraps

From the project objectives in section 1.2, objective 3 was:
"To conduct a simulation study with and without the transmission 'bootstraps' providing additional capacity to the Scotland-England link"

To complete this objective, the simulations at various installed capacities of wind power were repeated, with different transmission HVDC connections, as described in section 5.2.

The expected values for spilled wind results for each scenario at the various installed capacities are shown in figure 6.2-1 below.

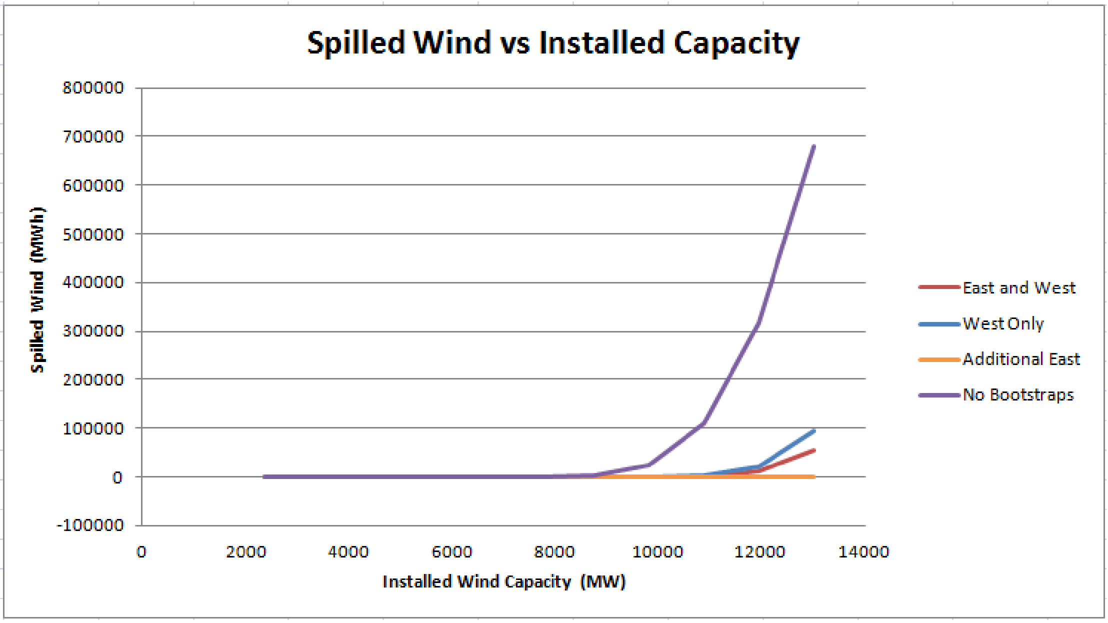


Figure 6.2-1. Spilled wind against installed wind capacity for each of the scenarios.

We can see from this graph that the spilled wind for the ‘No Bootstraps’ scenario is greater than that of any of the other scenarios, up to almost seven times as much by the time the installed wind capacity reaches that of SKM scenario 1. Also wind energy begins to be spilled at a lower installed capacity in this case, at around the 9GW installed wind capacity mark. To illustrate the other scenarios more clearly, a graph featuring all except ‘No Bootstraps’ is shown below:

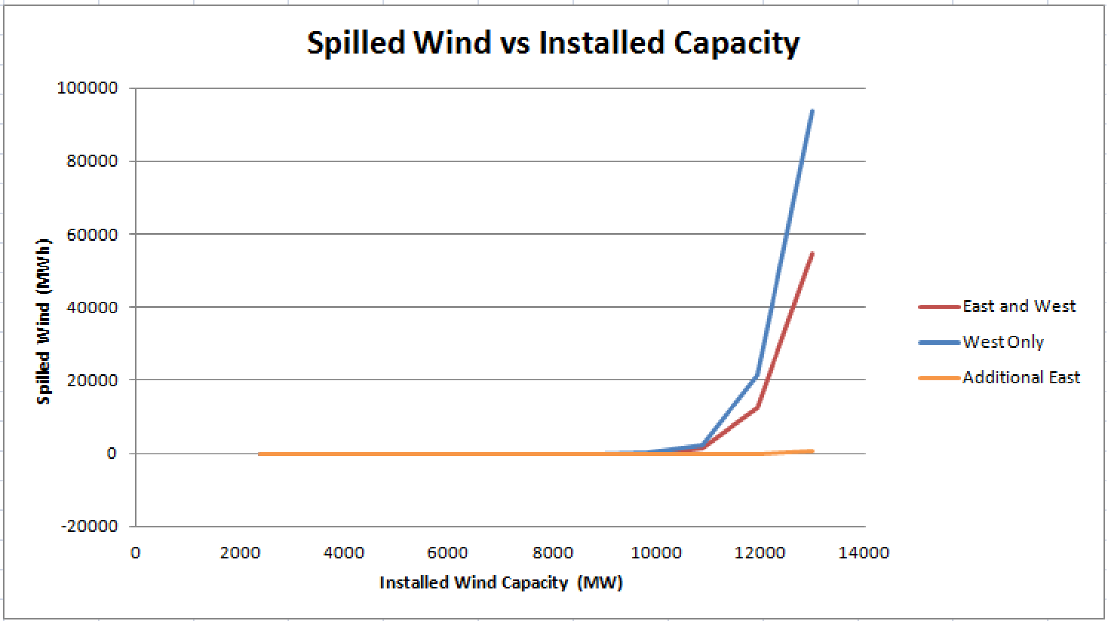


Figure 6.2-2 Spilled wind against installed wind capacity for all scenarios except No Bootstraps

We can see from this graph that when the east bootstrap is discounted the difference of expected of spilled wind is almost double that of when both bootstraps are present in the model. We can also see that for both scenarios the figure of 10GW installed capacity is the turning point for spilled wind.

The additional east bootstrap seems to improve the amounts of spilled wind greatly, with only 819MWh of spilled wind at the full installed wind capacity of SKM scenario 1. Tables of results for spilled wind and spilled energy are available in Appendix 1.

6.3. Additional Results

6.3.1. Unsupplied Energy

ANTARES also provides results for the expected unsupplied energy for each area. The expected values for unsupplied energy in Scotland for each scenario is shown in Figure 6.3.1-1 below.

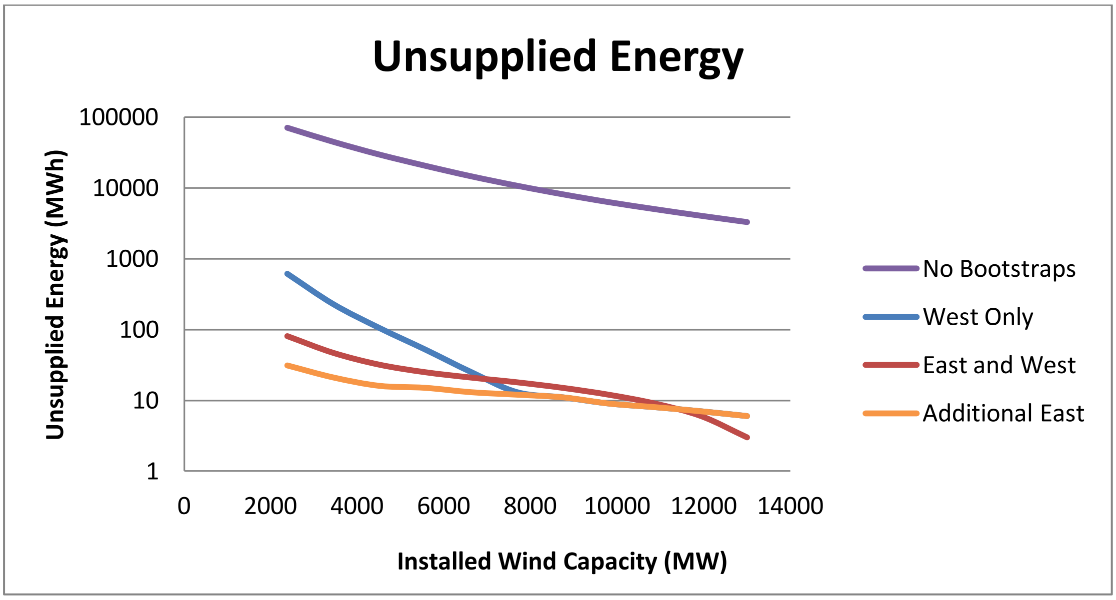


Figure 6.3.1-1 Expected values for unsupplied energy for each scenario.

These values are for the installed generation capacities of SKM scenario 1 with a reduction in coal generation and the assumption of no replacement of nuclear, so all of these unsupplied energy values represent this 2020 scenario with varying levels of installed wind capacity, and varying transmission scenarios.

A recent report by National Grid quoted recent values of unsupplied energy as 97.71MWh for SPT and 64.23MWh for the SHETL areas in 2007-2008 [53]. We can see from this figure that the unsupplied energy is considerably greater than this for the No Bootstraps scenario. The other scenarios vary with lower installed wind capacity, and then reach similar low levels after around the 8GW installed wind capacity mark. On the whole the amount of unsupplied energy is greater when the transmission capacity is lower, and the unsupplied energy falls as installed wind capacity is increased.

The table of results for unsupplied energy for each scenario is available in Appendix 1.

6.3.2. Bootstrap Flows

Power flows from Scotland to England for each scenario were graphed, showing the expected, expected plus one standard deviation, minimum and maximum values over the 200 Monte Carlo year simulation for the full installed wind capacity of SKM scenario 1. These are shown below in Figures 6.3.2-1 to 6.3.2-4.

These graphs give several results. On each graph, the maximum values have been curtailed by the transmission capacity. On the West only and No Bootstraps graphs (figures 6.3.2-2 and 6.3.2-4 respectively) we can see that the expected plus one standard deviation values are also curtailed. The stepped appearance of these curtailed values is due to the seasonal variation in transmission capacity included in the model.

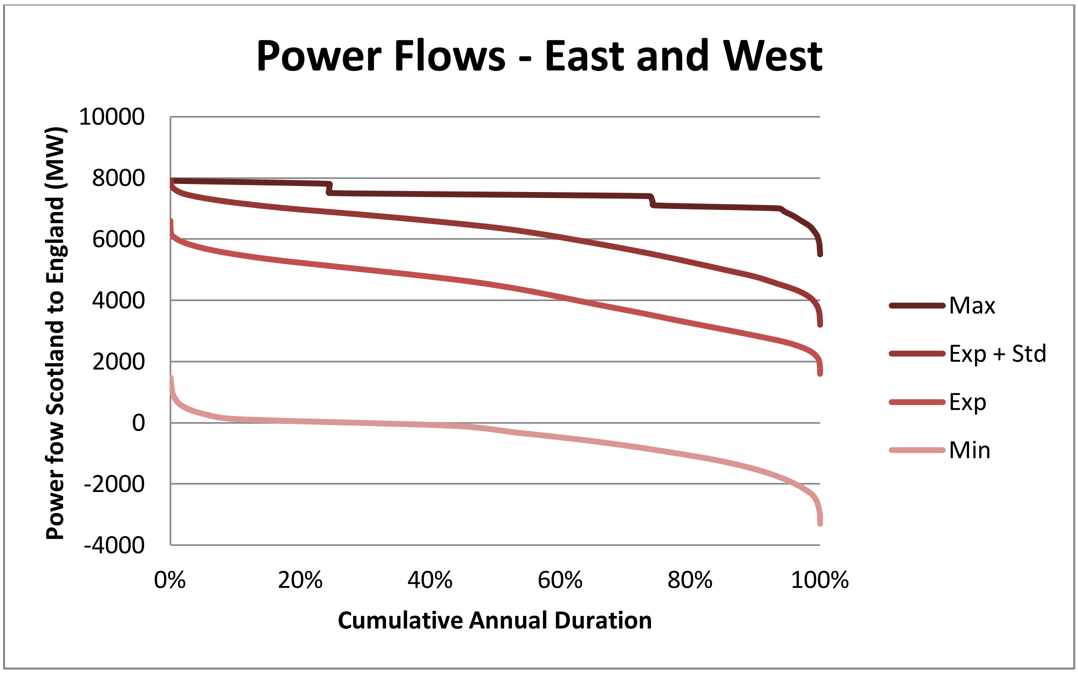


Figure 6.3.2-1 Power Flows, East and West scenario. From this graph we can see the maximum values have been curtailed by the transmission capacity.

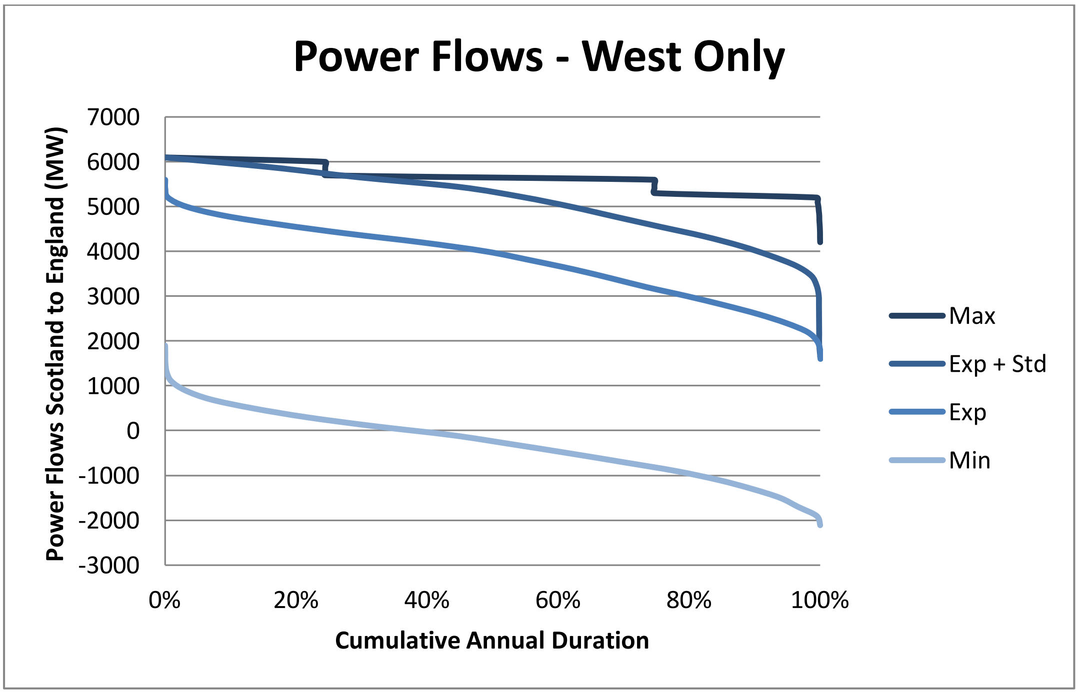


Figure 6.3.2-2 Power Flows, West Only scenario. From this graph we can see the maximum values and some of the higher expected plus one standard deviation values have been curtailed by the transmission capacity.

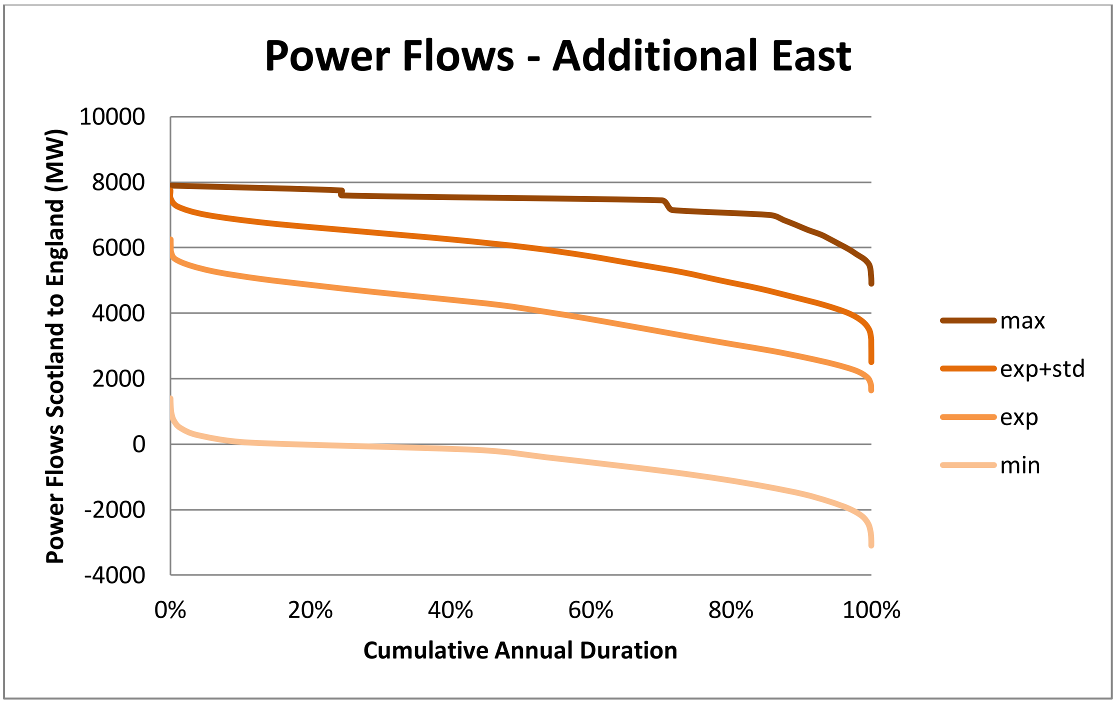


Figure 6.3.2-3 Power Flows, Additional East Scenario. From this graph we can see the maximum values have been curtailed by the transmission capacity.

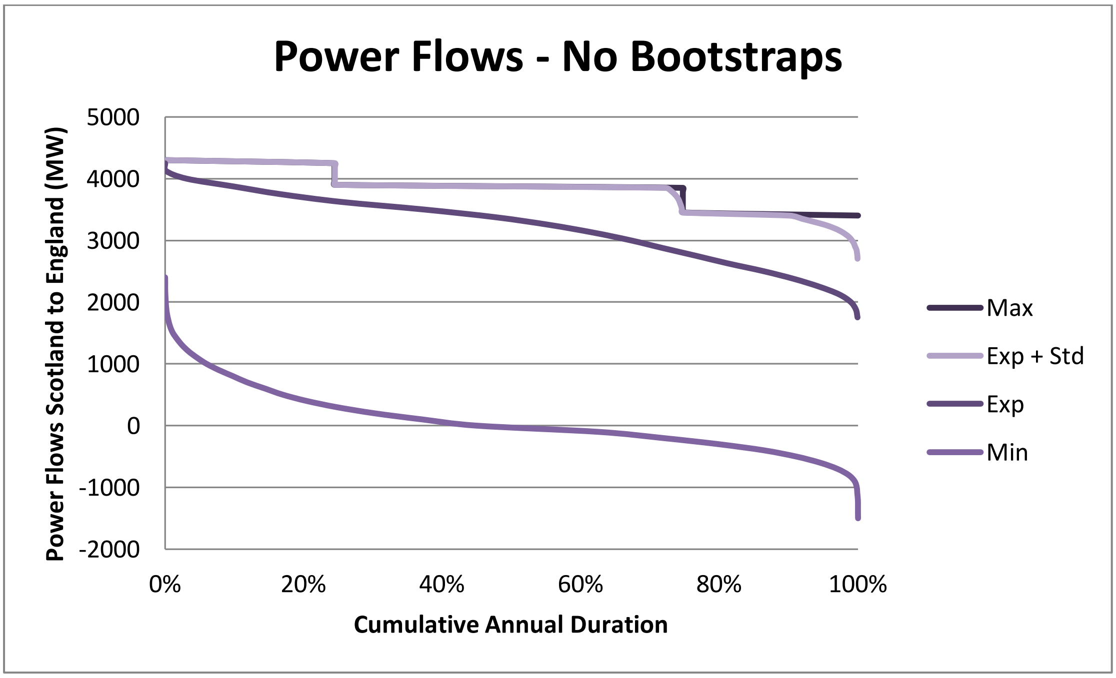


Figure 6.3.2-4 Power Flows, No Bootstraps scenario. From this graph we can see the maximum values and many of the expected plus one standard deviation values have been curtailed by the transmission capacity.

7. Discussion

7.1. Factors Affecting Results

There are various types of uncertainties that must be considered when modelling predicted electrical power systems. Technical issues such as planned or unplanned outages throughout the system, changes in demand due to climate change or technological advances (eg electric cars), economical issues such as changes to incentives changing the makeup of the system (eg a greater proportion of ROCs being awarded to marine renewables such as wave, tidal and offshore wind) and future changes to demand side management could all impact majorly on the future energy supply in Scotland. This project focuses on one predicted scenario, which could be affected by all of these variables and so will most likely not describe the power systems of 2020 exactly.

Power systems are particularly sensitive to outside temperature, as stated by Doquet et al [28] in their model of the French electrical grid “In wintertime, each degree below statistical expected brings about 2.1GW additional peak power”. The ANTARES software allows us to model the extremes in power generation and indeed in load requirements by the process of using hundreds of different Monte-Carlo years in simulations. Minimum and maximum results give an idea of these extremes that could occur, whilst the expected values and standard deviation give an idea of the spread and probability of these results occurring.

7.2. Overall Findings

In section 6.1 we observed a graph having a point of change in the relationship between installed capacity and spilled wind. With the model set up as SKM scenario 1 in 2020 and with both transmission bootstraps, this point of change was around 10GW installed wind capacity. Later in section 6.2 we saw that with no transmission bootstraps this point fell to 9GW installed wind capacity, whilst with one transmission bootstrap it remains at 10GW.

In the case of East and West and West Only all of the spilled energy occurred in the SHETL N region. This was why the additional case of the SHETL east HVDC link was included. The addition of this link caused the spilled wind results to fall greatly.

In the case of the West Only and No Bootstraps scenarios, we saw a minimum spilled energy greater than zero (912MWh and 113673MWh respectively at the full installed wind capacity of SKM scenario 1). This signifies that this spilled energy occurs in all cases of this simulation.

In each scenario, the 'spilled' energy is far less than the total produced energy. In fact, the spilled wind at the installed wind capacity of the SKM scenario 1 is shown in the table below as a percentage of the total produced wind energy.

Scenario	**Spilled Wind/Produced Energy**
East and West	0.143 %
West Only	0.244 %
Additional East	0.002 %
No Bootstraps	1.772 %

Table 7.2-1 Spilled wind energy as a percentage of produced wind energy.

In section 6.3 we saw that even introducing one transmission 'bootstrap' greatly reduces the amount of unsupplied energy to Scotland. Increasing values of installed wind capacity also reduced the unsupplied energy values, to the point at over 7GW installed wind capacity where even with only one transmission bootstrap the unsupplied energy is identical to a scenario with both bootstraps. In the 'No Bootstraps' scenario the unsupplied energy is very high and so in the case that the transmission bootstraps are not delivered in time, it could be that additional standby capacity is required for periods of low wind.

Regarding the power flows results in section 6.3, we observed that the maximum values were curtailed by the transmission capacities of the links. This suggests that under extreme conditions that could cause more energy to be generated or required (high winds, low temperatures) the transmission capacity of the links between Scotland and England will still be a limiting factor. For the West only and the No Bootstraps scenarios, the 'expected plus one standard deviation' values are curtailed and so without both bootstrap links this transmission capacity was enough in less than 68% of cases (assuming a normal distribution).

For the East and West and Additional East scenarios, the ‘expected plus one standard deviation’ values were not curtailed and so it can be concluded that with both transmission bootstraps, in at least 68% of cases this transmission capacity was enough. Additional graphs in Appendix 2.3 with values for ‘expected plus two standard deviations’ show that these lines are curtailed, so transmission capacity was enough for 68% of the cases, but was not quite enough for 95% of the cases in these scenarios. From these graphs we can also see that with the Additional East bootstrap, curtailment occurs to a lesser extent and so a greater proportion of cases will have enough transmission capacity.

7.3. Conclusions

From the results presented, the author would have to agree with the SKM report that transmission capacity will be a key limiting factor in utilising the electricity created by a high proportion of renewables in the Scottish energy mix. If we presume that the East and West ‘bootstraps’ are completed on time we can reach the following conclusions:

It has been shown that with a supply of renewable energy equal to the Scottish electrical demand, as part of a wider generation mix, there was no increase to unsupplied energy. There will be some spilled energy, which increases rapidly with installed capacity after around the 10GW mark; however this spilled energy is a fraction of the actual usable energy. With both bootstraps, the transmission capacity will be enough in over 68% of cases.

Finally, the Additional East bootstrap between Caithness and Moray improves the spilled wind and unsupplied energy figures greatly and will be of benefit to the transmission system.

8. Further Work

If time had been permitting, the following further work could have been completed:

- Modelling of wave power, at least one simplified time series.
- Modelling of tidal power more realistically, using a power conversion curve for the whole tidal farm and using more than one time series to allow for outages due to maintenance.
- Modelling wind power with more weather data, and more reliable weather data, also a more rigorous verification of capacity factors, preferably regionally.
- Offshore wind power generation for England would have been dealt with separately and using offshore weather data.
- Modelling of biomass, other renewables and other thermal more realistically (with associated operational costs).
- More work in effectively modelling interconnectors.

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Appendix 1 Additional Tables

Installed Capacities – Region by Region

Region	Generation Type	Installed Capacity
SHETL N	Hydro (pumped storage)	600MW
	Hydro (ROR)	657MW
	Wind (onshore)	1917MW
	Wind (offshore)	1420MW
	Biomass	25MW
	Other	9MW
	Tidal	500MW
	Total	**5128MW**
SHETL S	Gas (CCGT)	1322MW
	Hydro (pumped storage)	440MW
	Hydro (ROR)	708MW
	Wind (onshore)	1505MW
	Wind (offshore)	400MW
	Biomass	10.5MW
	Other	37MW
	Total	**4422.5MW**
SPT	Coal	1713MW
	Coal (with CCS)	571MW
	Nuclear	1215MW
	Hydro (ROR)	135MW
	Wind (onshore)	3893MW
	Wind (offshore	3350MW
	Biomass	114.5MW
	Other	107MW
	Total	**11098.5MW**
Upper North	Gas (CCGT)	144MW
	Coal	230MW
	Hydro (ROR)	5MW
	Wind (offshore)	1463MW
	Biomass	299MW
	Total	**2141MW**
North	Gas (CCGT)	7716MW
	Gas (OCGT)	168MW
	Coal	8700MW
	Nuclear	3612MW
	Hydro (pumped storage)	2050MW
	Hydro (ROR)	78MW
	Wind (offshore)	5637MW
	CHP	1428MW

	Biomass	580MW
	Total	**29969MW**
Midlands	Gas (CCGT)	6440MW
	Gas (OCGT)	50MW
	Coal	2968MW
	Wind (offshore)	1200MW
	Wind (onshore)	659MW
	CHP	218MW
	Total	**11535MW**
Central	Gas (CCGT)	11961MW
	Gas (OCGT)	319MW
	Coal	363MW
	Nuclear	1207MW
	Hydro (ROR)	45MW
	Wind (offshore)	4062MW
	CHP	158MW
	Biomass	350MW
	Total	**18465MW**
South West	Gas (CCGT)	905MW
	Gas (OCGT)	140MW
	Nuclear	1932MW
	Wind (offshore)	1138MW
	Total	**4115MW**
Estuary	Gas (CCGT)	4584MW
	Nuclear	1081MW
	Wind (offshore)	1577MW
	Total	**7242MW**

Table A1-1 Generation capacities in model.

Results – Spilled Wind

Installed Wind Capacity	Region(s)	Expected Value	Standard Deviation	Minimum Value	Maximum Value
East and West					
2383	None	0	0	0	0
3445	None	0	0	0	0
4506	None	0	0	0	0
5568	None	0	0	0	0
6630	None	0	0	0	0
7692	None	0	0	0	0
8753	None	0	0	0	0
9815	SHETL N	48	474	0	5928
10877	SHETL N	1478	4788	0	31205

11938	SHETL N	12365	25142	0	124575
13000	SHETL N	54739	89975	0	393891
West only					
2383	None	0	0	0	0
3445	None	0	0	0	0
4506	None	0	0	0	0
5568	None	0	0	0	0
6630	None	0	0	0	0
7692	None	0	0	0	0
8753	None	0	0	0	0
9815	SHETL N	75	705	0	8870
10877	SHETL N	2152	5311	0	40502
11938	SHETL N	21231	28712	0	129583
13000	SHETL N	93656	92763	912	401190
Additional East					
2383	None	0	0	0	0
3445	None	0	0	0	0
4506	None	0	0	0	0
5568	None	0	0	0	0
6630	None	0	0	0	0
7692	None	0	0	0	0
8753	None	0	0	0	0
9815	None	0	0	0	0
10877	None	0	0	0	0
11938	SHETL N	23	270	0	3715
13000	SHETL N	819	2889	0	30390
No Bootstraps					
2383	None	0	0	0	0
3445	None	0	0	0	0
4506	None	0	0	0	0
5568	None	0	0	0	0
6630	None	0	0	0	0
7692	SHETL N	56	542	0	7350
8753	SHETL N	1885	4415	0	36655
9815	SHETL N	23207	29169	0	133658
10877	SHETL N&S	110314	93696	3329	376184
11938	All	315695	204243	33812	876912
13000	All	679221	361875	113673	1692209

Table A1-2 Spilled Wind Results for all Scenarios

Results - Spilled Energy

Installed Wind Capacity	Region(s)	Expected Value	Standard Deviation	Minimum Value	Maximum Value
East and West					
2383	None	0	0	0	0
3445	None	0	0	0	0
4506	None	0	0	0	0
5568	None	0	0	0	0
6630	None	0	0	0	0
7692	None	0	0	0	0
8753	None	0	0	0	0
9815	SHETL N	100	913	0	11609
10877	SHETL N	2141	7133	0	48126
11938	SHETL N	15897	33086	0	167683
13000	SHETL N	66618	111111	0	488751
West only					
2383	None	0	0	0	0
3445	None	0	0	0	0
4506	None	0	0	0	0
5568	None	0	0	0	0
6630	None	0	0	0	0
7692	None	0	0	0	0
8753	None	0	0	0	0
9815	SHETL N	83	762	0	9409
10877	SHETL N	2814	7102	0	53849
11938	SHETL N	26228	37008	0	134060
13000	SHETL N	111231	116841	912	494745
Additional East					
2383	None	0	0	0	0
3445	None	0	0	0	0
4506	None	0	0	0	0
5568	None	0	0	0	0
6630	None	0	0	0	0
7692	None	0	0	0	0
8753	None	0	0	0	0
9815	None	0	0	0	0
10877	None	0	0	0	0
11938	SHETL N	30	374	0	5185
13000	SHETL N	1026	3524	0	35476
No Bootstraps					
2383	None	0	0	0	0
3445	None	0	0	0	0

4506	None	0	0	0	0
5568	None	0	0	0	0
6630	None	0	0	0	0
7692	SHETL N	63	590	0	7932
8753	SHETL N	2418	5579	0	45017
9815	SHETL N	28875	37780	0	175365
10877	SHETL N&S	129783	117946	3329	472630
11938	All	359726	254479	33812	1044499
13000	All	756705	442727	113673	1962978

Table A1-3 Spilled Energy Results for all Scenarios (includes spilled wind)

Results – Unsupplied Energy

Installed Wind Capacity	Region(s)	Expected Value	Standard Deviation	Minimum Value	Maximum Value
East and West					
2383	All	81	816	0	10498
3445	All	47	503	0	6721
4506	SHETL N &SPT	32	387	0	5439
5568	SHETL N &SPT	25	338	0	4798
6630	SHETL N &SPT	21	293	0	4157
7692	SHETL N &SPT	18	248	0	3516
8753	SHETL N &SPT	15	216	0	3062
9815	SHETL N &SPT	12	172	0	2443
10877	SHETL N &SPT	9	128	0	1824
11938	SHETL N &SPT	6	85	0	1205
13000	SHETL N &SPT	3	41	0	586
West only					
2383	All	608	3543	0	40606
3445	All	227	1846	0	24354
4506	All	105	1116	0	14848
5568	SHETL S &SPT	52	602	0	7548
6630	SHETL S	25	335	0	4748

	&SPT				
7692	SHETL S &SPT	13	183	0	2592
8753	SPT	11	149	0	2106
9815	SPT	9	134	0	1894
10877	SPT	8	119	0	1682
11938	SPT	7	104	0	1470
13000	SPT	6	89	0	1258
Additional East					
2383	SPT	31	270	0	3377
3445	SPT	21	229	0	3164
4506	SPT	16	209	0	2951
5568	SPT	15	194	0	2739
6630	SPT	13	178	0	2527
7692	SPT	12	164	0	2318
8753	SPT	11	149	0	2106
9815	SPT	9	134	0	1894
10877	SPT	8	119	0	1682
11938	SPT	7	104	0	1470
13000	SPT	6	89	0	1258
No Bootstraps					
2383	All	70733	123921	0	864735
3445	All	44726	88333	0	630347
4506	All	29593	64813	0	467464
5568	All	20520	48495	0	334184
6630	All	14561	36992	0	266500
7692	All	10698	29378	0	233376
8753	All	8087	23726	0	204203
9815	All	6269	19453	0	177532
10877	All	4993	16347	0	154822
11938	All	4027	13952	0	135794
13000	All	3281	11996	0	119264

Table A1-4 Unsupplied Energy Results for all Scenarios

Appendix 2 Additional Graphs

A2.1 Spilled Wind

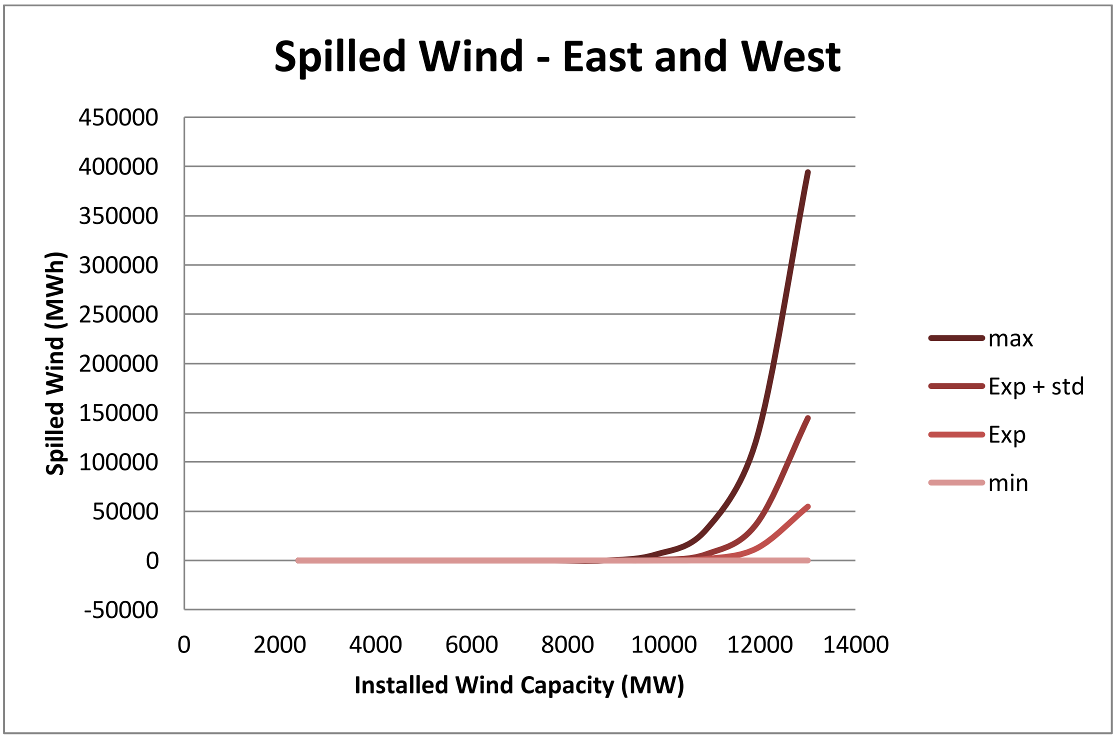


Figure A2.1-1 Spilled Wind – East and West Scenario

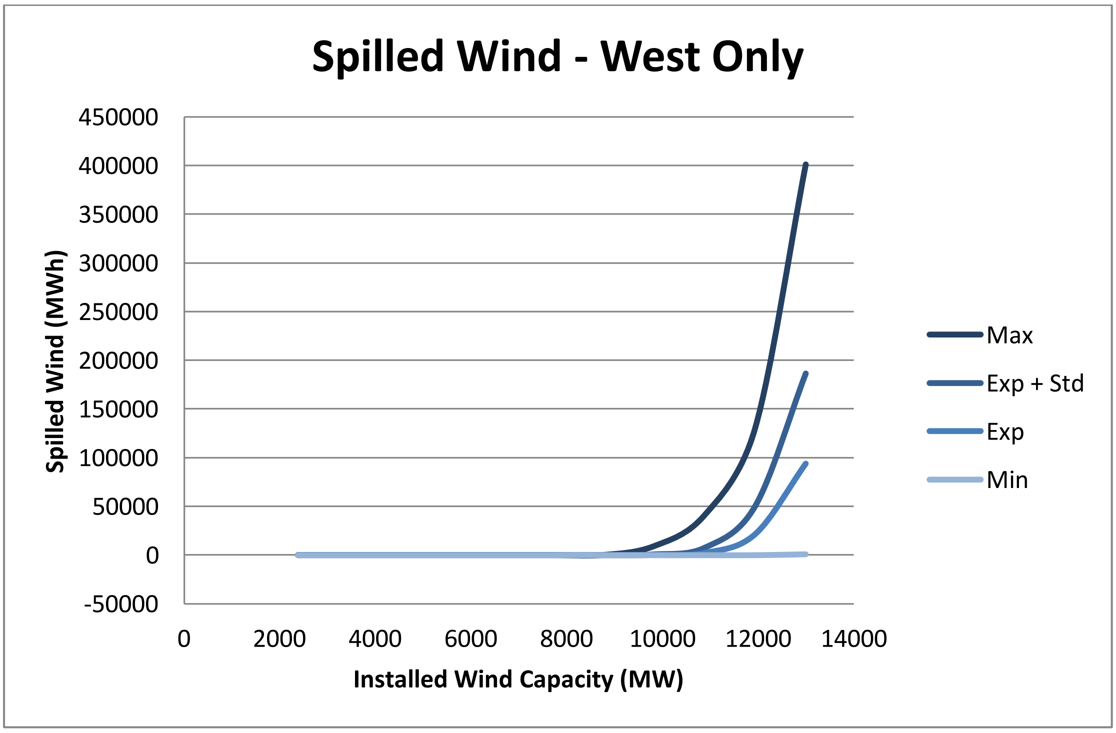


Figure A2.1-2 Spilled Wind –West Only Scenario

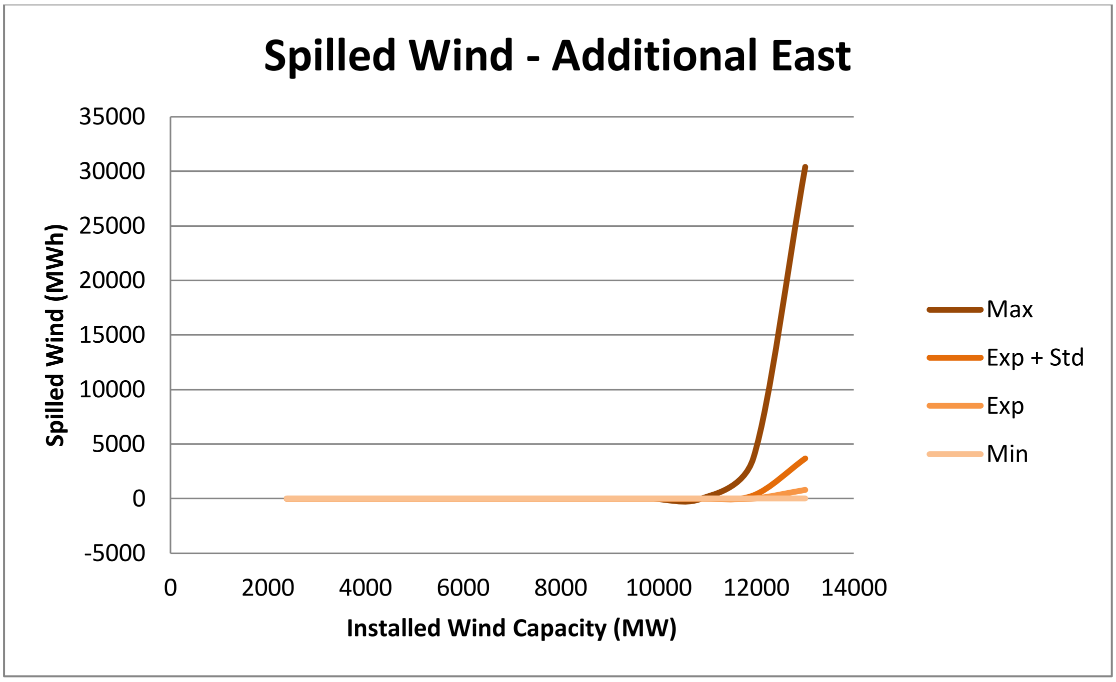


Figure A2.1-3 Spilled Wind – Additional East Scenario

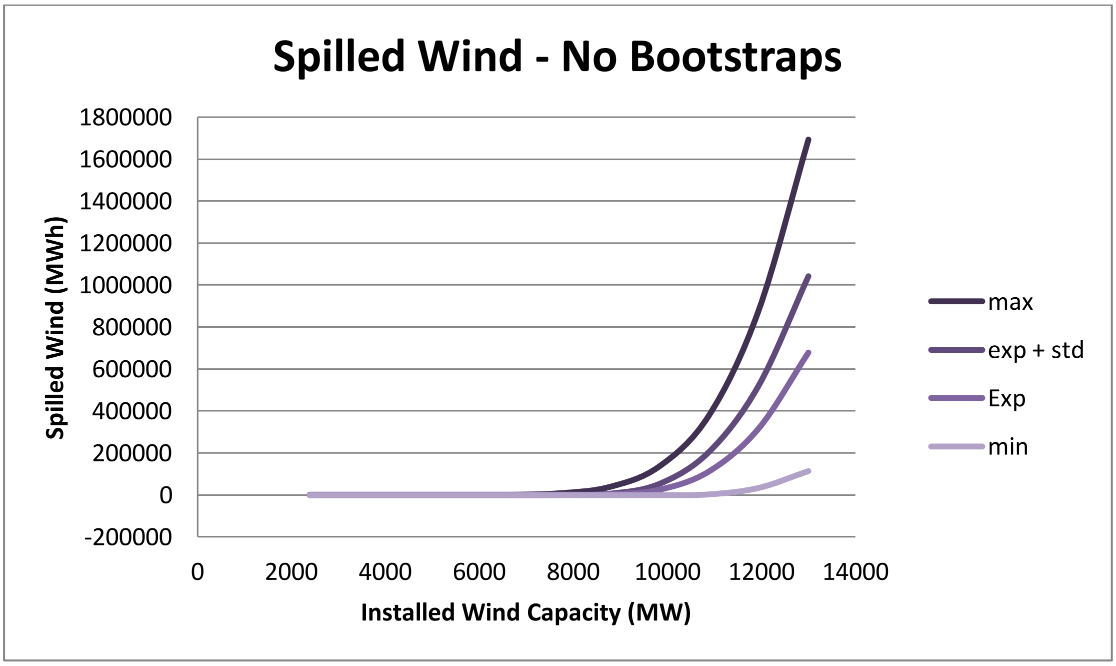


Figure A2.1-4 Spilled Wind – No Bootstraps Scenario

A2.2 – Spilled Energy

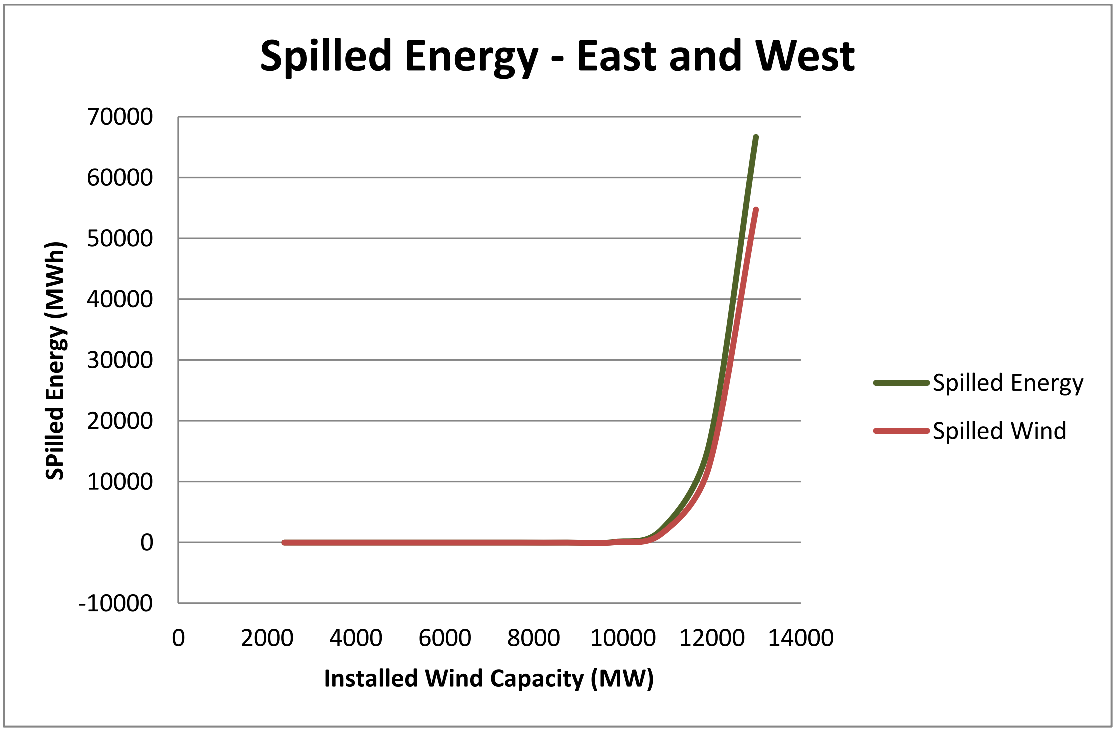


Figure A2.2-1 Spilled Wind – East and West Scenario

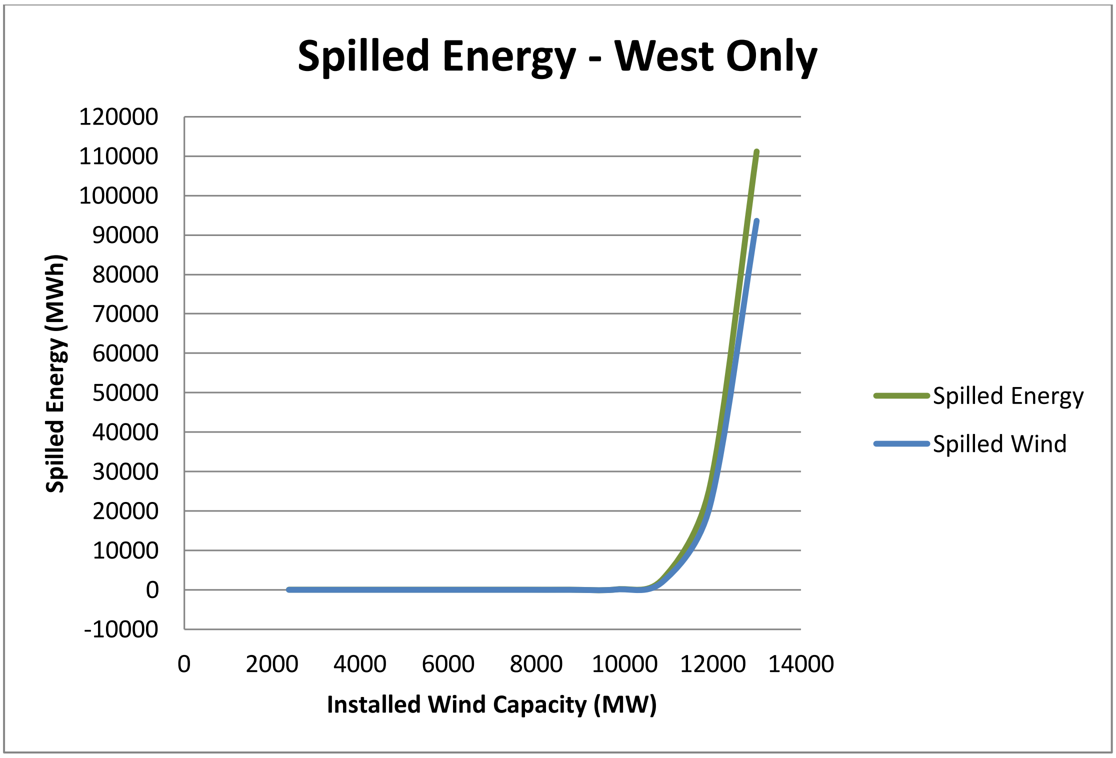


Figure A2.2-2 Spilled Wind –West Only Scenario

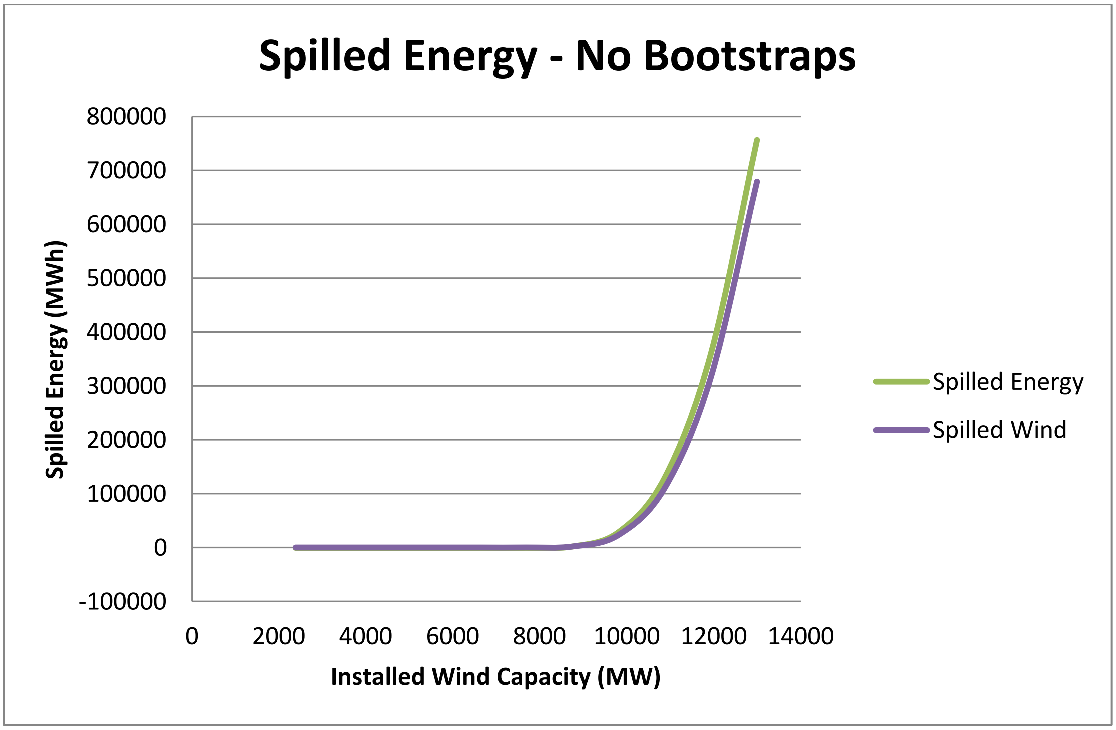


Figure A2.2-3 Spilled Wind – No Bootstraps Scenario

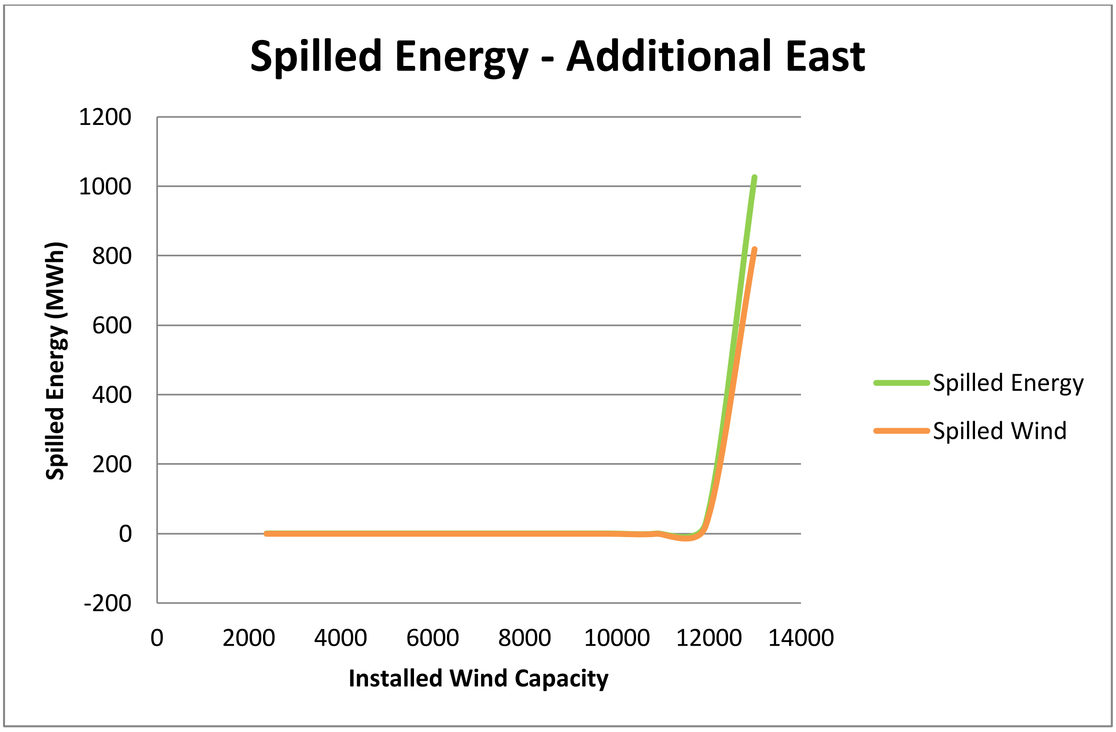
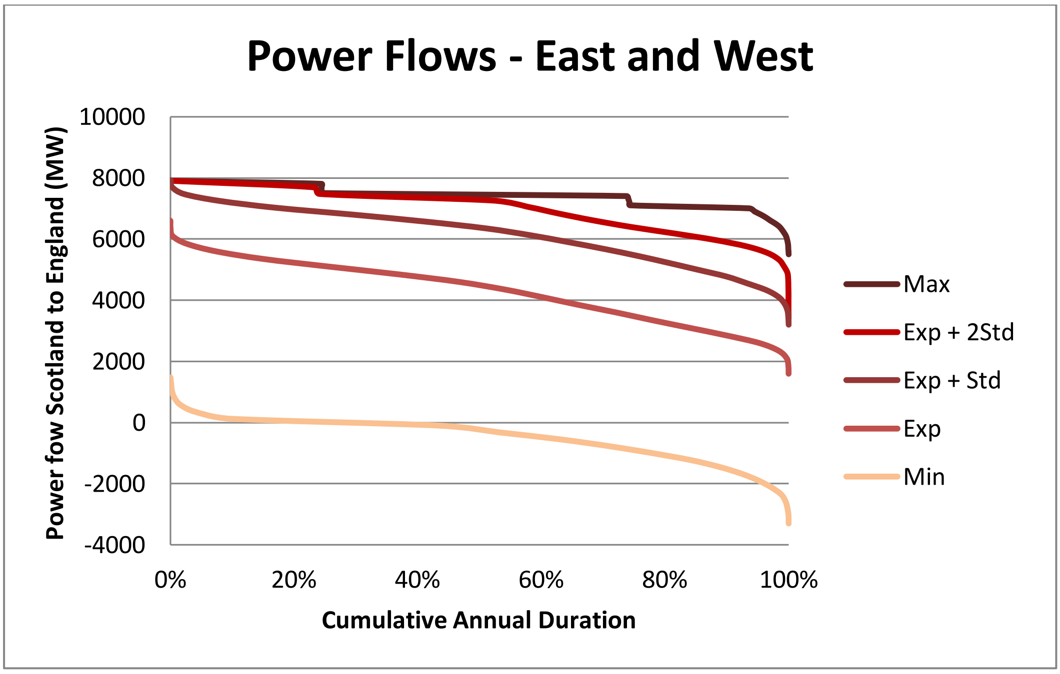


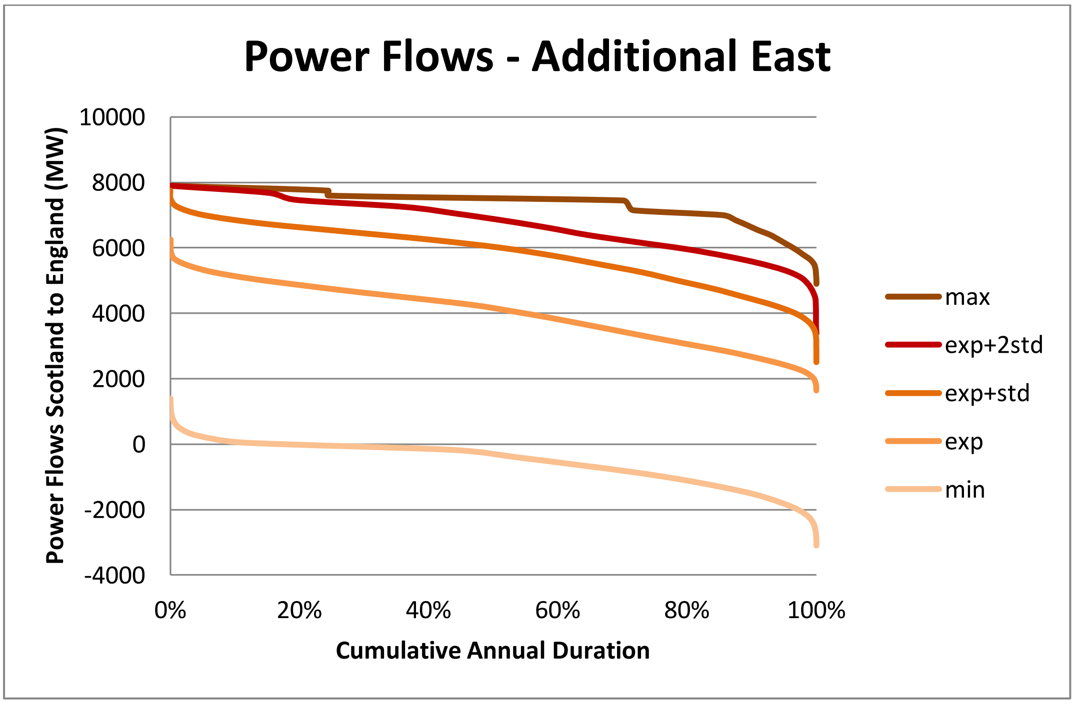
Figure A2.2-4 Spilled Wind – Additional East Scenario

A2.3 – Power Flows Additional Graphs

These graphs are included to show the additional expected value plus two standard deviations for those scenarios not curtailed at the expected plus one standard deviation values.



A2.3-1 Power Flows – East and West Scenario



A2.3-2 Power Flows – Additional East Scenario