Department of Mechanical and Aerospace Engineering

The Role of Additional Pumped Hydro Storage in a Low Carbon UK Grid

Author: Thomas Hoy

Supervisor: Dr Andrew Grant

A thesis submitted in partial fulfilment for the requirement of the degree

Master of Science

Sustainable Engineering: Renewable Energy Systems and the Environment

2015

Copyright Declaration

Abstract

Electricity from renewable sources in 2014 contributed to a fifth of the total energy generated in the UK. There is a clear trend leading to larger percentages of renewables in the total installed generating capacity of the national grid. As these numbers creep higher, problems of balancing supply with demand and preventing curtailment of valuable renewable energy will become increasingly difficult. One solution to this is energy storage and currently the only grid level form of storage is pumped hydro. Luckily for the UK, various appraisals have identified pumped hydro storage as an under-developed resource with the Highlands of Scotland and much of Wales having the right geography for expansion of this tried and tested energy storage technology.

Actual supply and demand data from 2014 was used to build a model that simulated increases in the UK's installed renewable and nuclear capacity, this allowed scenarios to be created that would show how much energy storage would be needed with various increases in renewable and nuclear capacity.

Key objectives were to arrive at a figure for the level of new pumped storage the UK would need to build to prevent curtailment of renewable energy supplies and minimise reliance on gas turbines for load following.

The results indicated that different mixes of generating capacity mandated different storage levels, but that once renewables that were mainly comprised of wind (as is likely to be the case in the UK) begin to contribute around 30% of total electricity generated then the amount of spilled energy will increase markedly. However, 200GWh of storage capacity would be able to save the majority of this otherwise curtailed energy. It was also discovered that storage size had little effect on the size of backup capacity required in the event of renewables not generating enough energy to meet demand.

The overall conclusion was that there was a very strong case for building between 150 and 200GWh of new pumped storage in the UK in the very near future. However realistically as renewable penetration increases so too must backup capacity in the form of combined cycle gas turbines.

Acknowledgments

I would firstly like to thank my wife Seonad for providing emotional and financial support during my return to higher education, I would not have been able to do this without her.

I am also greatly indebted to my supervisor Andy Grant who made himself available whenever I needed a meeting and was always very quick in his responses to my numerous emails.

I would finally like to thank the University of Strathclyde and Dr Paul Strachan for allowing me the opportunity to return to continue my education after such a long break.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

PHS	–Pumped Hydro Storage
CCGT	–Combined Cycle Gas Turbines
OCGT	–Open Cycle Gas Turbines
HVDC	–High Voltage Direct Current
DUKES	–Digest of United Kingdom Energy Statistics
GWh	–Giga Watt Hours
OFGEM	– Office of Gas and Electricity Markets

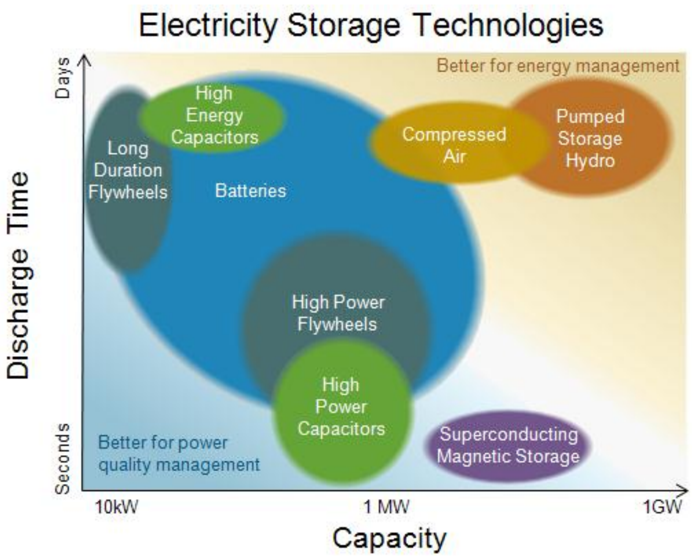
1. Introduction

1.1. Background

Renewables are making up an ever larger proportion of the total installed generating capacity of our national grid, as this trend continues the role of storage will possibly change from one of a purely load balancing mechanism to one that also includes what could be described as a supply balancing mechanism. This means currently pumped hydro storage (PHS) primarily exists in the UK to help deal with surges and falls in demand but in the future this may change to primarily deal with surges and falls in supply as the percentage of our electricity from variable supplies increases.

Pumped hydro storage is the only grid level form of energy storage currently available to us although battery, flywheel, compressed air and super capacitor technology continue to mature they do not yet store energy in the way we require to power a grid in terms of storage capacity or discharge times (Figure 1).

Figure 1 Capacity vs Discharge time of Energy Storage Technologies



(EIA.GOV, 2011)

Luckily for the UK it has an abundance of the type of geography that PHS requires, lots of high hanging valleys sitting above large bodies of water exist in both Scotland and Wales.

As the variety and size of planned future renewable capacity is uncertain and affected by the vagaries of both politics and economics knowing when and in what size energy storage will be required is a hard value to quantify, this project aims to hopefully answer some of these questions.

1.2. Project Objectives

- To arrive at a figure for how much new pumped hydro storage the UK will require under a variety of supply scenarios.
- To find out how much reserve capacity must be kept to backup renewables under these same scenarios.
- To find out at what level of installed renewables it will become desirable to have additional energy storage built into the national grid.

1.3. Project Scope

The project will focus specifically on how much storage will be required under various scenarios that are designed on the premise that the UK's national grid is cut off from all other countries, imports/exports of energy will not be considered as the future make-up of foreign electrical grids and their demand/ supply characteristics would be difficult to model.

Future demand side changes were left out also to keep the number of scenarios investigated to an acceptable level.

1.4. Methods

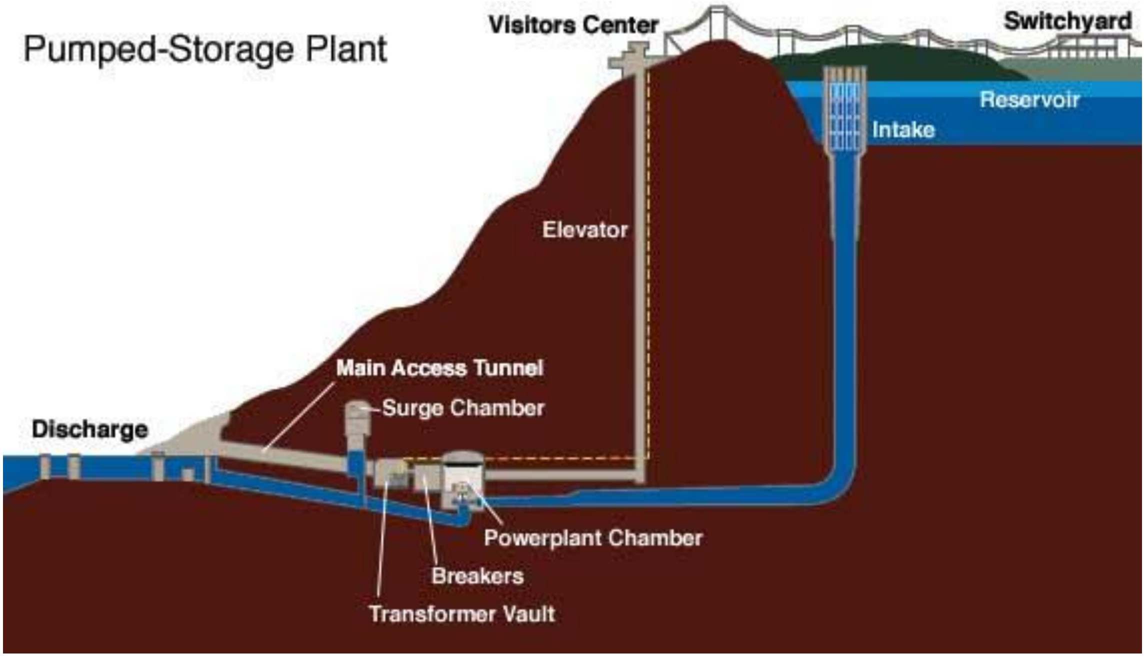
To be able to investigate the storage and reserve capacity needs of various mixes of renewables, nuclear power and fossil fuels a model was built based on the supply/generating profile for the year 2014, this data was used to estimate what various factor increases in the generating capacity of each technology type would look like if installed.

A more complete explanation of this process is contained in Section 3.

2. Literature Review

2.1. Pumped Storage

Figure 2 Wind Resources Across Europe



(Wikipedia, 2015)

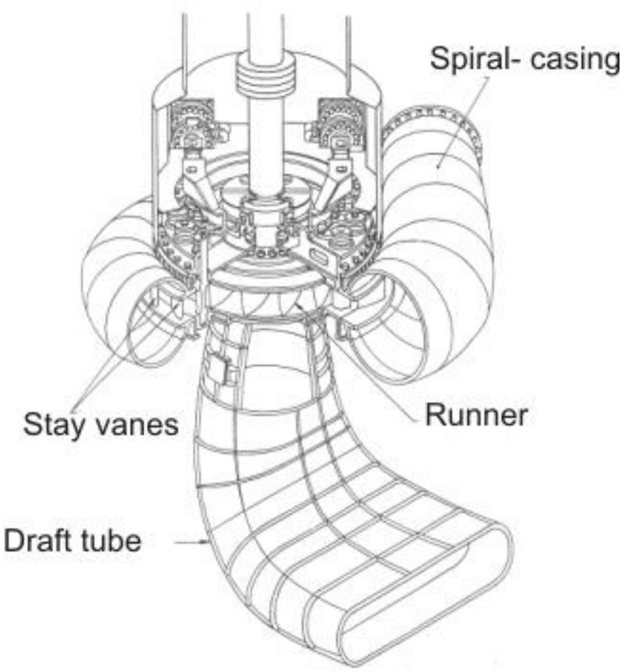
Pumped Hydro Storage (PHS) is a form of hydropower used primarily for load balancing and energy storage that involves the pumping of water from a low lying body of water to a higher one. Subsequently the water is run back down to the lower reservoir to generate electricity. PHS does not on its own generate electricity and is in fact a net consumer. It can better be thought of as a giant battery. Like any other battery it has a round trip efficiency, normally in the region of 80% (Ter-Gazarian, 1994, p. 97)

It is currently still the only grid scale form of energy storage. Although battery, compressed air and flywheel technology have come far in the last twenty years there is nothing that approaches PHS capacity, storage levels and storage times.

2.1.1. Turbine Types

A reaction turbine is the type most commonly used in pumped hydro as it has the ability to run in reverse as a pump. In reaction turbines the mechanism that turns the energy of the water into rotational energy (i.e. the runners) are fully submerged in the water flow. The energy from the pressure differential resultant from this flow across the runner vanes is used to turn the turbine.

Figure 3 Diagram of a Standard Francis Turbine



(NPTEL,2015)

Francis Turbine

The most commonly used reaction turbine in PHS is the Francis turbine (Figure 3), used typically for heads of between 15-500m (Hermann-Josef Wagner, 2011,p.77). The water comes through the spiral casing and is guided by the stay vanes efficiently onto the runner section. The flow of the water causes a pressure differential across the runner vanes, which are specially shaped to utilise this and convert it into a shaft torque.

Figure 4 Photograph of Large Francis Turbine

https://en.wikipedia.org/wiki/Francis_turbine

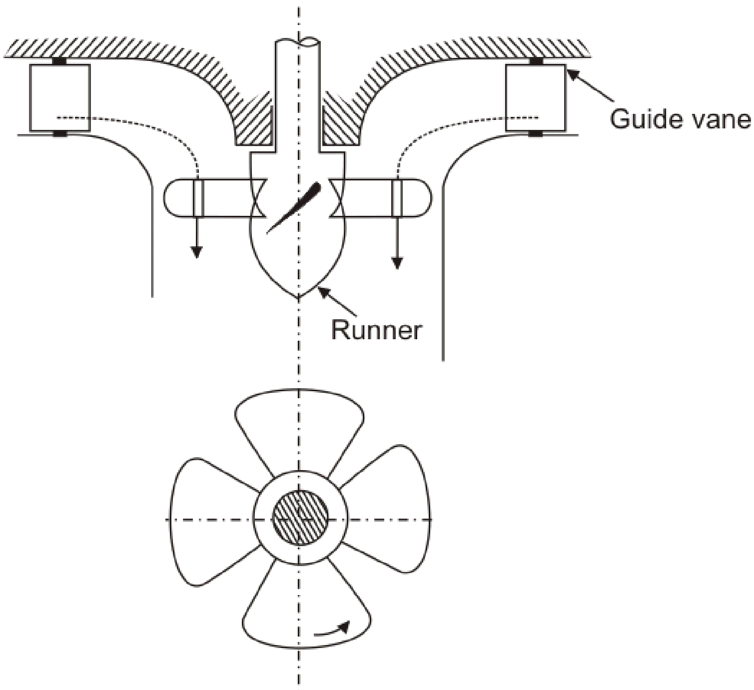
Note Figure 4 which shows the guide vanes of a turbine from the Chinese Three Gorges Dam: The vanes, while being slightly curved at the top part of the vane to produce the pressure differential, also tend to “bucket” at the bottom. Francis turbines can also be called mixed flow turbines, as the water across the vanes flows both axially and radially. (Hermann-Josef Wagner, 2011,p72). The water having left the turbine then drops out of the draft tube which is designed to reduce the velocity of the outrushing water to preserve pressure at the turbine exit. This prevents unwanted backflow and allows the turbine to operate as close to the tail race as possible.

Kaplan Turbines

Kaplan turbines are the other type used in PHS, though these are much less commonly seen in pumped storage systems. Kaplan turbines are better utilised for high flow rates, with low head heights of around the 25m range (Hermann-Josef Wagner, 2011,p87). This means that they are ideal for running between the very large volumes with small altitude differences which are commonly seen in natural bodies of water or in large river systems.

Figure 5 shows the basic schematic of a Kaplan turbine. They are axial flow and work in a similar way to the Francis turbine in that the water flow is initially guided by guide vanes to flow down through the turbine blades, in doing so lift forces which turn the turbine are created.

Figure 5 Kaplan Turbine Diagram



(NPTEL, 2015)

2.1.2. <u>Reservoirs</u>

Reservoirs are perhaps the most critical aspect when designing a PHS as they dictate the location of the system. Many factors must be taken into account when looking at prospective sites such as environmental concerns, height difference between the reservoirs, and rock type upon which they will be built. With so many criteria it is no wonder it can be a difficult task to find new PHS sites.

The upper and lower reservoirs can also sometimes be referred to as the forebay and afterbay respectively. The approach with which the upper and lower reservoirs are created can tend to differ in both location and in the type of landscape they utilize. (Barnes & Levine, 2011, p63)

Upper Reservoir

The upper reservoir of a PHS can be obtained by using existing natural bodies of water such as lochs or lakes, these can be further enhanced by damming them so as to allow increased storage capacity. A river or stream can be damned upstream across the valley floor, this is also suitable for creating a lower reservoir though great care must be taken to allow for the release of floodwater, and in some cases fish (Ter-Gazarian, 1994, p92).

An upper reservoir can also be created by damming a hanging valley that was previously devoid of water. This allows a lot more potential sites as there is no need to look for an existing body of water at suitable height. Cruachan in Scotland is a good example of this.

An upper reservoir will have to deal with the natural inflows that will inevitably occur from the surrounding landscape, and so a construction of a spillway is sometimes necessitated to allow any additional water to leave the reservoir without any harm to the system.

Lower Reservoir

Lower reservoirs can be created in many of the same ways upper reservoirs can, through damming of a valley or use of an existing body of water (either natural or man-made). A very large river may be used for a lower reservoir as long as it can cope with large volumes of water being depleted from and added to it without harm to the local ecosystem. (Ter-Gazarian, 1994,p92)

There are two further possible lower reservoirs, both at the cutting edge of pumped hydro systems. One would be an underground storage cavern. This would have the advantage of greatly expanding the number of PHS sites available, though engineering and cost limitations at the moment mean there are no real world examples. The other is to use the sea as a lower resevoir. The Okinawa Yanbaru Seawater facility in Japan is a 30MW station that pumps seawater 150m high for storage and as of 2015 is the only one of its kind. Pumping seawater brings its own set of challenges, such as enhanced corosion from saline water. Yanbaru has overcome this through the use of stainless steel and fibre reinforced plastic. (Fujihara,1998)

Penstocks

The penstock is what carries the water down from the upper reservoir to the turbine hall. In older systems it was commonly an outside pipe that went down the mountain, though nowadays most systems have their penstocks kept inside the excavated mountain. (Ter-Gazarian, 1994, p88)

The best pumped hydro systems have a penstock length to head height ration as close to 1:1 as possible. This would mean ideally the the entrance to the penstock would be directly above the turbine itself (Barnes & Levine, 2011, p67). A more conventional figure is 4:1 (Ter-Gazarian, 1994, p92).

Surge Tanks

Surge tanks branch off of the penstock and are located between the upper resevoir and turbine. The purpose of a surge tank is to protect the water channels and machinery from harmful changes in pressure, though it can also be used as a way of regulating load. (Barnes & Levine, 2011, p69)

2.1.3. Pumped Storage in the UK

Worldwide capacity of PHS is in the region of 132GW with the UK contributing 2.8GW to this value. (EIA, 2012)

In the UK PHS was built for two reasons. One was as a way of storing nuclear power overnight when demand was low. Nuclear power stations are mostly unable to throttle their output, and so the pumped hydro stations would be able to use this excess power to fill their upper reservoirs and then run the turbines during times of peak demand. The other was as a quick response measure for grid stability as PHS can act as both a large supplier and consumer of electricity in very short time frames. It is therefore ideal for balancing out sudden surges or drops in demand.

There is a final use for PHS in the UK and that is as a ‘black start’ mechanism for the grid. A black start is the process of returning a power station, part of the grid or even the entire grid to being fully functional (National Grid, p.8). As most power generators require an external electricity feed before they themselves can begin to generate power, the grid needs certain ‘black start’ capacity. This means that if a part of the grid or the whole grid goes down, a supply of electricity can be provided to allow the majority of other plant to begin generating electricity. PHS can provide this, as to get it operational is as simple as opening up the pipeline gates (these gates are normally powered by a backup diesel generator).

Current PHS Capacity

The UK currently has only four pumped hydro schemes, they are:

Table 1 Existing Pumped Hydro Storage in UK

station	power (GW)	head (m)	volume (million m^3)	energy stored (GWh)
Ffestiniog	0.36	320–295	1.7	1.3
Dinorwig	1.8	542–494	6.7	9.1
Foyers	0.3	178–172	13.6	6.3
Cruachan	0.4	365–334	11.3	10

Source: (MacKay, 2008)

As the UK’s pumped storage was primarily built for overnight storage of nuclear power and as a response to sudden surges/drops in demand, they are not designed to store enough energy for more than around 20 hours at full output.

Planned and Proposed new PHS

There are a number of new PHS schemes that have either been mooted or are in the planning stage, they are:

Planned

1. Coire Glas: A 300-600MW SSE scheme that utilises Loch Lochy as its lower tailpond and an artificial dam built 500m above. Storage capacity is expected to be in the order of 30-40GWh. (SSE, 2012)
2. Balmacaan: Another 300-600MW SSE scheme with around 30-40GWh of storage, this time utilising Loch Ness as the lower tailpond and an existing Lochan that will be enlarged by a new dam or dams. (Lannen, 2012)

Proposed

3. Glyn Rhonwy Scheme: A proposed 600MW site situated in Snowdonia national park that utilises old slate quarries with a head height of 300m (Holmes, 2015)
4. Loch Sloy conversion: The current conventional Loch Sloy hydro site has been proposed for conversion to PHS. If pumping capacity was added now then the station could hold 20GWh, but with the dam heights raised by 40m it is estimated that around 40GWh could be stored. (MacKay, 2008,p.193)

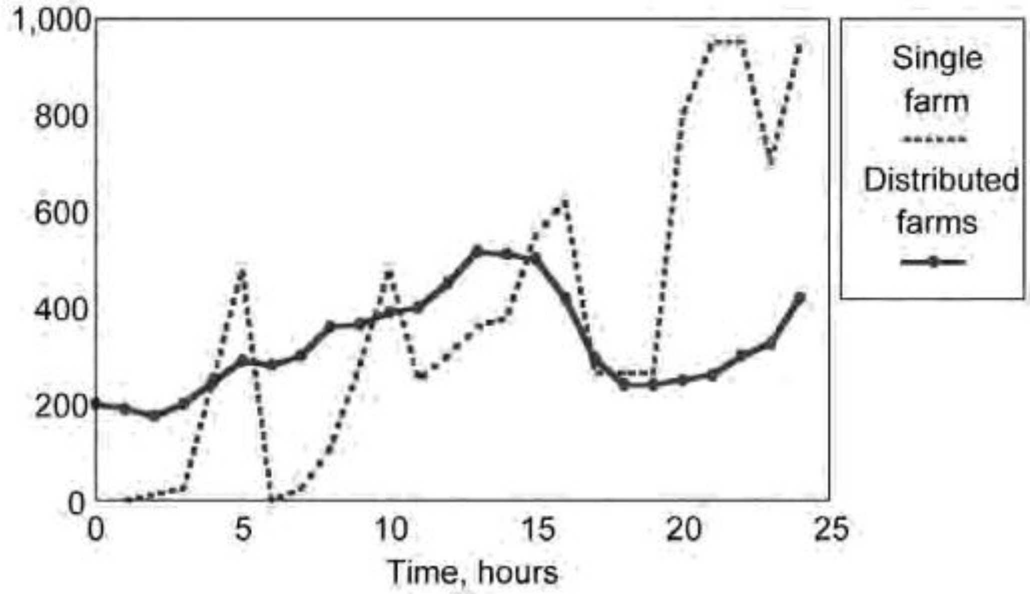
2.2. UK Renewable Intermittency and Variability

2.2.1. Wind Power Output

Wind power output is related to two main things: turbine size and wind speed. The bigger the turbine, the more power it is able to produce when conditions are windy. Also, generally the windier it is the more power will be produced, though most turbines will have a cut-out speed where the turbine will cease turning at very high wind speeds to prevent damage to the equipment. Because power output is directly affected by wind speed it means that given the generally stochastic nature of wind then the power output of a wind turbine is itself stochastic.

Fortunately though, by having windfarms that are geographically spread throughout a country or region, then fluctuations for the overall installed capacity will be smoothed out to some extent.

Figure 6 Output of Single vs Distributed Windfarms



Source: (Boyle, 2007,p37)

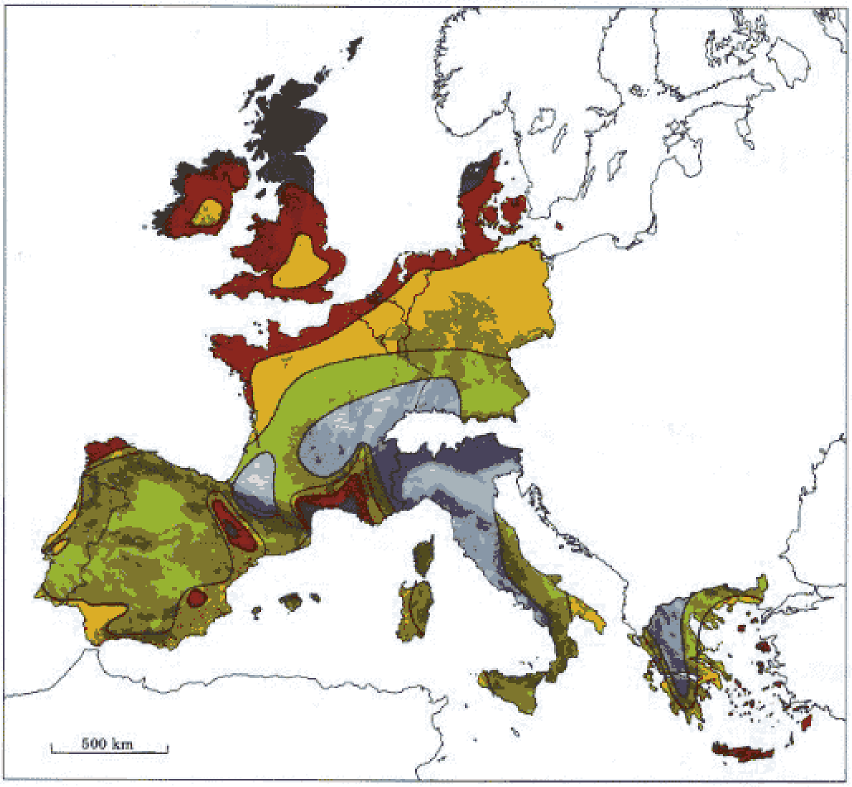
Figure 6 illustrates this perfectly. It shows the output over a day for a single 1000MW wind farm versus the output of 1000MW worth of geographically distributed farms. By having a geographically spread out wind capacity the violent peaks and dips in output can be mostly avoided. (Boyle, 2007,p36)

Although a geographically diverse installed capacity will go some way to smooth out the variability of output that is usually seen in wind, it cannot completely ameliorate the effects that wind speed variability brings, as we will see for cases in the UK.

Wind in the UK

The UK has the best resource for both onshore and offshore wind in Europe (Figure7). This still does not mean that wind resources in the UK are totally reliable or that we are able to anticipate wind speeds over long time-frames with a very high degree of accuracy.

Figure 7 Wind Resources Across Europe



Wind resources[1] at 50 metres above ground level for five different topographic conditions

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

(WASP, 2015)

Winds in the UK tend to be stronger and less intermittent in the winter months, and weaker and more susceptible to lulls and with lower wind speeds in summer. Also, generally speaking wind speeds tend to be stronger during the day than during the night (Sinden, 2005).

Figure 8 UK Wind Power Output in 2013

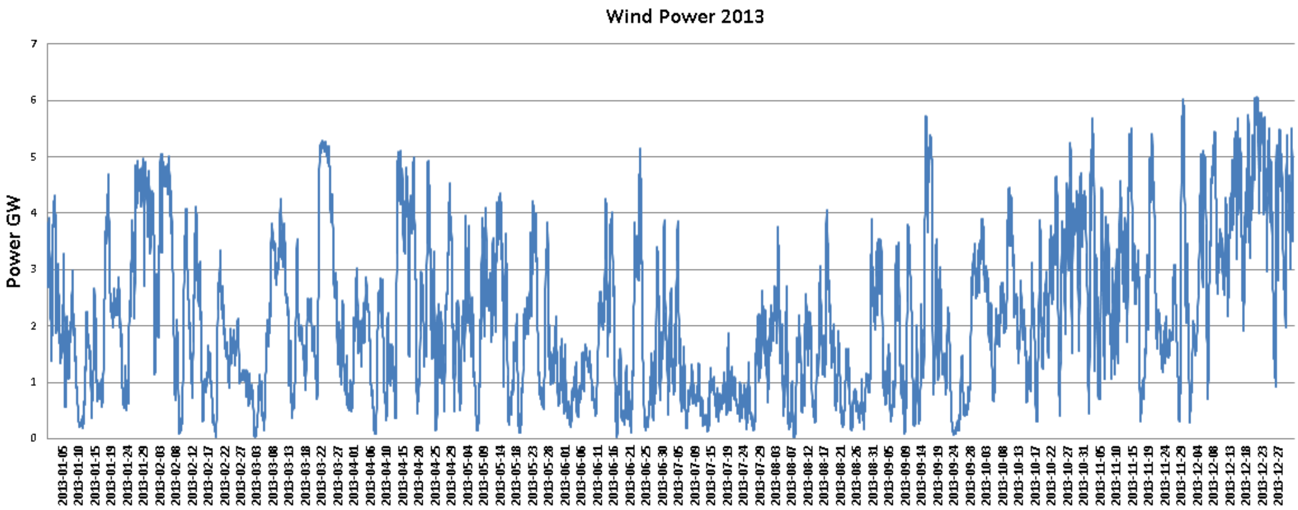
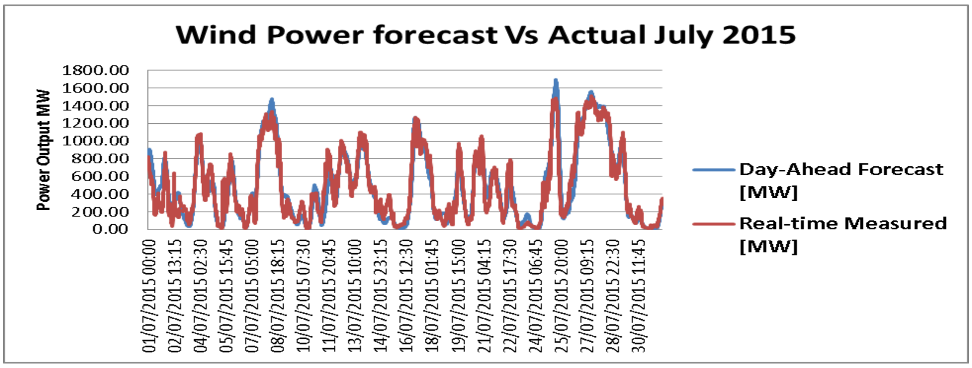


Figure 8 shows the total output of the UK's entire fleet of wind turbines for the year 2013. Note that even in the winter there are massive variations in output over days.

Wind Forecasting

Just because the wind is intermittent and largely random it does not mean that we do not have the ability to forecast the wind over very short timeframes. Figure 9 shows the day ahead forecast of a Belgian offshore wind farm for the month of July.

Figure 9 Forecast vs Actual Wind Power Output



Data Source: http://www.elia.be/en/grid-data/power-generation/wind-power

Note that although not completely accurate on a day to day basis, wind output was broadly able to be accurately forecast, this means other generating capacity can be brought on and offline in anticipation of falling and rising wind power.

Onshore and Offshore Capacity Factors

When discussing variability in the output of wind turbines it is also important to highlight the difference in capacity factors between turbines sited onshore and those offshore. The wind offshore tends to be stronger and so correspondingly power output is greater. Also the wind is less variable and so offshore farms can supply a steadier power output. (Markian M. W. Melnyk, 2009, p309)

In the UK, the average capacity factor for an onshore wind farm is around 26% while offshore is 34% (DEAC, 2015) This means that on average, a turbine sited offshore can expect to generate 1.3 times as much electricity as the same one sited onshore. In terms of grid stability this means it is better to build offshore than onshore, but economically it is much more expensive though prices will ineveitable fall as the technology matures.

2.2.2. Solar Power Output

The output of solar panels is affected by many different factors such as: latitude, angle and pitch of panels, efficiency, panel temperature, shading or obstructions and dirt on the panels. Some of these factors may be intrinsic to the location of the panels while others are in some way controllable (cleaning the panels for example.) The main factors in terms of grid stability we are concerned with is the local climatic conditions i.e. direct and diffuse radiation at any one time, and the factors that affect them such as length of day and cloud cover.

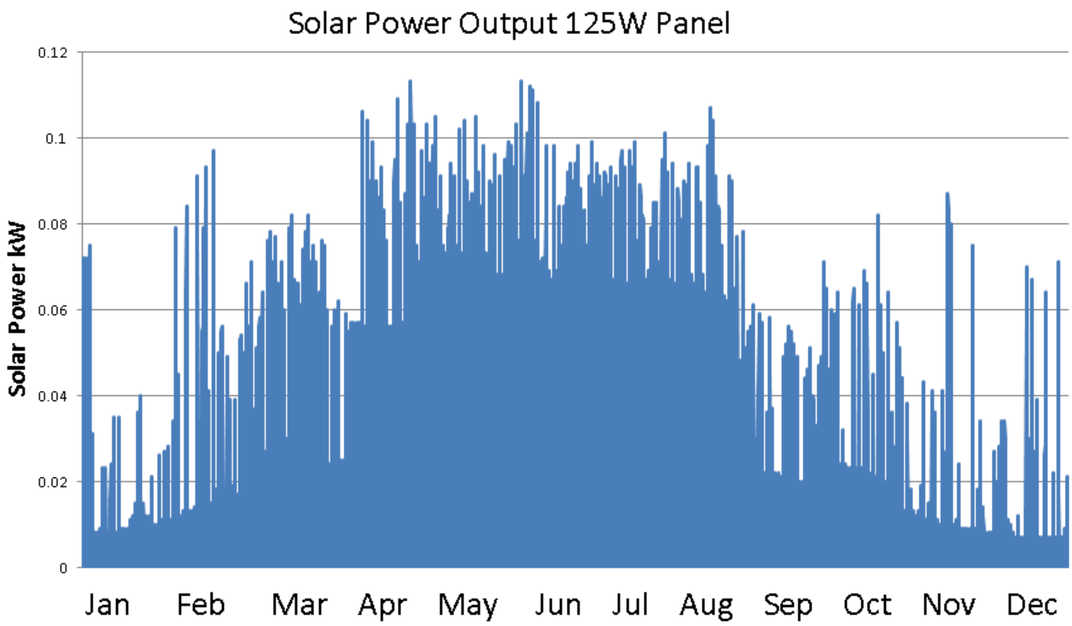
Unlike wind, solar power output can change very rapidly as when a panel is not receiving sunlight its output falls to practically nothing in very short timeframes. This means that when clouds move in they have an immediate and profound effect on solar output. The effect can again, like wind, be partially offset by having an installed capacity geographically spaced out.

Photo Voltaics benefit from being able to be located practically anywhere, from rooftops to vacant fields, with little in the way of the environmental concerns that can slow down, or stop, wind farms and thermal power plants being built. (IEA, 2003,p53)

Solar Intermittency

Just as with wind, the solar output of PV installations have high intermittency to deal with.

Figure 10 Annual Solar Output for Single 125W Panel



Data from merit Simulation

Figure 10 shows the output of a single south-facing 125W panel located in the south of England over a typical year. Note that there are broad trends throughout the year, with winter months having at times around one fifth the output in summer. Variance/intermittency is especially seen on the hourly scale, Figure 11 shows the output of a 250W panel in Cambridge over a day in August 2012

Figure 11 Daily Output from 250W Panel

(CambridgeSolar, 2015)

Again, broad trends can be seen, with solar output gradually rising to a peak at mid-day before falling again until sunset. However within the broad trend, there are numerous dips as cloud cover comes in and goes out.

The factors which affect solar output hour to hour are climatic and geographic in origin. Time of day and season are the largest reasons for the biggest differences locally, while more generally the location of the panels has an effect. For the UK generally speaking the farther south the greater solar output the panels will have (Figure 12)

Figure 12 Solar Resource Across the UK

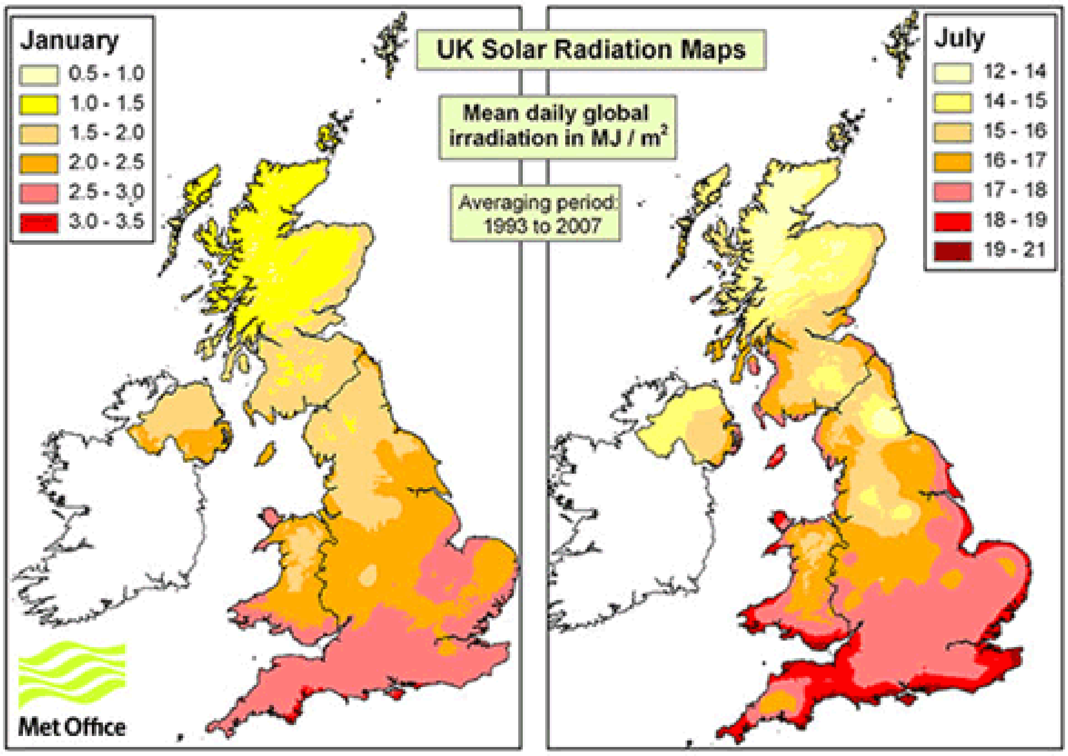


Image Courtesy of the Met Office

When contrasting Figures 8 and 10 we can see that solar power is less intermittent than wind and that trends throughout the year are generally predictable. The major problem with the intermittency of solar is that when the sun goes down there is no power. Also in the dark, cloudy winter months, effectively again solar output is approaching zero - this unfortunately coincides with when demand is at its peak, this will have consequences for grid stability.

Solar Power in the UK

As of August 2014, the UK has an installed solar capacity of 5GW with more than half of it located in the south of the UK where solar radiation is highest, and therefore variability is lowest (Figure 13).

Figure 13 UK Regional Population of Solar Panels

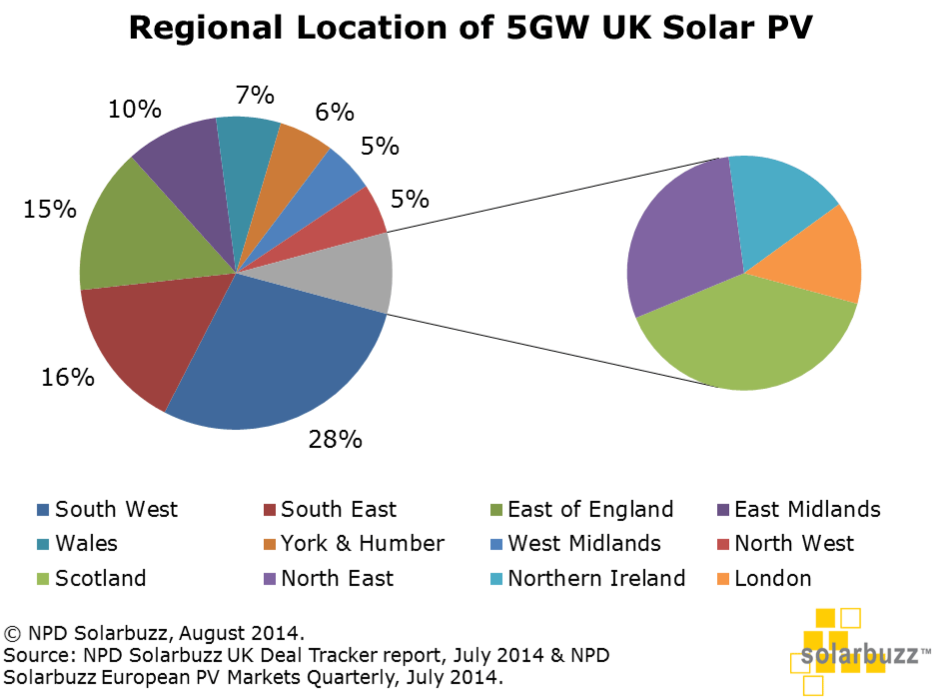


Image courtesy of Solarbuzz

Figure 14 shows where the installed capacity is located, with a third being on residential homes, and 45% located as ground mounted systems. The remainder is located on commercial rooftops. The geographically diverse nature of the installed capacity of Solar PV in the UK will be beneficial in terms of a smooth total power output as local climatic conditions will be offset by areas with different conditions owing to the distances involved.

Figure 14 Application Split of Solar PV

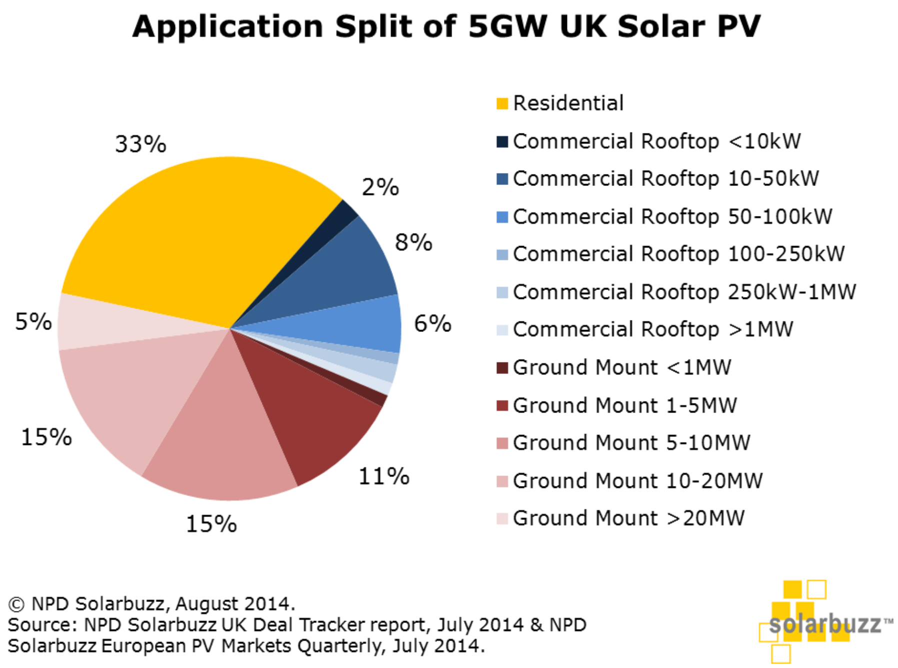


Image courtesy of Solarbuzz

2.2.3. <u>Hydro Output</u>

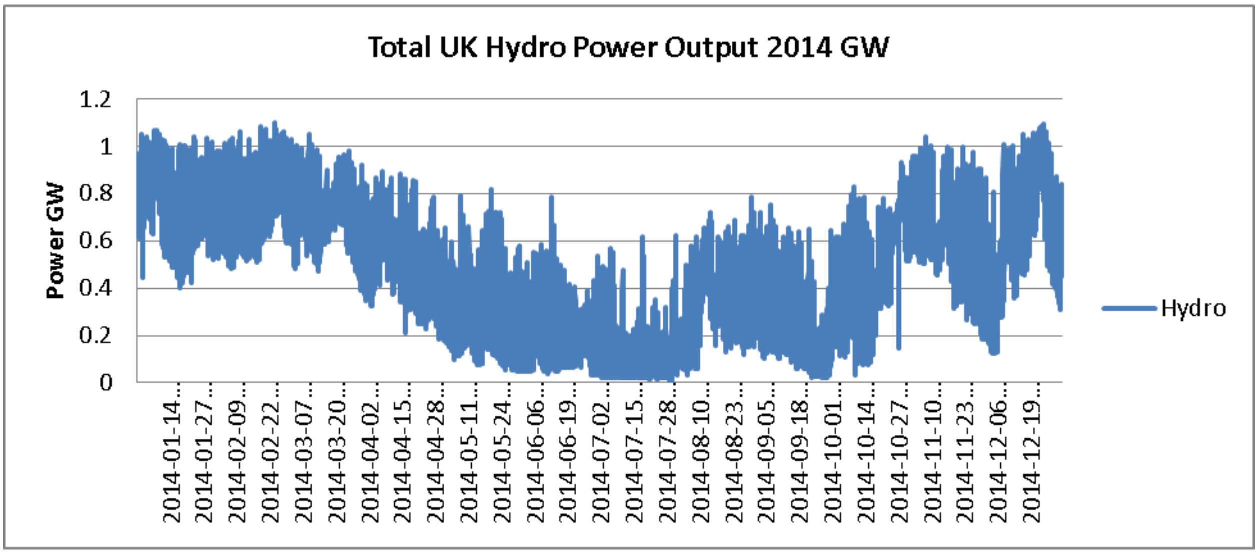
Hydro power was the first large scale power generator, and even today it is the largest source for renewable energy in the world. As opposed to pumped hydro storage, when we talk of hydropower we mean usually run of the river hydro or a dammed river with no ability to pump the water back up for storage. In terms of intermittency and variability, hydropower is, except for perhaps biomass, the most consistent of the renewables. It has a worldwide load factor of around 44% (Elliot, 2013, ch2 p1), although this can vary from site to site. The Three Gorges Dam in China has a load factor of 50%, while the Hoover Dam has one of 23%.

Hydropower output is, like wind and solar, related directly to climatic conditions, more specifically rainfall. Rainfall varies a lot less than wind, and seasonal changes are broadly forecastable although with climate change more severe weather fluctuations may lead to increased difficulty when trying to anticipate futre hydropower output. Also hydro sites with dams have the ability to control their output by storing water behind the dam, so power generation is more even.

Hydro in the UK

Hydro power in the UK is very small, as it only makes up around 1.5GW of installed capacity, with an average load factor in the region of 38%. It can fall as low as 22% in years with very low rainfall. (Elliot, 2013,Ch2 p2)

Figure 15 UK 2014 Hydropower Output



Source:Gridwatch

Figure 15 shows the output of the UK's conventional hydro plants for the year 2014. There are clear stable trends to the output throughout the year, with a steady value of around 1GW for the winter months, and a slowly falling output from spring to summer that bottoms out around 0.2GW before beginning to rise again in autumn.

Although there is some variability, in power production terms this is a fairly stable output.

2.2.4. Nuclear Power Variability

Nuclear power, though not a renewable source, is relatively carbon free and so a popular option amongst some policy-makers and scientists in that it goes alongside renewables as the best way to a carbon free power system. In terms of variability, nuclear power's problem is not that it is very variable, but that it is in fact not variable. To a large extent nuclear power has no ability to load follow; the output of reactors cannot modulate to suit demand as a nuclear reactor runs most efficiently and cheaply when it is run continuously and as close to its rated capacity as possible.

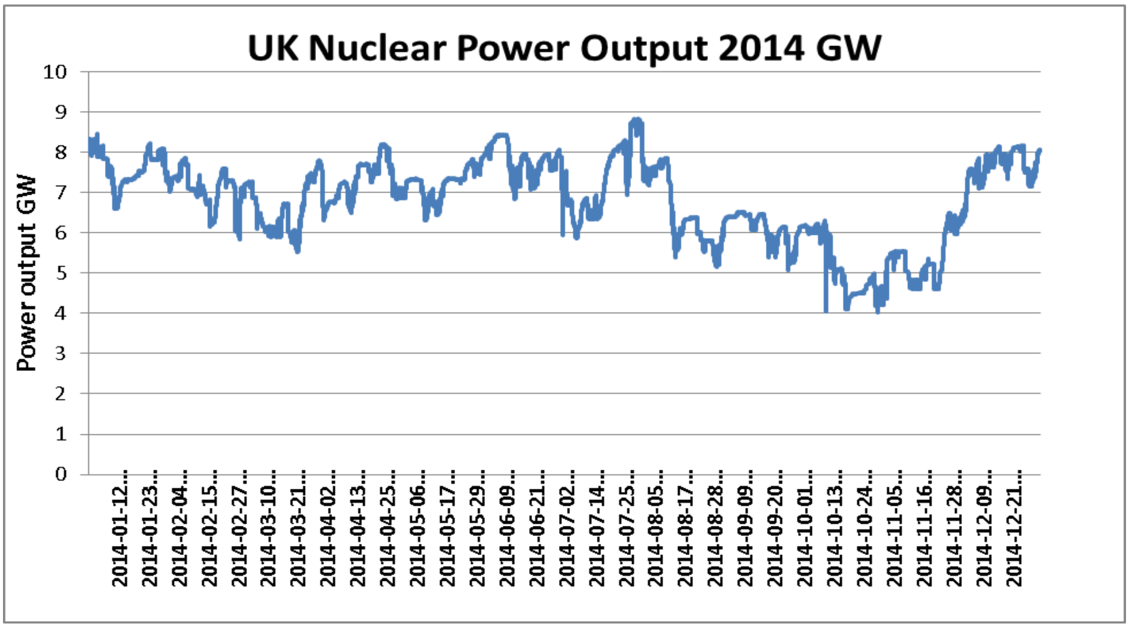
This means that nuclear is suitable to meet base load demands in the grid, but is unsuited to respond to sudden surges and dips seen throughout the day, or even to deal with the lower demand requirements at night. One way previously discussed to get around this is to use nuclear in conjunction with PHS so that nuclear energy produced during the night when there is no demand can be stored for times of peak demand. France gets around 90% of its electricity from nuclear power. It handles its load following by use of “grey" control rods which slow down reactions within the reactor without the need to clean the water after Boron control rods are used, though this does have a corresponding impact on overall efficiency and therefore cost (World Nuclear Association, 2015).

France also can deal with gluts of nuclear power by exporting to other countries such as Germany, Belgium, the UK, Italy, Switzerland, and Spain.

Nuclear Power in the UK

The UK has just under 9GW of installed nuclear capacity spread out over 16 plants. They contribute around 19% to the total electricity generated in the UK over a year (DUKES, 2012). For the reasons previously discussed, nuclear power plants in the UK are run continuously and as close to maximum capacity as possible. Figure 16 shows the output of the UK's fleet of nuclear power plants over 2014. For most of the year, the nuclear fleet will put out around 8GW of power, though there are variations in output as plants come offline for scheduled maintenance or because of malfunctions. This means that even though nuclear is generally seen as a reliable steady source of power, it still does need backup generating capacity to deal with these outages (World Nuclear Association, 2015). In fact, according to the UK's Department of Energy and Climate Change, the average nuclear load factor between 2007 and 2011 was 60% (DECC, 2012)

Figure 16 UK 2014 Nuclear Power Output



Source:Gridwatch

2.3. <u>Grid Stability with Renewables</u>

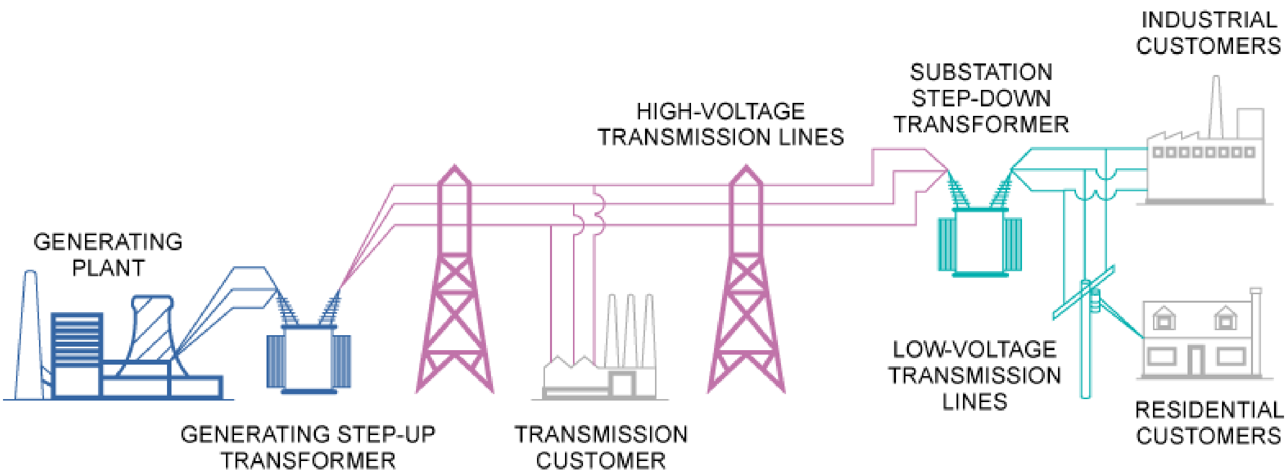
As we have seen in the previous sections, the carbon free generating capacity brings problems of variability and lack of ability to modulate output to suit demand in any great amount. As we move towards a carbon free generating mix in the UK, this variability and inflexibility will put an ever increasing strain on the national grid.

2.3.1. <u>An overview of the Grid</u>

In an electric grid, power is generated, transmitted, distributed and then consumed. Conventionally AC power is generated at a large station, where the voltage is kicked up to very high voltages for transmission to reduce electrical losses. The power is transmitted along transmission lines to substations, where the voltage is again kicked back down for distribution and then consumption.

For all electrical grids, the overall power output of the system at any one time must closely match the demand at that time. If there is not enough power being generated to meet demand, this leads to a “voltage dip” which means the frequency of the power being supplied dips for a short period of time. This can lead to what is known as a brownout - lights can dim and motors can slow down. This can be damaging for modern electronics that rely on a high quality power source to function correctly. On the other side, where generation exceeds demand, this can lead to a power surge, where frequency of the electricity goes above acceptable levels. This can lead to total blackouts if the surge is great enough to trip safety features, or even damage transmission equipment. If it is a minor surge, it can lead to an increase in voltage in all devices across the network, leading them to burnout or trip their fuse breakers.

Figure 17 Typical Grid Layout



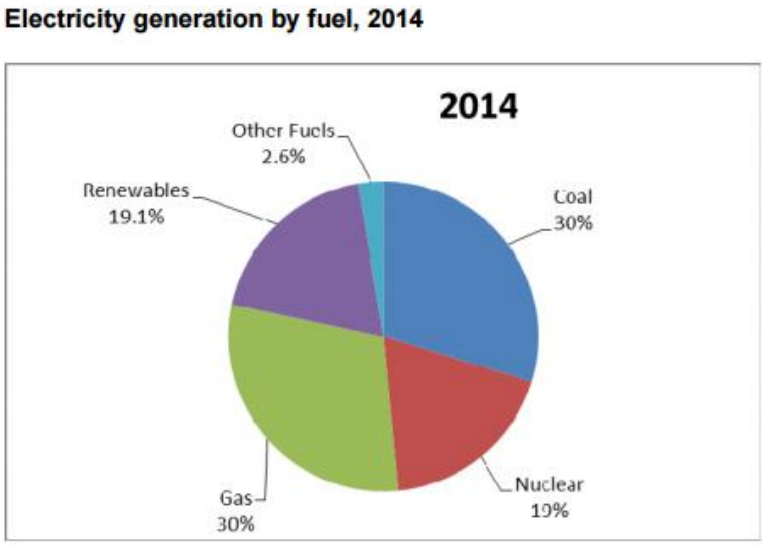
Source: http://www.democratandchronicle.com/

Figure 17 shows the typical configuration of a national grid with the generating, transmission and distribution equipment shown.

Fuel Use in the UK Grid Today

In the UK today, we have a mix of conventional fossil fuels making up the bulk of our generating capacity, but with an ever growing amount of renewables being added into the mix.

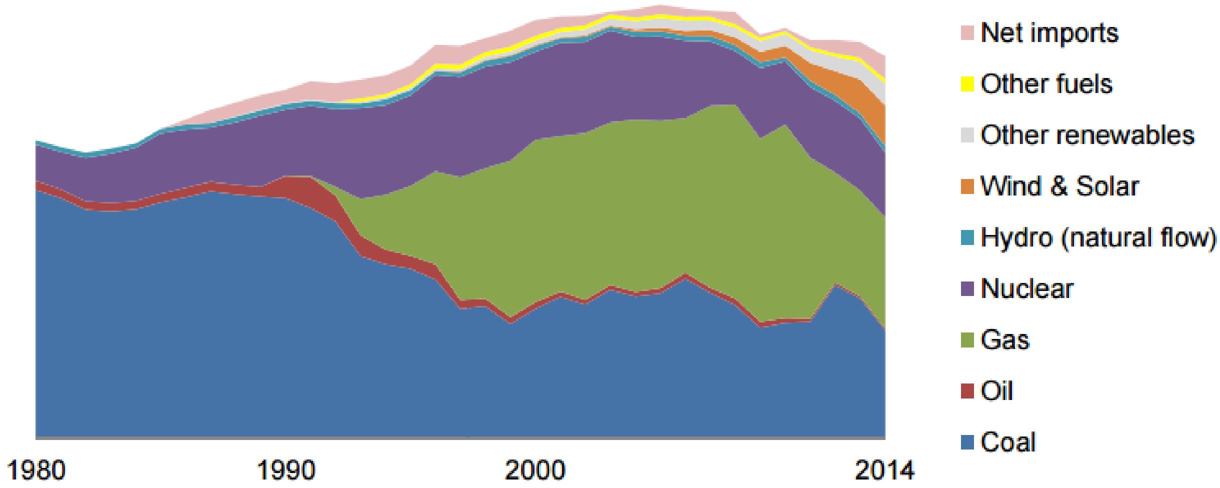
Figure 18 Electricity by Fuel Source 2014



Source: (Department of Energy and Climate Change, 2015)

Figure 18 shows the makeup of the UK's electrical output by fuel type. Nuclear and coal will provide base load, while the renewables will contribute whenever they are available. Gas will modulate to keep the supply-demand balance even.

Figure 19 Type of Electricity Generated 1980-2014

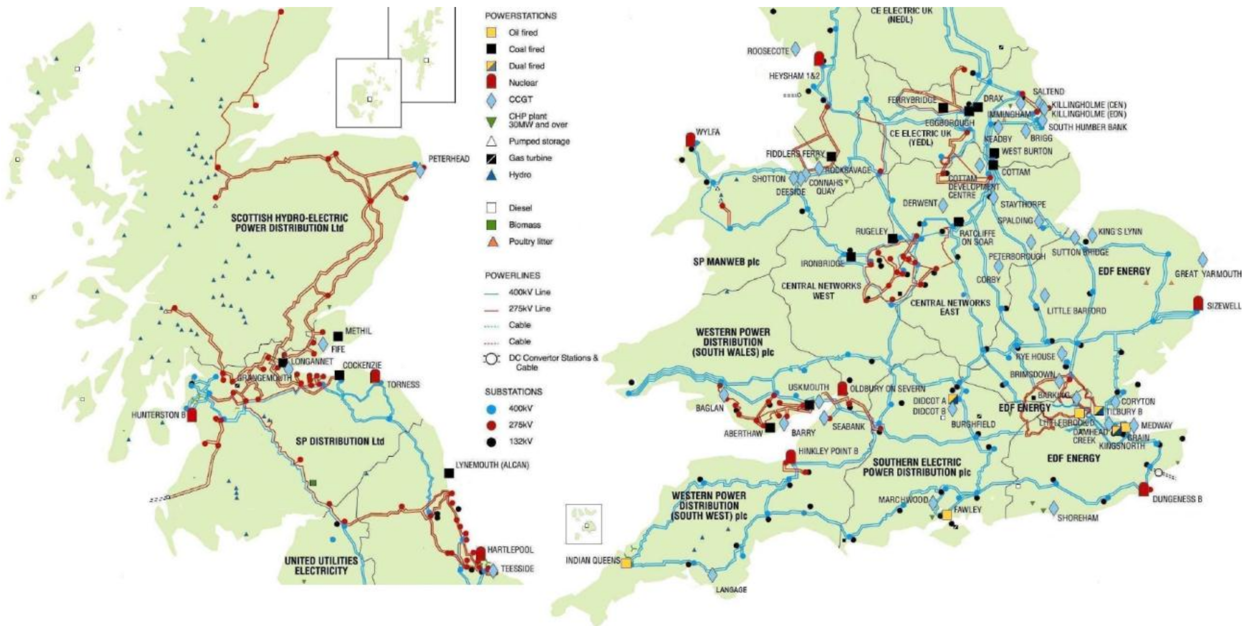


(Department of Energy and Climate Change, 2015)

Figure 19 shows the trend in the UK of decreasing oil and coal use, with increasing amounts of gas and renewables in the mix.

<u>Transmission Infrastructure in the UK today</u>

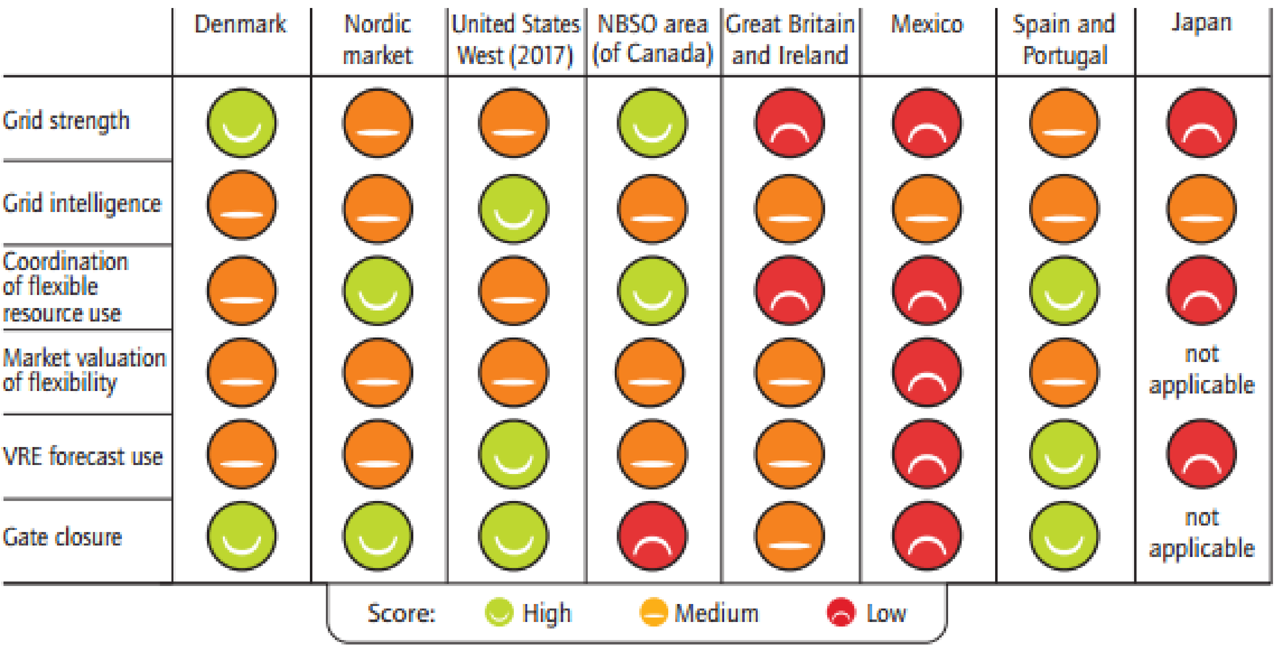
Figure 20 UK Electricity Transmission Network



Source: National Grid

The UK, when compared to most other Western countries has an aging grid network in need of modernisation; its ability to transmit large amounts of power is severely limited by the bottlenecks in the transmission networks. (IEA, 2011) Most of the UK's infrastructure was built in the '50s and '60s and so was not designed for a low carbon generation mix. OFGEM have suggested that the cost of improvement could be as much as £32 billion. (OFGEM, 2010) There are currently no 400kV lines that run from the places where the wind, wave and tidal resources are greatest (the north of Scotland) to the population centres where demand is greatest (the south of England). Figure 20 shows the status of the national grid as it stands today. Note the dearth of 400kV lines in Scotland, where wind and hydro resources will be greatest.

Figure 21 Comparison of Grid Strength in Various Countries



Source: (IEA, 2011,p78)

The diagram above shows an appraisal by the International Energy Association of various countries' grids' ability to handle variable renewable energies (VREs). The

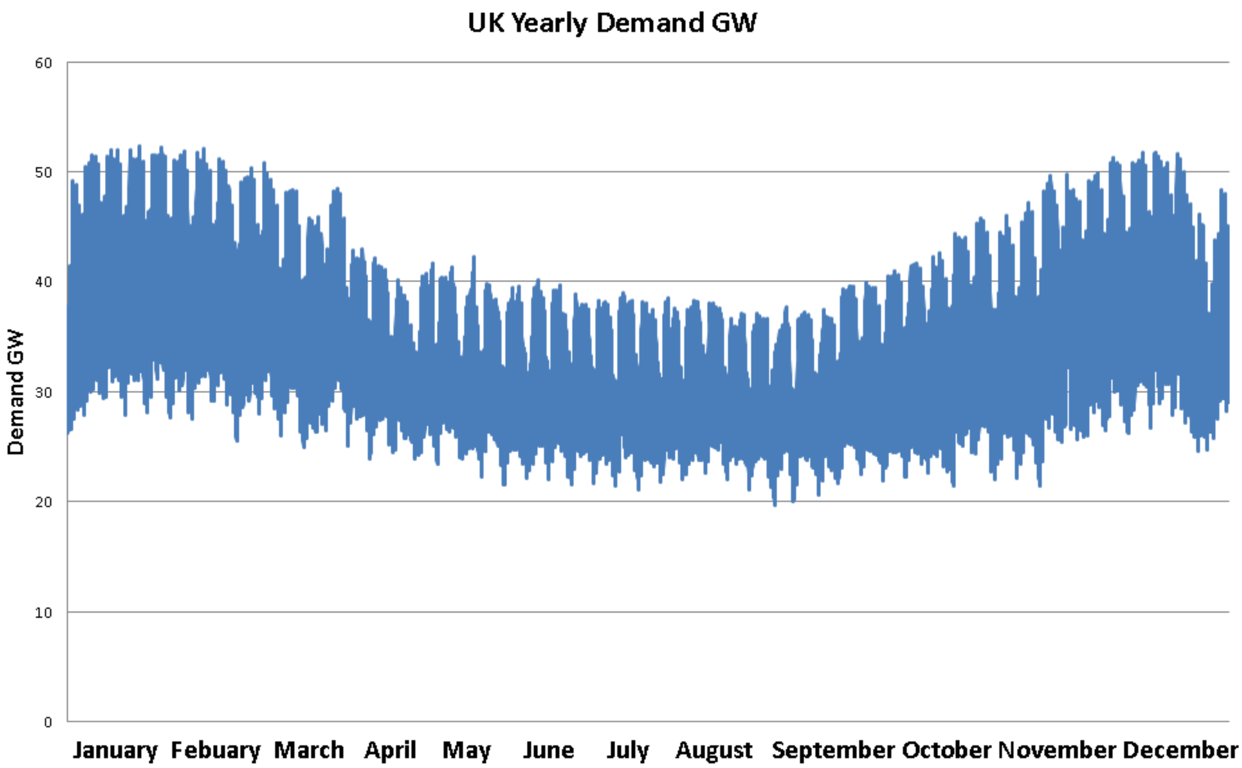
UK lags behind its northern European neighbours. If the UK wishes to greatly increase the amount of energy it receives from variable renewable sources, it will have to spend money on expanding and reinforcing its grid infrastructure. Luckily it has already began this process, with the 400kV Beauly-Denny line that runs from the north of Scotland to the central belt, where it can connect to other 400kv lines that lead to the population centres in England.

UK Demand Characteristics

The UK has a fairly typical demand profile, seasonally peaking in winter when demand for electric heating is greatest, and on a day to day basis having a small peak in the morning when people wake up and begin their day, followed by another peak in the evening when most people arrive home after work. For the most part this is broadly forecastable, though something as innocuous as a TV programme being more popular than anticipated can lead to sudden surges.

UK Typical Annual Profile

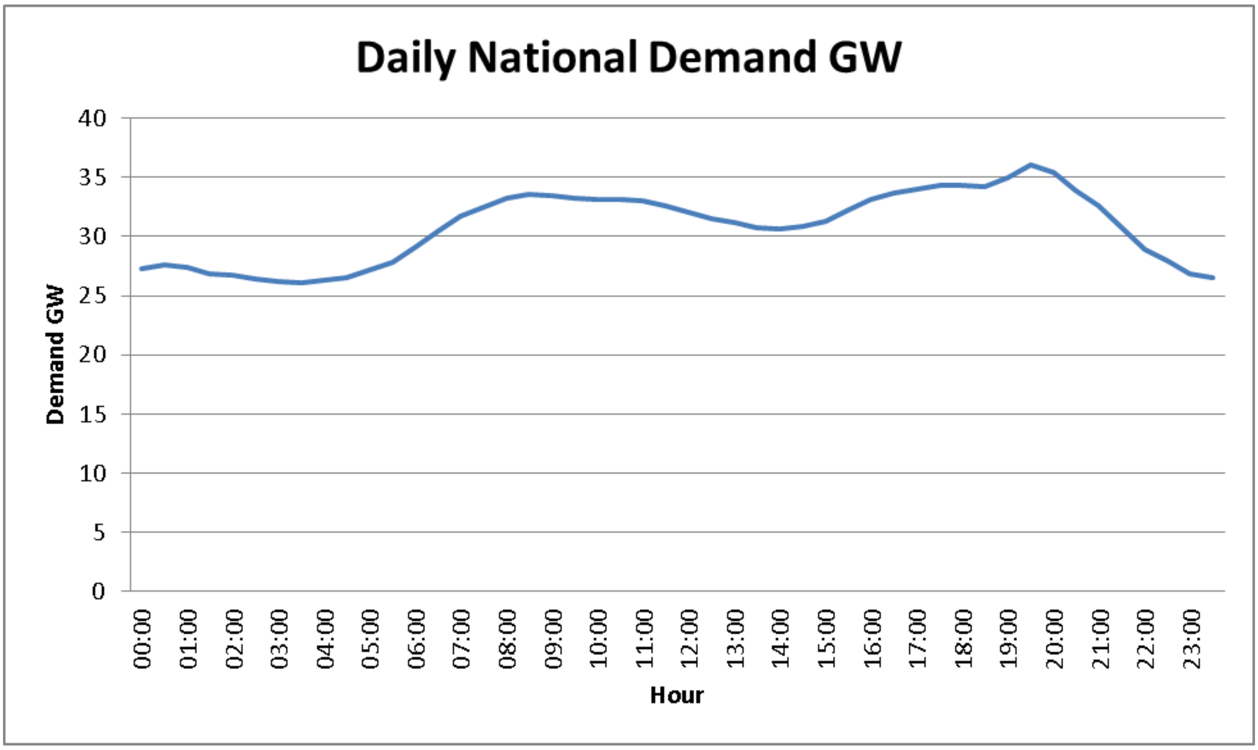
Figure 22 Typical UK Annual Demand Profile



Source:Gridwatch

The UK varies annually between a peak during winter evenings of around 53GW and a minimum during the summer nights of around 20GW.

Figure 23 Typical UK Daily Demand Profile



Source: Gridwatch

Figure 23 shows the typical fluctuations seen in the national grid over a day. This was for a day in April, so the lowest and highest demands are between those you would expect to see in winter and summer.

Grid Resilience Measures

There are a number of measures the national grid has in place to make sure the frequency of a grid is kept at a steady 50Hz (National grid deems a variance of ±0.5Hz to be within acceptable limits)

Pumped Storage

As discussed previously, PHS can be used to respond to sudden surges and drops in demand. It has an almost instantaneous response time, and also has the ability to store excess power that would otherwise have to be ‘spilled’.

Spinning Reserve

Spinning reserve is the process of having plant (usually CCGT) putting in power to the grid but at a certain fraction of its total possible output. This means that if there are sudden surges in demand, the spinning reserve can come up to full power in a short period of time to meet the demand. If the plant was simply switched off, it could take up to an hour before the plant was ready to input into the grid. Note that because the plants are only operating at part load, there are negative consequences in terms of efficiency leading to increased cost and higher carbon emissions per MWh produced than would be the case for plant operating at close to maximum.

Fast Start: Generation Units

This involves the start-up from cold of certain generating capacity, usually diesel generators owing to the relatively short time they need to start up before they are ready to input into the grid.

NG Frequency Service

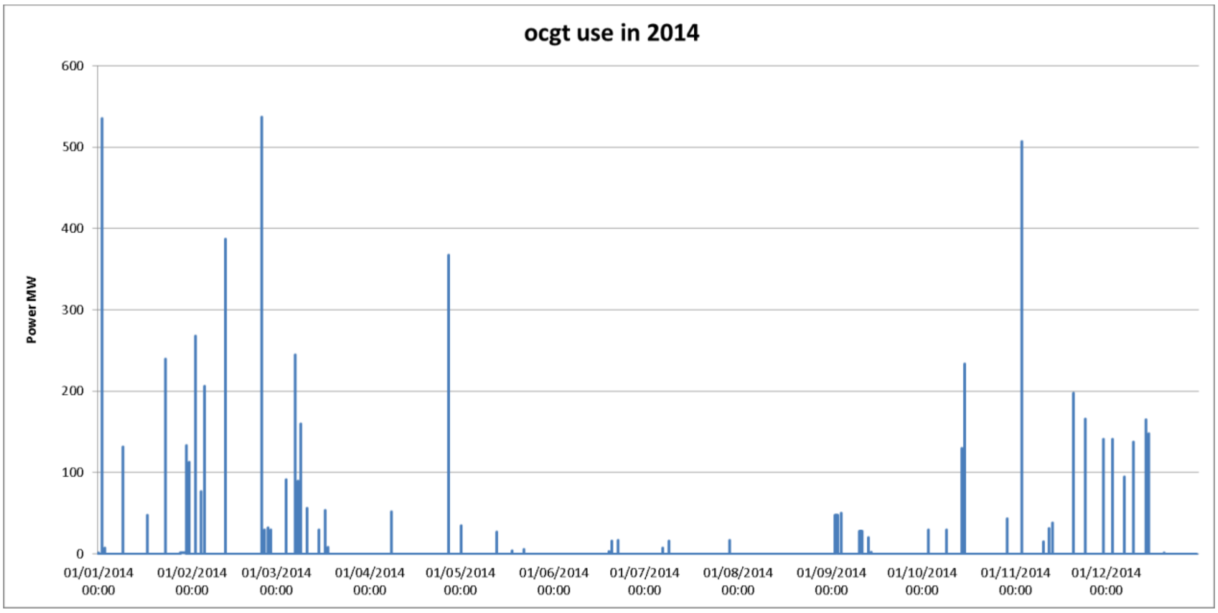
This is a system whereby in exceptional cases of demand, the national grid can ask certain large scale consumers of electricity, who have agreed to the service in exchange for financial reimbursement, to suddenly switch of their power supply. An example of this could be a steel mill or manufacturing plant.

Reserve Capacity

Reserve Capacity involves open cycle gas turbines (OCGT's) and oil generators that will sit unused for most of the year and only be switched on in times of extreme demand, usually only seen in especially cold winters.

The below graph in figure 24 shows the operation of OCGTS's during 2014, you can note that they are used sparingly throughout the year and mostly for short bursts in the winter.

Figure 24 OCGT use in 2014



2.3.2. The Challenge of Variable Renewables

In previous sections we have discussed how and why renewable sources are variable; we have also seen how the national grid must constantly balance the supply and demand sides of its network. As renewables play an ever increasing role in the way we generate our electricity this balancing act will become more and more difficult.

Fluctuating Supplies

As previously seen, generally sources of renewable power fluctuate in their output timescales as short as seconds or as long as months. This means that currently for the supply and demand sides of our grid to match, we must have enough flexible capacity that can modulate its output quickly to maintain this balance. Currently with the very small amounts of renewables in our generation mix, this has proved simple enough as the fluctuations on the demand side will vary much more than on supply side. (IEA, 2011, p31)

Going forward into an age of large penetrations of renewables in our generating capacity will mean the need for either more forms of energy storage, increased flexible and reserve capacity on the generating side, or increased demand management in the grid where we tailor our demand to suit supply rather than the opposite case we currently experience.

Power When You Do Not Need It

As you have no control over when renewables can produce energy (with the exception of some forms of hydro), economically speaking it is best to be able to make use of all the resource available. As more and more wind is installed in the UK there will come a time where large amounts of wind are generated at a time when no-one is demanding it. When this happens companies have no option but to “spill” the wind. This effectively means that some of the turbines are turned off so that they do not overload the grid. This can be seen as wasted energy, and from an economic view adds to the cost of renewable systems as they are not paid for electricity they could be generating.

Too Little Power When You Do Need It

The opposite of this is that, no matter how geographically diverse the renewables are, there will be times when output from them is effectively zero. For solar this happens in the long dark, cloudy, winter months when demand is highest. In the UK there will be days with no wind and even sometimes large anti-cyclones, where for anything up to a month no wind will blow over the entire country. In a system where renewables make upwards of a 40% contribution to the supply side of the grid, this could lead to major blackouts and all the social and economic turmoil they bring.

Unpredictability

Obviously there is already some amount of inherent unpredictability in our national grid. Power plants can malfunction and come offline at any time, damage to transmission equipment can occur, and some surges in demand can be unpredictable. However, with the inclusion of renewables in the mix, it makes it much harder to operate the grid. Instead of having to deal with sudden surges and falls in demand and the occasional equipment malfunction, you have to deal with a constantly changing supply. We have seen how renewable output can be forecast, but even very small changes in output must be taken into consideration to avoid dips and rises in frequency.

2.4. Storage with Large Renewable Penetrations

Storage can function in two useful ways when dealing with the problems renewables can bring to the grid. The first is in load balancing, as we have seen with PHS storage which can act as both a load and a supply. This is very good for grid stability as it is no longer reliant on backup capacity that takes time to come on and off. With PHS it is a matter of seconds before it can draw from the grid or supply to it. Storage allows the peaks and troughs seen in demand to be smoothed out; this creates a more flexible responsive grid.

The second role is in storing energy. The less wind you have to spill or solar panels you have to disconnect, the more efficient the system is. Storage increases the efficiency of renewables by taking power from the supply side at times of increased output and storing it for use at times of great need. This means no wind or solar resource is wasted, while also reducing the need for additional capacity of renewables at times of peak demand.

3. Modelling of Grid

To investigate the amount of PHS that would be required for various penetrations of renewables and nuclear in the generation mix, a model was built. The model would allow a user to input various factorial increases in the current installed capacity of various generator types - 3x current wind capacity, 2x nuclear etc. The result would then show you how much storage would be required such that supply always met demand. In the case where storage runs dry, the model would then show how much backup CCGT would be required to make up for the renewable and storage shortfall.

3.1. Demand and Renewable Data Source

The source of the data most of the supply and demand was modelled on was from the balancing mechanism reports the national grid releases (http://www.bmreports.com/)

they provide real time data from the national grid in five minute increments; the data is archived and was available for the years 2010-2015. The actual data the model utilised was downloaded from the Gridwatch website, a site that takes the BM reports from national grid and displays live the demand and supply makeup of the national grid. It also collates all the data from previous years into excel form.

The datasets included information on

- demand
- grid frequency
- coal generation
- nuclear generation
- CCGT generation
- wind generation
- pumped hydro generation
- conventional hydro generation
- biomass generation
- oil generation
- OCGT generation
- French imports/exports
- Dutch imports/exports
- Irish imports/exports

To simulate different capacity increases in nuclear and the various renewables, the output for each type of technology over the year was multiplied by a chosen factor. For instance, if on a specific date and time the output from wind turbines was 3GW and the model wanted to see what a capacity increase of 3x would look like, it would simply multiply the figure by three. There are assumptions and consequently drawbacks to this method that will be discussed in the weaknesses section.

The pumped hydro was looked at by allowing a pre-selected maximum storage level in GWh. Any excess power above demand was then put into the pumped hydro column until it reached this maximum figure allowed, and when the maximum is reached the model then dumps the remaining excess energy into the curtailed renewables column. Conversely, when the PHS column reached zero and supply from generating capacity and storage failed to meet demand the model would take this energy deficit and use it as the amount of energy that the gas turbines would have to supply. A round trip efficiency of 80% for the PHS was implemented as this is a common efficiency, to avoid putting additional energy into the system that wouldn't have been necessarily otherwise generated it was assumed the energy store would start the year empty.

This overall allowed the model to simulate what effect larger capacities in renewables and pumped hydro storage size would have on fossil fuel use.

3.2. Solar Modelling

Solar power is one of the fastest growing renewable technologies in the world. The price of solar has come down by the most amount in the shortest time of any renewable in history. In five years alone, the UK solar capacity went from effectively zero to 5GW. As solar performs best in summer, many see it as a complementary technology in the UK to wind which maximises output in the winter months.

Unfortunately the BM reports do not provide data on solar generation, but merely showed up any solar input into the grid as a fall in demand. Nevertheless it was felt that to omit solar power from the model would hamper its ability to forecast the future generation scenarios in the UK.

To simulate solar input into the grid, a series of Merit simulations were run using various locations in the UK. The simulation was run for a 2kW south facing system in each region of the UK. The results were then factored up so that they represented 5,000,000 homes or 10GW of installed capacity. The results from the different regions were then weighed to the percentage of panels installed that each region currently possessed and subsequently combined. This would best reflect the geographical distribution of solar panels any increase in capacity would entail. The total output for all regions was then inputted into the model. The end result is that 1x factor input into the model will equate to 10GW of installed capacity installed across the UK but with most panels centred on the south.

3.3. The 2014 Base Case

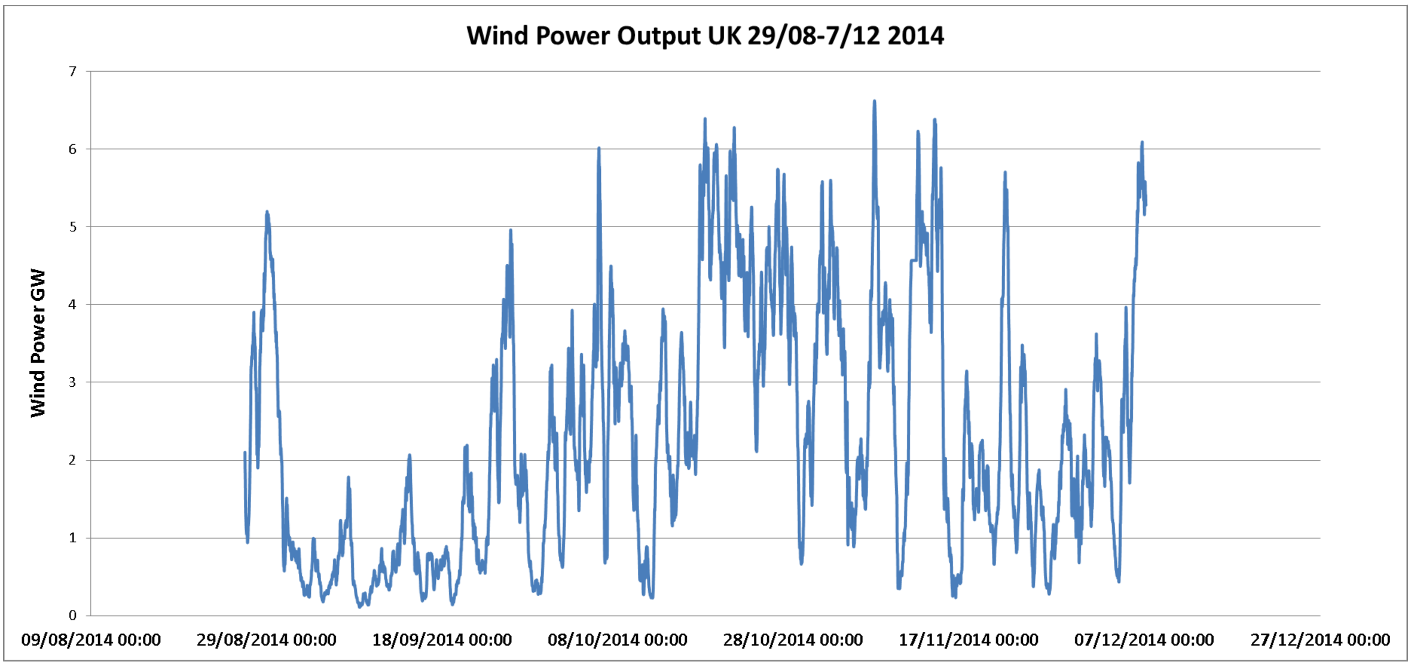
Except for the solar data which for reasons previously mentioned had to be simulated, and the CCGT data which works purely in response to the balance between supply, demand and storage, all other data was based on the actual operating conditions of the grid during the year 2014.

3.3.1. Wind

By the end of 2014 the installed capacity of wind turbines in the UK was 12.44GW. This was a 13% rise in installed capacity on the previous year and was composed of roughly 60% onshore and 40% offshore. (EWEA, n.d.)

The actual wind resource in the UK suffered from two long lasting high pressure systems. One at the end of August which lasted well into September, and as such, as Figure 25 shows, wind power at this time struggled to get above the 2GW mark. This happened again in December, where for the first week in December again wind power was substantially lower than what could be normally expected at that time of year (MetOffice, 2014). Although all simulations will show this massive drop in wind power, it is not seen as a weakness in the model as high pressure systems are not uncommon in winter in the UK and by having two in in relatively quick succession allows the model in terms of wind power to be based on a 'worst case' scenario.

Figure 25 Wind Power Output Winter 2014



Still overall electricity supplied from wind was up 20% on the previous year which allowing even for the increase in capacity was still better than 2013. (BusinessGreen, 2015)

3.3.2. Nuclear

During 2014, the UK had an installed capacity of 9.3GW of nuclear power, this consisted of 16 plants at 8 separate sites. Figure 16 showed the output of nuclear power during 2014, there is a steady drop in nuclear power seen between August and October which is explained by the fact that during this time, four reactors at Heysham and Hartlepool had to be brought offline for eight weeks due to a fault being found in a boiler unit (BBC, 2014). This again is not an uncommon thing to happen, and in fact for 2013 similar drops in nuclear output were recorded at different points during that year. Therefore it was felt these drops added a robustness to any model the data was built upon, as any new nuclear capacity will be subject to a similar amount of downtime due to fault or maintenance and so to remove or partially offset the drops in output would in fact detract from and scenario created by the model

3.3.3. Coal

Coal accounted for 101TWh of energy production in the UK, around 30% of the total electricity generated that year. (DUKES, 2015,CH5) Installed capacity was around the 20GW mark, though this decreased over the year as some stations were decomissioned or converted to biomass. In terms of variability coal had a fairly steady output of 16GW in the winter months and getting as low as 5GW in summer, this is due to the fact that although coal power stations cannot load follow in the short term, they can be brought offline for seasonal changes in demand.

3.3.4. Conventional Hydro

The UK in 2014 had 1.65GW of installed hydropower. For the start of the year, hydro power put out a fairly consistent 1GW, beginning to fall in the spring months to a summer output of 0.4GW before rising again to 1GW for the winter months. In 2014, hydro generated a record 6TWh of electricty, rising 25% on the previous year (DUKES, 2015, ch6). This was an especially strong year for UK hydro power as the year was exceptionally wet and would not be seen as typical year for the UK (Guardian, 2014).

Given the small amount of installed capacity hydro power represents to the total generating capacity of the UK, it was deemed this would not harm the model.

3.3.5. Biomass

Electricity generated from biomass rose from a 2013 value of 4,176 GWh, to 13,105 GWh. This represented a 300% increase, mostly due to a unit at DRAX coal fired power station being converted to biomass. Output was a fairly consistent 1.1GW, although there were four instances where output dropped to 0.8GW when stations came offline for maintenance. (DUKES, 2015,ch6)

3.3.6. CCGT

As of 2014, the UK has around 32GW of CCGT capacity (DUKES, 2015, Ch 5.6), although the maximium output of CCGT's was around 24GW. In total for 2014, CCGT's supplied around 86TWh of electricity to the UK grid, or around a quarter of total power generated.

3.3.7. Other Supply Options

Some supply options in 2014 were left out of the model. All exports were left out as it would be difficult to anticipate another country's ability to supply or receive power. OCGT and oil burners were left out as they are only used in emergencies, and so with different capacities installed and different storage levels, their 2014 operating times would bear no resemblance to any future scenarios.

3.3.8. Demand in 2014

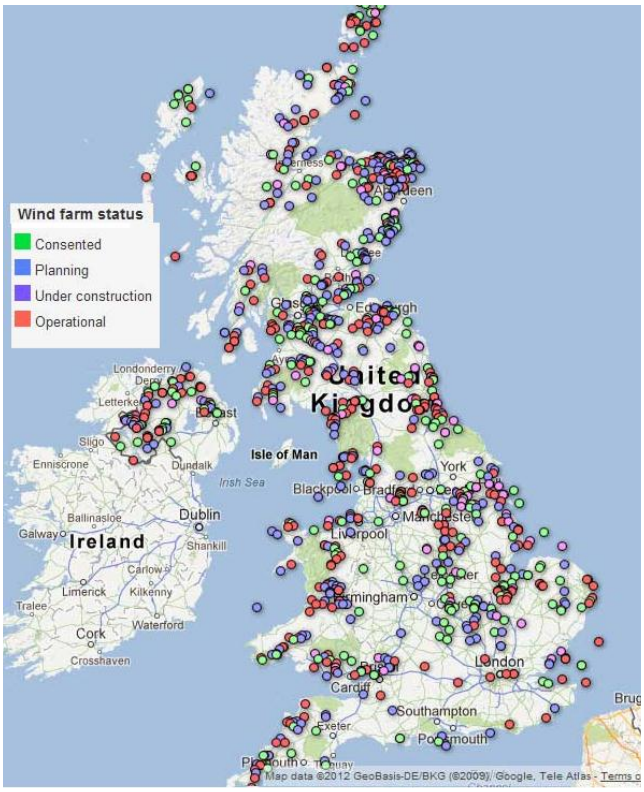
Consumption of electricity was down 5.6% on 2013 with a total generation of 339TWh. This fall is fairly consistent with current trends. This creates a problem with the model, as it bases future demand on the 2014 case. It is possible to change demand by factors as was done with generating capacity, but as it is difficult to extrapolate whether fall in demand would be uniform over a whole year or affect certain seasons more than others it was decided to keep demand identical to 2014.

3.4. Weaknesses

In the solar data there are obvious flaws in the way it was created. It would not take into account the 'smoothing' effect which having geographically diverse panels in each region would have on output. Also, different test reference years had to be used for each location as there was no single test reference year for the UK as a whole. It was felt though as 'test reference years' were picked to be what was seen as the typical climate of each location in any given year, then combining them would not detract from the strength of the model when compared to leaving solar out.

The wind data will not be totally representative of what the various increases in capacity investigated would actually look like. In 2014, the UK had an installed wind capacity of 12,440MW. The majority of this is onshore wind, and as of 2014 around 5,000MW of the total is offshore. As the model simulates increased capacity based on 2014 data, then it will model for a continued 60% onshore 40% offshore split. From recent government actions and planned offshore expansion, it looks likely this ratio will swap. Unfortunately the model will not be able to simulate for the increased capacity factor that offshore farms will have.

Figure 26 Geographical Distribution of Existing and planned UK Wind Farms



Source: Map Template by Derek Eder, Data by RenewableUK

Also with any increase in onshore wind capacity, the model will replicate the geographical distribution of current farms. This may not be a large weakness because as Figure 26 shows, all currently planned and under construction onshore wind farms follow this pattern.

3.5. Scenarios Investigated

The model allows input of any scenario of installed renewable, nuclear and storage capacity and will show the resultant amount of curtailed renewables and the amount of backup CCGT needed in both terms of maximum capacity and energy out over the year in GWh.

A set of scenarios have been devised to show the impact of carbon free technology on the grid, and also the role of storage in helping to reduce curtailment of renewables and reduce the need for CCGT to provide load following in the grid.

Scenarios 1-4

Figure 27 Scenarios 1-4 Factor increases in Capacity

Scenario 1		Wind	Nuclear	Solar	Hydro	Biomass	Coal
	Factor increase to 2014's capacity:	3	1	0	1	1	0
Scenario 2		**Wind**	**Nuclear**	**Solar**	**Hydro**	**Biomass**	**Coal**
	Factor increase to 2014's capacity:	6	1	0	1	1	0
Scenario 3		**Wind**	**Nuclear**	**Solar**	**Hydro**	**Biomass**	**Coal**
	Factor increase to 2014's capacity:	9	1	0	1	1	0
Scenario 4		**Wind**	**Nuclear**	**Solar**	**Hydro**	**Biomass**	**Coal**
	Factor increase to 2014's capacity:	12	1	0	1	1	0

The first four set of scenarios were intended to investigate the value of storage for various capacities of wind. Scenario 1 had 3x the 2014 installed capacity, with each subsequent scenario increasing the installed wind capacity by 3x the 2014 value. At 12x the 2014 capacity it would be the equivalent of almost 145GW of wind. This would entail installing turbines in around a third of shallow waters and a third of 25m-50m waters around the UK. (MacKay, 2008, p60-62) This increase is unlikely to happen for obvious reasons, but it is helpful to analyse extreme examples for a more complete picture of storage's role in balancing renewables. The grid was kept identical to 2014, except that coal production was put to zero to allow a better look at how renewables could offset fossil fuel use.

Scenarios 5-8

Figure 28 Scenarios 5-8 Factor increases in Capacity

		Wind	Nuclear	Solar	Hydro	Biomass	Coal
Scenario 5	Factor increase to 2014's capacity:	1	0	3	1	1	0
Scenario 6	Factor increase to 2014's capacity:	1	0	6	1	1	0
Scenario 7	Factor increase to 2014's capacity:	1	0	9	1	1	0
Scenario 8	Factor increase to 2014's capacity:	1	0	12	1	1	0

These scenarios were identical to the first four, but it was solar capacity instead of wind that was increased. It should be noted that as the solar data is based on MERIT simulations and not on actual solar data from 2014 so 1x entered into the scenario simulator does not equate to 1x the 2014 installed capacity of solar. In fact between Q3 2013 and Q3 2014, solar installed capacity increased by around 67% (SolarBuzz, 2014). This rapid increase would have made it difficult to model had the data been available from the national grid as information on what the capacity was at any time of the year was unable to be obtained. Instead the 1x factor equates to 10GW of installed solar spread across the UK, but centred on the areas where most solar is currently installed. This is the equivalent of around 2.8 million homes having the UK average sized system of 3.5kW.

Scenario 9

Figure 29 Scenario 9 Factor increases in Capacity

Scenario 9		Wind	Nuclear	Solar	Hydro	Biomass	Coal
	Factor increase to 2014's capacity:	6	1	6	1	1	0

Scenario 9 was designed to see what role storage would play if the grid had a mix of both wind and solar, given the rapid fall in the price of solar seen in the last few years and the commitment to continued offshore wind indicated by the current government. This scenario was deemed to be more likely to represent what the grid will look like in the future when compared to the previous scenarios which concentrated on the increase in capacity of one renewable only.

Scenario 10

Figure 30 Scenario 10 Factor increases in Capacity

Scenario 10		Wind	Nuclear	Solar	Hydro	Biomass	Coal
	Factor increase to 2014's capacity:	4	2.17	3	1	1	0

This scenario was designed to replicate the fact that the UK plans create around 19GW of new nuclear to replace old plants. As Sizewell-b is not expected to be decommissioned until 2035, this would equate to an installed capacity 2.17 times that of 2014.

Scenario 10 had reasonably realistic increases to wind and solar. The wind value represents about what would be installed if all rounds of offshore wind are completed, and an additional 4GW of onshore put in place as well. The solar value was the equivalent of eight and a half million homes having the UK average solar setup of 3.5kW installed.

Scenario11

Figure 31 Scenario 11 Factor increases in Capacity

Scenario 11		Wind	Nuclear	Solar	Hydro	Biomass	Coal
	Factor increase to 2014's capacity:	3.3	1	3	1	3	0.8

This scenario was designed to replicate what the grid could look like in the next 10 years. The 3.3x wind capacity equates to the installed wind capacity once all rounds of offshore have been constructed, and assuming approximately one third of the planned 2500 onshore turbines in the planning stage get built. Coal use has decreased by one fifth which equates roughly to 4GW. This 4GW has been replaced with biomass as 3 times the current capacity will be just over 4GW. The solar as in scenario 9 equates to 8.5 million homes. This may seem a lot, but the price of solar has been steadily dropping and installation of panels has been rapidly increasing.

Scenario12

Figure 32 Scenario 12 Factor increases in Capacity

Scenario 12		Wind	Nuclear	Solar	Hydro	Biomass	Coal
	Factor increase to 2014's capacity:	10	0	5.25	2.722	5	0

The purpose of Scenario 12 was to look at what a grid completely free of coal and nuclear base load would look like, and what role storage would play in it. All renewables have been increased by the amount that would be theoretically possible, but certainly not likely to be installed. Hydro has increased to 2.72x its current capacity as some studies say there is an additional 2.841GW of unexploited hydropower in the UK, mostly in Scotland (DECC, 2008).

Biomass has increased fivefold to around 6GW of installed capacity, though it remains to be seen whether the amount of solid or gaseous fuel required for such a system could be obtained sustainably.

Scenarios 13-15

Figure 33 Scenarios 13-15 Factor Increases in Capacity

Scenario 13		Wind	Nuclear	Solar	Hydro	Biomass	Coal
	Factor increase to 2014's capacity:	1	4.7	0	1	0	0
Scenario 14		Wind	Nuclear	Solar	Hydro	Biomass	Coal
	Factor increase to 2014's capacity:	5.2	2.17	2	2.722	5	0
Scenario 15		Wind	Nuclear	Solar	Hydro	Biomass	Coal
	Factor increase to 2014's capacity:	9.6	0	6.5	2.722	5	0

These scenarios were to show how much storage would be required to entirely manage without CCGT's load following abilities. They were not attempts to replicate any foreseeable scenario in the future, but to show how much storage is required to replace gas turbines' load following capabilities. The various scenarios involved:

- Scenario 13: Storage requirements if all generating capacity except already existing wind and hydro were replaced by nuclear.
- Scenario 14: Storage requirements if all fossil fuels were replaced by a nuclear/renewable mix.
- Scenario 15: Storage requirements if all generating capacity was renewable and there was no need for backup CCGT.

4. Results

4.1. Scenarios 1-4

Table 2 Scenario 1 Results

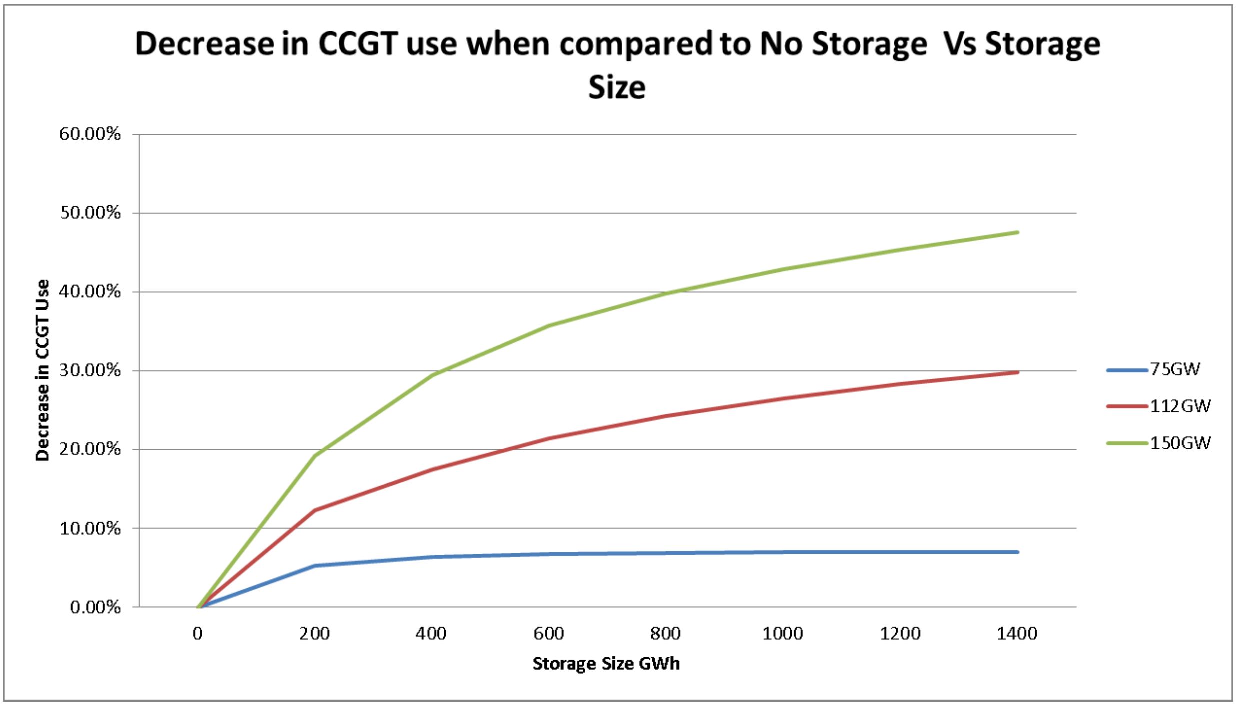
Scenario 1		Wind	Nuclear	Solar	Hydro	Biomass	Coal	
	Factor increase to 2014's capacity:	3	1	0	1	1	0	
37GW								
Storage Amount GWh	0	200	400	600	800	1000	1200	1400
CCGT Max Capacity Needed GW	41	41	41	41	41	41	41	41
CCGT Output over year GWh	166287	166287	166287	166287	166287	166287	166287	166287
Percentatage decrease in CCGT use from no storage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
CCGT Operation Reduction from 2014	-92.71%	-92.71%	-92.71%	-92.71%	-92.71%	-92.71%	-92.71%	-92.71%
Percentage Renewables Spilled	0%	0%	0%	0%	0%	0%	0%	0%
Total CO2 Saving compared to 2014 Emmisions (MtCO2e)	62.19	62.19	62.19	62.19	62.19	62.19	62.19	62.19
% of energy supply from renewables	25%	25%	25%	25%	25%	25%	25%	25%

For scenario 1, the level of storage made no difference to the amount of spilled renewables or consequently reliance on CCGT. The wind resource was not enough on any day to do more than partially offset CCGT use, so this meant there was no excess energy to store. The 3x capacity is just less than what can be expected once all rounds of planned offshore wind farms have been completed. Without coal, reliance on CCGT has almost doubled, but due to the extra wind and gas turbines' lower carbon emissions, the grid has actually cut around 60 million tonnes of carbon dioxide. As previously stated, there is only around 25GW of CCGT available currently, so this scenario is unlikely to happen unless the price of gas continues to fall. With this level of capacity only one quarter of the energy supply is from renewables, so storage will not be much of an issue. This is why it is useful to simulate higher penetrations of wind.

The levels of wind penetraion in Scenarios 2-4 did have enough renewable energy to merit storage. Figure 34 shows the extent to which storage affected the amount of work CCGT's had to perform to balance the grid.

Note that the decrease in CCGT use is compared to if there was no storage in the system not the decrease in CCGT use compared to 2014's CCGT output.

Figure 34 Decrease in CCGT Use When Compared to having No Storage



Note that the more wind capacity you have in the system, the more effective storage is at reducing reliance on gas turbines, and also the more useful storage remains at larger levels of energy storage. For all scenarios, eventually the value of storage becomes one of diminishing returns. The reason for this is that a small amount of storage will be utilised often, as there will be many times over a year when windpower output necessitates storage of 100GWh for brief periods of time. However, incidences where the wind power necessitates 1200GWh of storage may only happen two or three times in a year.

Figure 35 250GWh PHS System Use Throughout Year

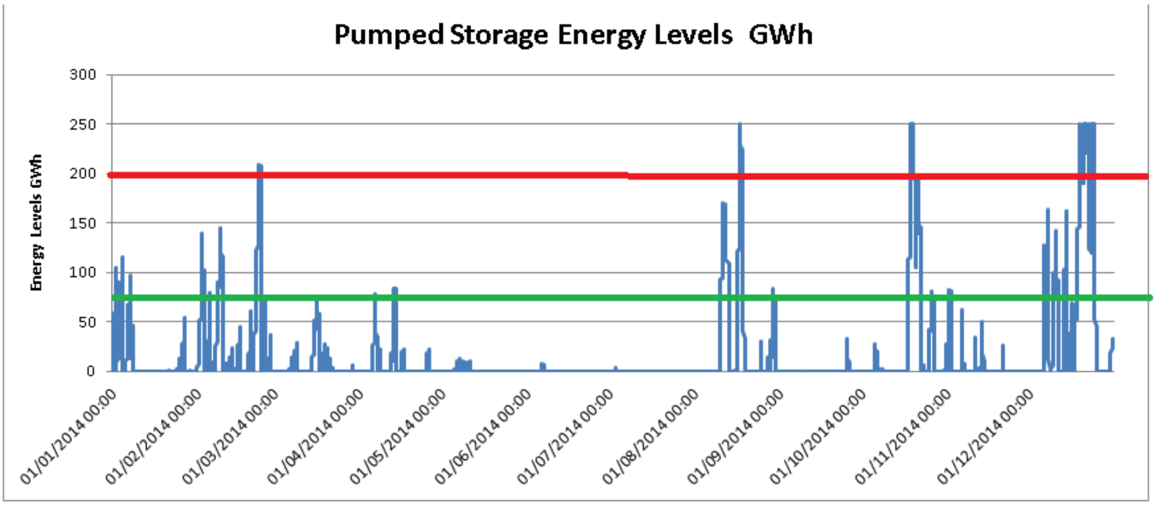
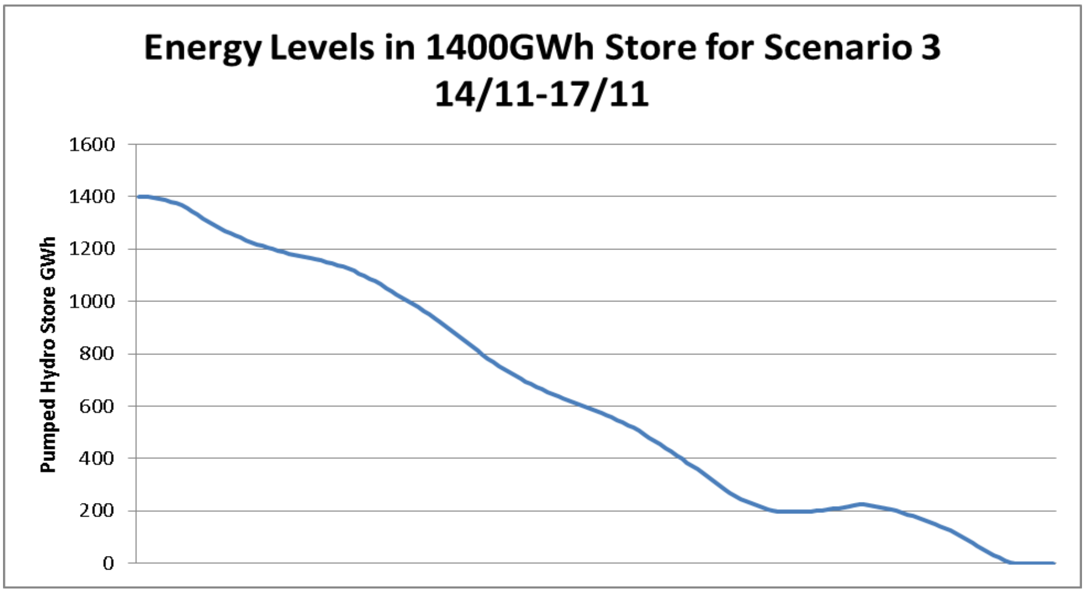


Figure 35 shows the energy levels in a PHS system with wind power feeding into it. The green line at 75Gwh has many times throughout the year where the store goes above it, meaning the store is getting depleted more and so is able to store energy multiple times. The red line which is at the 200GWh level is used four times in a year, so this is an extra 125GWh of storage to store maybe three lots of 50GWh.

From the simulations it also shows that the size of the energy store makes no difference to the maximum power output of the backup CCGT. This is because the times when the CCGT needs to put out maximium power coincides with the times when the energy store is depeleted i.e. when there are no renewables feeding into the system. For the scenarios run, this occurred in December, when the previously mentioned high pressure system occurred. At that time, wind energy input was effectively zero for a week, while demand was high due to the fact it was in the cold winter months.

Figure 36 Scenario 3 Energy Store Level 14-17 November



The graph above shows the storage levels for the scenario 3 case with a PHS amount of 1400GWh. In just three days the store went from full to empty, and as the lull in wind lasted weeks this meant that the CCGT had to do the job of 112GW of installed wind capacity.

In terms of carbon emissions, Scenario 2 led to an increase in use of CCGT of 29% though with an additional 200GWh of storage this would fall to 22%. The maximum output of the CCGT turbines was 40GW wich was practically identical to scenario 1. Even though it had double the wind capacity of scenario 1, it made little difference to the need for size of backup capacity, as when the wind resource is not there it makes little difference to the number of turbines you have. In terms of of spilled renewables, just 200GWh of storage prevented 5% of all renewable energy being curtailed.

Scenarios 3 and 4 had what could be deemed unrealistic levels of installed wind capacity, but they made the biggest difference to carbon emissions. Scenario 3 used backup CCGT 8% less than was used in 2014, despite having no coal to provide baseload. This jumped to 25% with the addition of 400GWh of storage preventing 7% of renewables being spilled.

Scenario 4's storage levels affected the use of CCGT backup the most. This was due to the effect the system had on the ability to utilize the high storage levels more throughout the year. With no storage, CCGT use was reduced 30%, but if the full 1400GWh of storage was available this would increase to 65%. 1400GWh would be equivalent of 35 Coire Glas's, (SSE's planned new PHS system in Scotland). This amount of PHS would be unlikely to be built in the UK due to environmental and financial issues.

4.2. Scenarios 5-8

For scenarios 5 and 6, due to the fact coal was missing from the generation mix, the need for storage was minimal much like the case was in scenario 1. The renewable output was only enough to partially offset CCGT use, and so there was no excess energy to store. It is still interesting to note however that the increased solar capacity in scenarios 5 and 6 led to a cut in carbon emissions of 57 $MtCO_2e$ and 67 $MtCO_2e$ respectively. This will partially be also due to the fact that coal use has been replaced once again with gas turbines, which have lower carbon emissions.

Figure 37 Decrease in CCGT Use Compared to Having No Storage

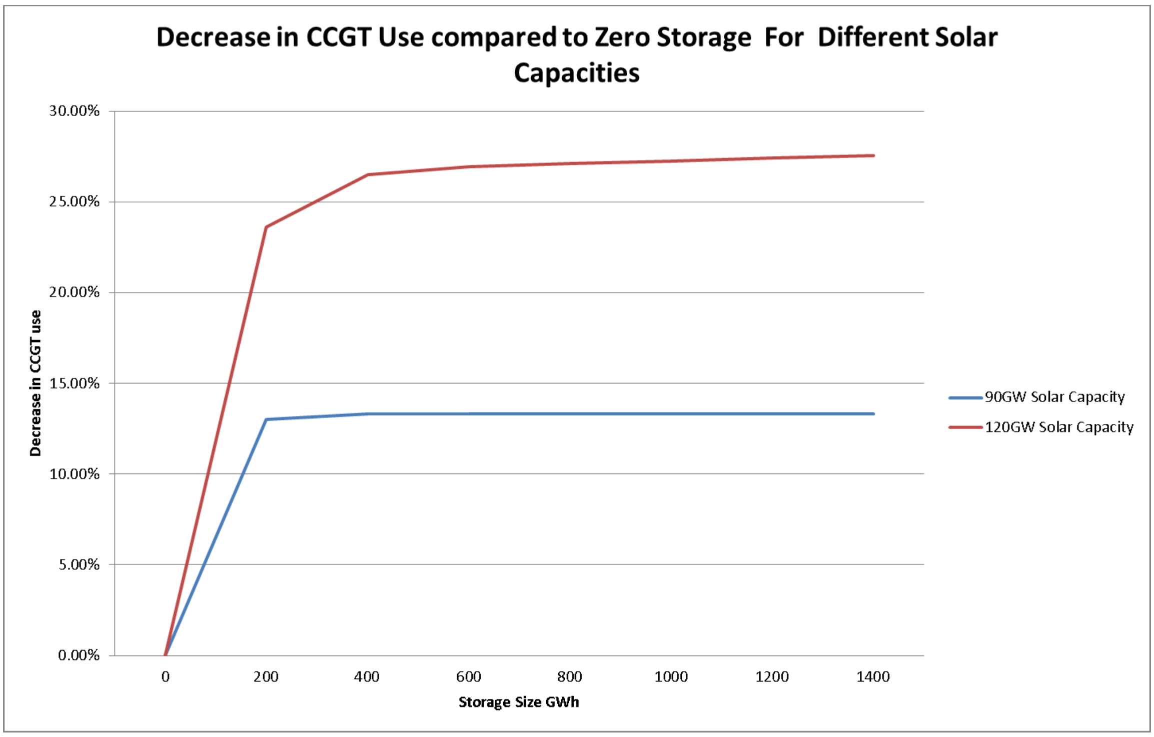


Figure 37 shows, that the diminishing value of storage at larger levels is much more extreme in the case of solar power than with that of wind. Again, like wind, the more installed capacity of the variable source, the more valuable storage is, but even for systems with enormous capacities of solar power anything past 200GWh of storage is unnecessary as it makes little difference to the decrease in backup CCGT use. This may be because unlike wind turbines, which can go through days of mostly continuous operation, solar power stops at sunset. This means the store will continuously fill and deplete every day, so that a higher storage amount is not needed.

Figure 38 Solar Energy vs Pumped Storage Energy 18th March Scenario 8

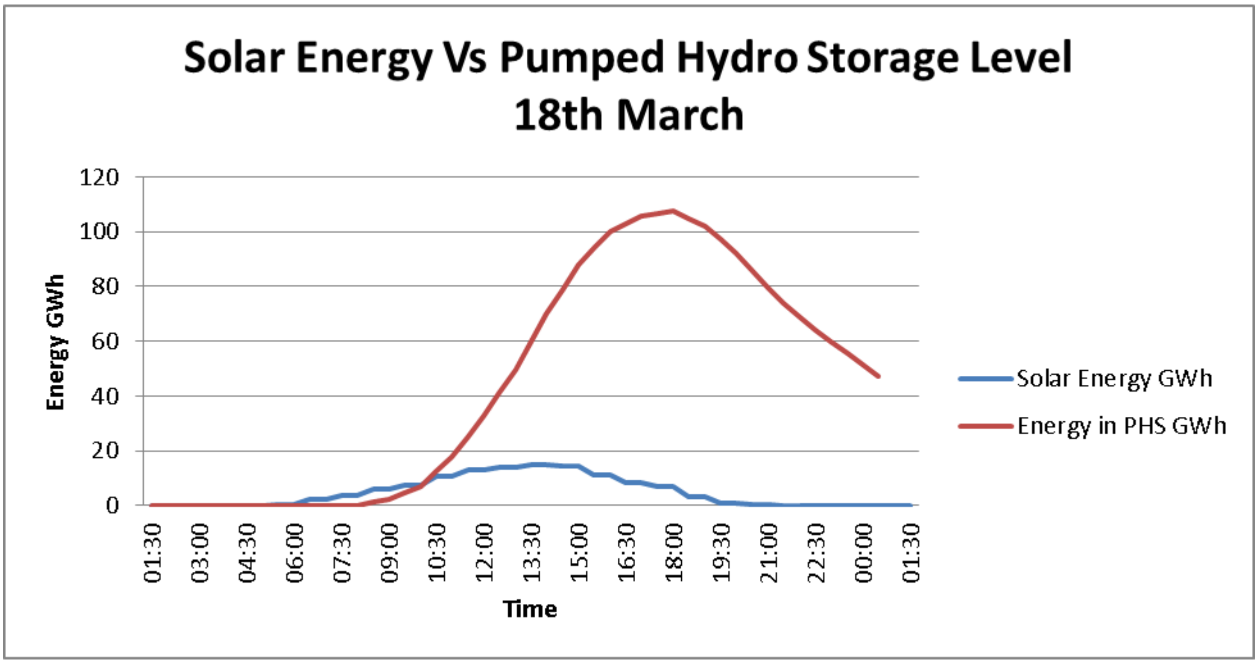


Figure 38 shows the amount of energy in storage compared to the energy being supplied form solar panels for a day in March for **scenario 8.** This shows why even with large capacities of solar inputting into the grid, large amounts of storage is not required. The energy store begins filling about 10am, as demand from the early morning lowers and the power from the sun increases. The store reaches its peak amount around 5pm, just as the sun begins to wane and evening demand surges. These daily demand patterns coinciding with the waxing and waning of solar resources means that the energy store is regularly being filled and depleted. This means that volumes of storage which would allow storage over days and weeks are not neccesary.

Again as with wind power, the storage size in a grid with only large amounts of solar has no bearing on the size of backup capacity in terms of power , as in winter the solar resource is next to zero and CCGT must make up the shortfall.

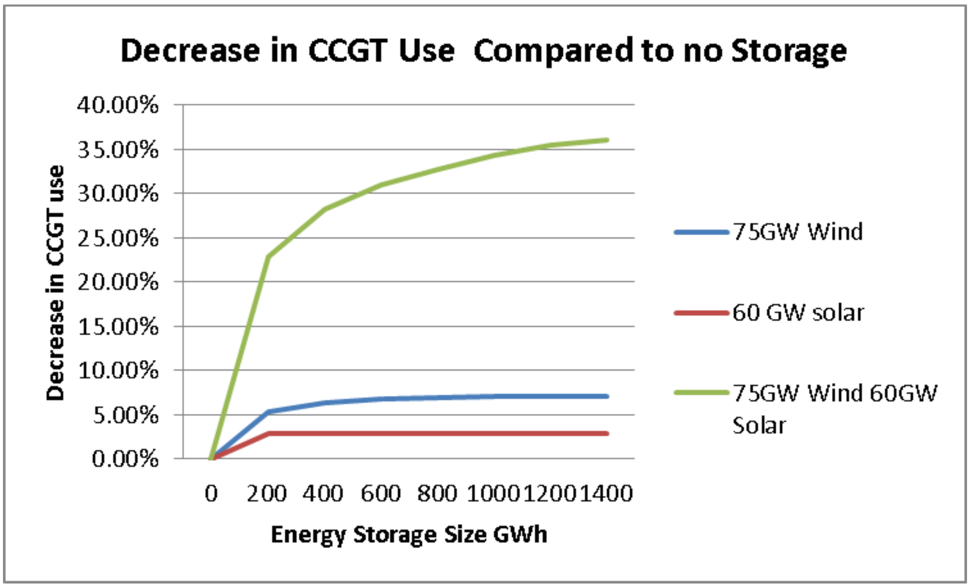
4.3. Scenario 9

Table 3 Scenario 9 Results

Scenario 9		Wind	Nuclear	Solar	Hydro	Biomass	Coal	
	Factor increase to 2014's capacity:	6	1	6	1	1	0	
Storage Amount GWh	0	200	400	600	800	1000	1200	1400
CCGT Max Capacity Needed GW	40	40	40	40	40	40	40	40
CCGT Output over year GWh	72203	55753	51816	49863	48647	47473	46645	46244
Percentatage decrease in CCGT use from no storage	0.00%	22.78%	28.24%	30.94%	32.63%	34.25%	35.40%	35.95%
CCGT Operation Reduction from 2014	16.33%	35.39%	39.95%	42.21%	43.62%	44.99%	45.94%	46.41%
Percentage Renewables Spilled	14%	5%	3%	2%	2%	1%	1%	0%
Total CO2 Saving compared to 2014 Emmisions (MtCO2e)	94.90	100.62	101.99	102.66	103.09	103.50	103.78	103.92
% of energy supply from renewables	56%	62%	63%	64%	64%	65%	65%	65%

Scenario 9 combined the installed capacities of solar and wind from scenarios 2 and 6. For both these scenarios, adding 200GWh only made around a 5% reduction in CCGT use. In the combined system the first 200GWh makes a 23% reduction. Figure 39 shows the decrease in CCGT use compared to having no energy store for scenarios 2, 6 and 9.

Figure 39 Decrease in CCGT Use at Different Wind Capacities



Having a mix of renewables seems to enhance the value of storage, and also reduce how quickly the value of increased levels of storage diminishes. A lot of this will be because there is more installed capacity in the combined system, and so more energy available to be stored. However it is also enhanced by the fact that generally speaking the need for energy storage for solar power occurs at a different time seasonally than when excess wind power needs to be stored.

Figure 40 Curtailed Wind Vs Curtailed

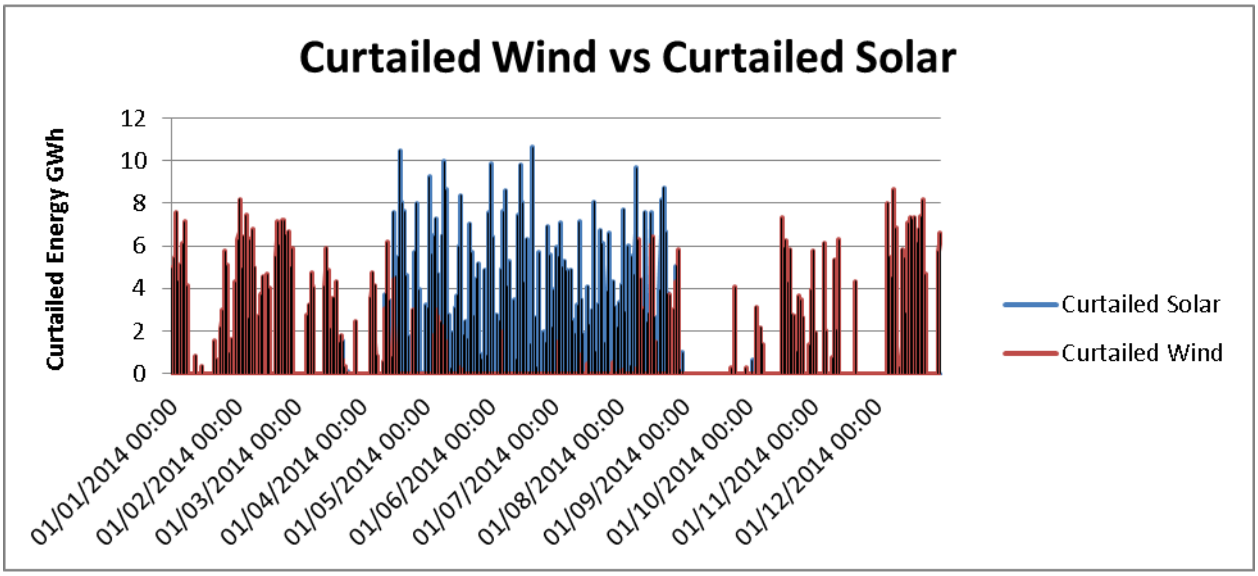


Figure 40 shows that all spilled solar happens in the summer and most spilled wind energy occurs in the winter months. This means the PHS system will be in use most of the year, and as such will be helping to reduce CCGT use in both summer and winter.

4.4. Scenario 10

Scenario 10 was intended to show the value of storage on a system with a strong mix of renewables and nuclear that would hopefully reduce reliance on CCGT.

Table 4 Scenario 10 Results

Scenario 10		Wind	Nuclear	Solar	Hydro	Biomass	Coal	
	Factor increase to 2014's capacity:	4	2.17	3	1	1	0	
Storage Amount GWh	0	200	400	600	800	1000	1200	1400
CCGT Max Capacity Needed GW	33	33	33	33	33	33	33	33
CCGT Output over year GWh	59212	49879	48167	47594	47185	46893	46893	46893
Percentatage decrease in CCGT use from no storage	0.00%	15.76%	18.65%	19.62%	20.31%	20.81%	20.81%	20.81%
CCGT Operation Reduction from 2014	31.38%	42.20%	44.18%	44.84%	45.32%	45.66%	45.66%	45.66%
Percentage Renewables Spilled	10%	2%	1%	1%	0%	0%	0%	0%
Total CO2 Saving compared to 2014 Emmisions (MtCO2e)	99.41	102.66	103.25	103.45	103.60	103.70	103.70	103.70
% of energy supply from renewables	37%	40%	41%	41%	41%	41%	41%	41%

The first 200GWh in this system leads to an almost 16% reduction in the need to use backup CCGT when compare to a system with no storage embedded in it.

Even with no coal in the system, CCGT use has reduced by over 30% compared to the actual 2014 figure. With additional storage this can get as high as 45%. These levels of installed capacity are very realistic, the installed wind capacity is only 26% higher than the UK's capacity will be once all planned offshore wind is completed. The installed solar capacity is equivalent to 8.5 million homes having a 3.5kW system installed. This would save almost 100MtCO2e, which would represent around an 83% cut in carbon emissions from electricity generation.

For storage, the first 200GWh will lead to an 80% reduction in spilled energy, but past 200GWh the levels of renewable installed would mean additional storage would be under utilised and so uneconomical.

4.5. Scenario 11

Table 5 Scenario 11 Results

Scenario 11		Wind	Nuclear	Solar	Hydro	Biomass	Coal	
	Factor increase to 2014's capacity:	3.3	1	3	1	3	0.8	
Storage Amount GWh	0	100	200	300	400	500	600	700
CCGT Max Capacity Needed GW	27	27	27	27	27	27	27	27
CCGT Output over year GWh	49197	42690	41319	40544	40000	39722	39524	39524
Percentatage decrease in CCGT use from no storage	0.00%	13.23%	16.01%	17.59%	18.69%	19.26%	19.66%	19.66%
CCGT Operation Reduction from 2014	42.99%	50.53%	52.12%	53.02%	53.65%	53.97%	54.20%	54.20%
Percentage Renewables Spilled	8.05%	2.61%	1.48%	0.84%	0.39%	0.16%	0.00%	0.00%
Total CO2 Saving compared to 2014 Emmisions (MtCO2e)	30.90	33.16	33.64	33.90	34.09	34.19	34.26	34.26
% of energy supply from renewables	38.18%	40.44%	40.91%	41.18%	41.36%	41.46%	41.53%	41.53%

Scenario 11 shows that once all offshore windfarms have been built, and if solar continues to increase to the point an additional 8 million people have a 3.5kW system, then without storage 8% of renewables will have to be curtailed. With the addition of just 100GWh of storage, curtailed renewables will fall to 3% and with 200GWh it would fall to 1%. The maximum capacity of backup CCGT need is 27GW, which is the close to the value as it currently stands. 8% of renewables spilled for scenario 11 equates to 10,000 GWh. This is the equivalent of the 400MW gas turbine at Corby running nonstop for just under three years, or the equivalent of over 3% of the total demand in 2014 being curtailed.

4.6. Scenario 12

Table 6 Scenario 12 Results

Scenario 12		Wind	Nuclear	Solar	Hydro	Biomass	Coal	
	Factor increase to 2014's capacity:	10	0	5.25	2.722	5	0	
Storage Amount GWh	0	200	400	600	800	1000	1200	1400
CCGT Max Capacity Needed GW	40	40	40	40	40	40	40	40
CCGT Output over year GWh	57560	42780	36961	33452	30765	28429	26730	25326
Percentatage decrease in CCGT use from no storage	0.00%	25.68%	35.79%	41.88%	46.55%	50.61%	53.56%	56.00%
CCGT Operation Reduction from 2014	33.30%	50.42%	57.17%	61.23%	64.35%	67.05%	69.02%	70.65%
Percentage Renewables Spilled	21%	17%	15%	14%	13%	12%	11%	11%
Total CO2 Saving compared to 2014 Emmisions (MtCO2e)	99.99	105.13	107.15	108.37	109.30	110.12	110.71	111.20
% of energy supply from renewables	81%	86%	88%	89%	90%	91%	91%	92%

At these levels of installed renewable capacity, the value of energy storage becomes apparent. No storage embedded means only a reduction in use of CCGT's by a third, but just 200GWh reduces this to almost half. 1400GWh, which is in all likelihood a figure the UK will never build, would lead to a 70% reduction in the use of gas turbines. At this point, 92% of electricity would be from renewables with no need for coal or nuclear to provide baseload. 40GW of backup CCGT capacity is still required though, purely because there is only biomass supplying some baseload and so when the wind stops, the gas turbines have to make up for around 130GW of wind.

4.7. Scenarios 13-15

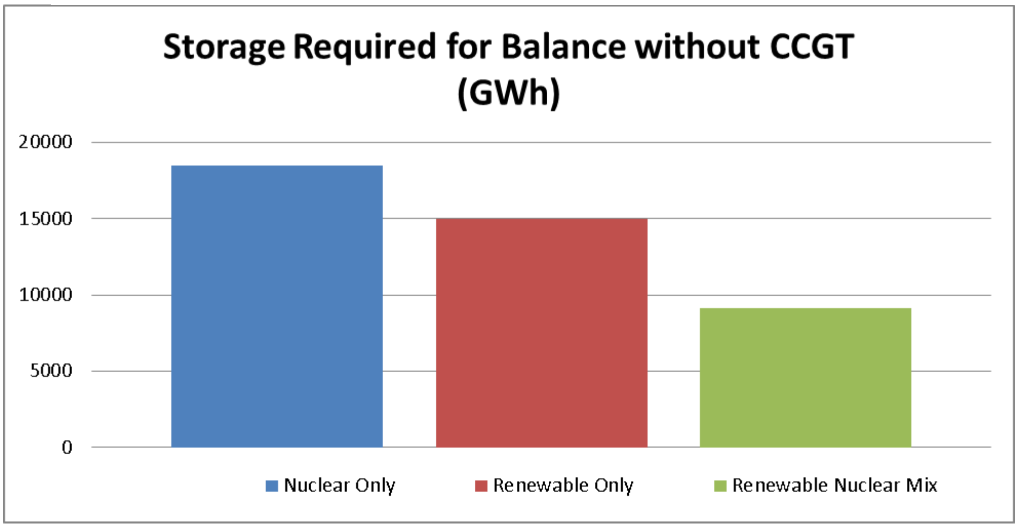
Table 7 Scenarios 13-15 Results

Scenario		Wind	Nuclear	Solar	Hydro	Biomass	Coal	Storage Required GWh
Scenario 13	Factor increase to 2014's capacity:	1	4.7	0	1	0	0	18500
Scenario 14	Factor increase to 2014's capacity:	5.2	2.17	2	2.722	5	0	9100
Scenario 15	Factor increase to 2014's capacity:	9.7	0	9	2.722	0	0	15000

The above table shows the best configurations that could be found that would both minimise storage levels and also installed generating capacity, such that supply could always meet demand without the need for gas turbines to be used to either load follow or as reserve capacity.

The model was slightly adapted for these scenarios as it assumed that the PHS would begin the year with 5000GWh, so it would be more likely to simulate what a real energy store would look like at the beginning of the year. Also for scenario 13, energy was not allowed to be curtailed as unlike a wind farm or solar panel, a nuclear power station cannot simply be switched off.

Figure 41 Storage Required To Replace CCGT Use



As you can see from Figure 41 nuclear alone needs the most storage to successfully load follow. This is because nuclear goes mostly at a flat rate all year, so must perform at a median output between minimum summer demand and maximum winter demand, and all the extra energy it stores in summer must be kept until the winter. 18000GWh is the equivalent of over four hundred 40GWh Coire Glas PHS sites (it must be noted Nuclear has some ability to throttle output but it hampers overall efficiency). The renewable only option is not much better, as the grid needs a lot of PHS to store up renewable power throughout the year so that it can be supplied almost entirely from pumped storage for the weeks in winter when high pressure systems hang over the UK. The lowest of the storage levels is a mix of the two, but still at 9100GWh would be, although technically feasible given the geographical nature of Scotland and Wales, politically and environmentally impossible to build.

5. Discussion

5.1. When Will Curtailment Start and Storage be Required?

The first thing to be said is that curtailment of renewable energy already happens to some degree within the national grid. Whitelee Wind Farm is curtailed at times throughout the year due to the fact it can only export its energy to the central belt as there is a bottleneck in the transmission lines down to population centres in the south, although the new western HVDC link hopes to alleviate this (GOV.UK, 2012). If the transmission infrastructure is reinforced adequately, then spillage will only be due to lack of storage and not because of an inability to move the power to where it is either neededor can be stored.

Curtailment will mean a few things to the renewable sector, as installed capacity gets higher spillage will increase and thus the value economically of adding additional capacity lessons this will likely disencentivise the large scale installation of renewables the UK needs to decarbonioze its electricty network. It also means more turbines will have to be installed to be able to do the job of less turbine plus storage wich will have ramifications in terms of land use. So after a certain point building additional storage will perhaps become econmoical and acceptable in terms of land use.

Analysis of the various scenarios shows that need for energy storage depends entirely on the make-up of the grid at the time. Scenario 11 is probably closest in appearance to what the national grid will look like in the next ten years. Even with no increase in installed solar capacity or biomass prescribed by scenario 11 around 6% of renewable energy would have to be spilled without storage.

From looking at the model, spillage seems to begin to rapidly increase at the mark where around 30% of total energy is from renewable sources mainly made up of wind capacity. Biomass and hydro due to their fairly consistent output do not lead to markedly increased spillage, solar only begins to contribute to spillage once additional installed capacity reaches 20GW. In all likelihood once the competition of all planned onshore and offshore wind is completed and if coal use is not reduced in favour of the more dynamic CCGT’s then we could see curtailment of renewables get as high as 10%

One added detail is that all simulations assume a 60/40 onshore to offshore split, but in fact what is currently planned is around 27GW of new offshore with new onshore being hampered by cuts in subsidies. The split will therefore be more likely to resemble a 75/25 ratio in favour of offshore. This means any simulations that have increased capacities of wind will be more energetic than what is modelled in the scenarios, and the need for storage will be enhanced further.

Given the rapid uptake in solar seen in 2014 and with the price of solar continuing to fall along with around 27GW of offshore wind that will in all likelihood be completed in the next five to ten years, we could expect to see significant increases in curtailment of renewable energy by 2025.

5.2. <u>How Much PHS Could be Built in the UK?</u>

The European Strategic Energy Technology (SET), which is part of the European Commission, funded a GIS appraisal of potential PHS across Europe. Its findings showed that the UK had a realisable potential storage capacity of over 9000GWh (Gimeno-Gutiérrez, 2013). The Geographic Information Systems (GIS) aspects of the appraisal included only existing grid infrastructure, so the potential storage for the UK will likely be higher still once the Beauly-Denny transmission line is completed, which would open up the possibility of new possible PHS sites in the Highlands.

Given this and the scenarios investigated which showed diminishing returns at increasing amounts of storage, the UK has as much potential PHS as it requires.

5.3. <u>What Scenario is best?</u>

There are numerous different types of configuration the UK could have in its balance of generating mix in the future and the scenarios selected were mostly picked to investigate what role additional storage could play with various mixes, no one scenario is any better than another, even the scenarios that involved 10 times the current capacity of renewables are technically achievable and only rely on political will for them to be implemented.

In all likelihood what we can say is that new nuclear plants will be built and they will be a higher capacity than the ones they are replacing and that all rounds of planned offshore currently planned will be built. The price of solar has continued to fall and even without subsidies they will be economical for those living in the South of the UK. A Final scenario was designed to take into account these factors and see how a realistic level of pumped hydro storage could help eliminate further reliance on gas turbines.

This final scenario involved an installed capacity of around 85GW of wind, 40GW of solar, 20Gw of nuclear power, hydro power was only increased marginally due to the lack of suitable sites and a 3 times increase in biomass was put in as over this the ability to source fuel sustainably would in all likelihood become an issue. None of these figures are very large and in fact given that the majority of the wind farms in the future will probably be offshore with higher capacity factors 75GW of installed wind will do the same job as what the model simulates 85GW will output. 40GW of solar involves just under 12 million homes having a 3.5kW system so definitely not outwith the realms of possibility of what we could see in the next 10-20 years.

Table 8 Final Scenario Results

FINAL SCENARIO		7	2.17	4	1.2	3	0	
Storage Amount GWh	0	100	200	300	400	500	600	700
CCGT Max Capacity Needed GW	30	30	30	30	30	30	30	30
CCGT Output over year GWh	25311	16451	13481	11755	10412	9167	8226	7536
Percentatage decrease in CCGT use from no storage	N/A	35.01%	46.74%	53.56%	58.86%	63.78%	67.50%	70.22%
CCGT Operation Reduction from 2014	70.67%	80.94%	84.38%	86.38%	87.93%	89.38%	90.47%	91.27%
Percentage Renewables Spilled	31.57%	27.47%	26.06%	25.21%	24.54%	23.91%	23.44%	23.08%
Total CO2 Saving compared to 2014 Emmisions (MtCO2e)	111.20	114.28	115.31	115.91	116.38	116.81	117.14	117.38
% of energy supply from renewables	49%	51%	52%	53%	54%	54%	54%	55%

With no storage in this system decrease in CCGT use is still 70% of the 2014 value but with the addition of 200GWh this could increase to around 85%, spillage would still be reasonably high but at this point CCGT's would only be in operation in times when high pressure systems where over the UK for longer periods of time. In terms of carbon emissions they would decrease from 2014's value of around 121 MtCO2e to less than 10 MtCO2e, a decrease in carbon emissions from the electrical supply of almost 92%. This is felt to be the best scenario that has a balance of what can be realistically implemented but also have radical cuts in carbon emissions.

5.4. How Much PHS Should be Built?

The amount of useful storage required by the grid depends entirely on how much renewables make up the total generating capacity. However from all scenarios investigated, there seems to be a very strong case for the building of 100-200GWh of new PHS, in all scenarios the addition of 200GWh led to a drastic reduction in curtailment of renewable energy and consequently reliance on CCGT's. If there are plans to build much more wind farms beyond those planned, or the capacity factors out at sea are higher than previously thought, then there could be a case for a further additional 200GWh to minimise spillage. However, beyond this the advantages of additional storage quickly diminish in terms of the economics of having large dams sit seldom used for long periods of time versus relying on gas turbines to get through the brief periods when renewables will effectively generate zero power.

5.5. Infrastructure Requirements to Store Surplus Renewable Energy

If the UK decided to build the recommended 200GWh of storage in all likelihood the majority of the sites would be located in the highlands of Scotland, unfortunately the Grid Infrastructure in place in these locations will be unlikely to handle the size of power flows involved. The largest of planned offshore windfarms Doggerbank will be around 5GW alone, this is more than a third of current installed capacity of wind and will likely connect to the mainland at Redcar and Cleveland in Teeside (RenwableEnergyMagazine, 2015). The existing transmission infrastructure between there and the Highlands has previously been shown in Figure 2.3.4 on Page 34, the majority of the distance is covered in 275kV lines that would increase electrical losses when compared to the 400kV lines the cover much of the South. Beauly Denny the current new transmission line running from the highlands to the central belt will help to relive some of the stresses that would inevitably be placed on the existing transmission lines handling such large power flows but in all likelihood additional lines will have to be put in place if all the renewable energy generated from the solar panels and offshore wind of England and Wales wishes to be stored in Scottish pumped hydro.

Luckily OFGEM have recently fast tracked £4 billion to improve transmission infrastructure in the Highlands and Islands so there is hope that by the time the need for storage arises then the national grid will have the infrastructure in place to move such large sums of energy to where it can be stored (HIE, 2015).

In terms of Policy for increased PHS to be viable then there must be an end to OFGEM’s current system of transmission charges being based upon distance as this severely disadvantages the movement of renewable energy from the places it can be generated to the places it can be stored and then on to where there is demand for it as this will involve much larger round trips than we currently see in conventional fossil fuel generation.

5.6. What This Means for CCGT's Role in the Grid

As the scenarios show, storage levels do not help reduce much the size of reserve capacity required to back-up the renewable-PHS system, as it requires massive amounts of both renewables and storage to see the UK through a high pressure system that lasts weeks. If the UK wishes to get rid of its coal power station and allow its nuclear power to be slowly decommissioned, then an additional 15GW of CCGT capacity would be required regardless of the amount of renewables installed.

There is a way reserve capacity could be reduced without adding lots of additional storage and that would be by running the CCGT's at the same time as the pumped hydro storage such that both the output power of the PHS and CCGT was reduced but each ran for longer, so instead of for example running 40GW of PHS for three days then 40GW of CGGT for 3 days you would run 20GW each simultaneously for 6 days.

This has one big disadvantage as your pumped hydro store could still run dry before the renewable generation begins to meet supply but you do not have any remaining spare capacity to meet demand, if this were to happen there would be massive blackouts and a probable total collapse of the national grid. The generally unpredictable nature of renewables would in all likelihood mean it would be better to utilize PHS energy stores for as long as possible and then move onto backup CCGT such that use of the previously stored renewable energy was always maximised, this has the unfortunate side effect of increasing the size of the reserve capacity needed.

6. In Conclusion

From the results the author would recommend that in around the next 10 years between 100-200GWh of new pumped hydro storage should be built purely to prevent the curtailment of renewable energy and reduce the use of CCGT's as a load following mechanism. Unfortunately this will also mean the adding of more CCGT capacity to act in reserve for when renewable output is negligible and the pumped hydro stores are empty, even if overall CCGT use will be far lower than as it currently stands.

To facilitate this the national grid will need to be strengthened such that large power flows may operate from England to Scotland and back again.

7. Further Work

If time or data available had permitted the following would have been added to the model:

- Offshore and Onshore wind capacity increases would have been spate to take into account their different capacity factors.
- An option for changing the demand side characteristics throughout the year would be added to take into account the increased focus seen in recent years on demand management.
- Wave and Tidal power would be added in to the model to complete the possible mix of renewables that can be expected to be seen in the future.
- Work out the required improvements to the transmission infrastructure if the various scenarios were implemented.

8. Works Cited

Association, W. N., 2015. *Nuclear Power in France.* [Online] Available at: http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/France/

Association, W. N., 2015. *Nuclear Power in the United Kingdom.* [Online] Available at: http://www.world-nuclear.org/info/Country-Profiles/Countries-T-Z/United-Kingdom/

Barnes, F. S. & Levine, J. G., 2011. *Large energy storage systems handbook.* Boca Raton, FL : CRC Press.

BBC, 2014. *Nuclear reactors may stay offline until end of year, EDF says.* [Online] Available at: http://www.bbc.co.uk/news/business-29058644

Boyle, G., 2007. *Renewable electricity and the grid : the challenge of variability.* London ; Sterling, VA : Earthscan .

BuisnessGreen, 2015. *UK wind power smashes annual output record.* [Online] Available at: http://www.businessgreen.com/bg/news/2388553/uk-wind-power-smashes-annual-output-record

CambridgeSolar, 2015. [Online] Available at: http://www.cambridge-solar.co.uk/

DUKES 2012. *ELECTRICITY STATISTICS.* [Online] Available at: http://webarchive.nationalarchives.gov.uk/20121217150421/http://decc.gov.uk/en/content/cms/statistics/energy_stats/source/electricity/electricity.aspx

DEAC, D. o. E. a. C. C., n.d. *UKWED Figures explained.* [Online] Available at: http://www.renewableuk.com/en/renewable-energy/wind-energy/uk-wind-energy-database/figures-explained.cfm

DECC, 2008. *Scottish Hydropower Resource Study,* Department of Energy and Climate Change.

Department of Energy and Climate Change, D., 2015. *Dukes chapter 5,* Department of Energy and Climate Change.

EIA.GOV, 2011. *Electricity storage technologies can be used for energy management and,power,quality.* [Online] Available at: http://www.eia.gov/todayinenergy/detail.cfm?id=4310

EIA, 2012. *International Energy Statistics ,* US Energy Information Administration.

Elliot, D., 2013. *Renewables: a review of sustainable energy supply options.* Bristol England Temple Circus.

EWEA, n.d. *Wind in Power 2014 statistics,* EWEA.

Fujihara, T., n.d. *Development of Pump Turbine for Seawater PumpedStorage,*

Gimeno-Gutiérrez, M., 2013. *Assessment of the European potential for pumped hydropower energy storage,* European Commision.

GOV.UK, 2012. *OUR ELECTRICITY TRANSMISSIO NETWORK:A VISION FOR 2020,* UK Goverment.

Guardian, 2014. *Renewables produce record high electricity for UK in 2014.* [Online] Available at: http://www.theguardian.com/environment/2014/aug/14/uk-renewables-record-start-2014

Hermann-Josef Wagner, J. M., 2011. *Introduction to Hydro Energy Systems.*

Holmes, D., 2015. *http://www.theengineer.co.uk/energy/in-depth/pumped-storage-a-new-project-for-wales/1020129.article.* [Online]

Available at: http://www.theengineer.co.uk/energy/in-depth/pumped-storage-a-new-project-for-wales/1020129.article

IEA, 2003. *Renewables for Power Generation.* s.l.:OECD Publishing.

IEA, 2011. *Harnessing Variable Renewables A Guide to the Balancing Challenge.* OECD Publishing.

Lannen, N., 2012. *New Pumped Storage Proposals,* SSE.

MacKay, D. J. C., 2008. *Sustainable energy : without the hot air.* Cambridge, England : UIT Cambridge.

Markian M. W. Melnyk, R. M. A., 2009. *Offshore Power: Building Renewable Energy Projects in U.S. Waters.* PennWell Books.

MetOffice, 2014. *September 2014 Summary.* [Online] Available at: http://www.metoffice.gov.uk/climate/uk/summaries/2014/september

National Grid, S. T. T., n.d. *Security of Electricity Supply in Scotland,* Scottish Government.

NPTEL, n.d. *Fluid Machinery.* [Online] Available at: http://nptel.ac.in/courses/Webcourse-contents/IIT-KANPUR/machine/ui/Course_home-lec28.htm

OFGEM, 2010. *BRITAIN NEEDS REWIRING TO THE TUNE OF £32 BILLION,* OFGEM.

RenwableEnergyMagazine, 2015. [Online] Available at: http://www.renewableenergymagazine.com/article/training-program-launched-to-accelerate-solar-pv-20131001-1

Sinden, G., 2005. *Wind Power and the UK Wind Resource [Online],* Wind Power and the UK Wind Resource. [Online].

SolarBuzz, 2014. *UK solar PV industry reaches 5GW installed capacity*. [Online] Available at: http://www.solarpowerportal.co.uk/guest_blog/uk_solar_pv_industry_reaches_5gw_installed_capacity_3467

SSE, 2012. *COIRE GLAS HYDRO SCHEME.* [Online] Available at: http://sse.com/whatwedo/ourprojectsandassets/renewables/CoireGlas/

Ter-Gazarian, A., 1994. *Energy storage for power systems.*. s.l.:Stevenage : P. Peregrinus on behalf of the Institution of Electrical Engineers .

WASP, 2015. [Online] Available at: http://www.wasp.dk/Wind-Atlas/European-Wind-Atlas

Wikipedia 2015. [Online] Available at: https://en.wikipedia.org/wiki/Pumped-storage_hydroelectricity#/media/File:Pumpstor_racoon_mtn.jpg

9. Appendix

Table 9 Appendix: Scenario 1 Results

Scenario 1		Wind	Nuclear	Solar	Hydro	Biomass	Coal	
	Factor increase to 2014's capacity:	3	1	0	1	1	0	
37GW								
Storage Amount GWh	0	200	400	600	800	1000	1200	1400
CCGT Max Capacity Needed GW	41	41	41	41	41	41	41	41
CCGT Output over year GWh	166287	166287	166287	166287	166287	166287	166287	166287
Percentatage decrease in CCGT use from no storage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
CCGT Operation Reduction from 2014	-92.71%	-92.71%	-92.71%	-92.71%	-92.71%	-92.71%	-92.71%	-92.71%
Percentage Renewables Spilled	0%	0%	0%	0%	0%	0%	0%	0%
Total CO2 Saving compared to 2014 Emmisions (MtCO2e)	62.19	62.19	62.19	62.19	62.19	62.19	62.19	62.19
% of energy supply from renewables	25%	25%	25%	25%	25%	25%	25%	25%

Table 10 Appendix: Scenario 2 Results

Scenario 2		Wind	Nuclear	Solar	Hydro	Biomass	Coal	
	Factor increase to 2014's capacity:	6	1	0	1	1	0	
75GW								
Storage Amount GWh	0	200	400	600	800	1000	1200	1400
CCGT Max Capacity Needed GW	40	40	40	40	40	40	40	40
CCGT Output over year GWh	111178	105294	104093	103695	103497	103312	103312	103312
Percentatage decrease in CCGT use from no storage	0.00%	5.29%	6.37%	6.73%	6.91%	7.08%	7.08%	7.08%
CCGT Operation Reduction from 2014	-28.84%	-22.02%	-20.63%	-20.17%	-19.94%	-19.73%	-19.73%	-19.73%
Percentage Renewables Spilled	6%	1%	1%	0%	0%	0%	0%	0%
Total CO2 Saving compared to 2014 Emmisions (MtCO2e)	81.35	83.39	83.81	83.95	84.02	84.08	84.08	84.08
% of energy supply from renewables	43%	45%	46%	46%	46%	46%	46%	46%

Table 11 Appendix: Scenario 3 Results

Scenario 3		Wind	Nuclear	Solar	Hydro	Biomass	Coal	
	Factor increase to 2014's capacity:	9	1	0	1	1	0	
112GW								
Storage Amount GWh	0	200	400	600	800	1000	1200	1400
CCGT Max Capacity Needed GW	40	40	40	40	40	40	40	40
CCGT Output over year GWh	79366	69594	65474	62320	60118	58373	56861	55722
Percentatage decrease in CCGT use from no storage	0.00%	12.31%	17.50%	21.48%	24.25%	26.45%	28.36%	29.79%
CCGT Operation Reduction from 2014	8.03%	19.35%	24.12%	27.78%	30.33%	32.35%	34.11%	35.43%
Percentage Renewables Spilled	20%	15%	13%	11%	10%	9%	8%	8%
Total CO2 Saving compared to 2014 Emmisions (MtCO2e)	92.41	95.80	97.24	98.33	99.10	99.71	100.23	100.63
% of energy supply from renewables	54%	57%	59%	60%	60%	61%	61%	62%

Table 12 Appendix: Scenario 4 Results

Scenario 4		Wind	Nuclear	Solar	Hydro	Biomass	Coal	
	Factor increase to 2014's capacity:	12	1	0	1	1	0	
150GW								
Storage Amount GWh	0	200	400	600	800	1000	1200	1400
CCGT Max Capacity Needed GW	39	39	39	39	39	39	39	39
CCGT Output over year GWh	60314	48699	42559	38740	36263	34459	32928	31574
Percentatage decrease in CCGT use from no storage	0.00%	19.26%	29.44%	35.77%	39.88%	42.87%	45.40%	47.65%
CCGT Operation Reduction from 2014	30.10%	43.56%	50.68%	55.10%	57.98%	60.07%	61.84%	63.41%
Percentage Renewables Spilled	32%	27%	25%	23%	22%	22%	21%	20%
Total CO2 Saving compared to 2014 Emmisions (MtCO2e)	99.03	103.07	105.20	106.53	107.39	108.02	108.55	109.02
% of energy supply from renewables	60.1%	64.0%	66.1%	67.5%	68.4%	69.0%	69.6%	70.1%

Table 13 Appendix: Scenario 5 Results

Scenario 5		Wind	Nuclear	Solar	Hydro	Biomass	Coal	
	Factor increase to 2014's capacity:	1	0	3	1	1	0	
Storage Amount GWh	0	200	400	600	800	1000	1200	1400
CCGT Max Capacity Needed GW	42	42	42	42	42	42	42	42
CCGT Output over year GWh	179494	179488	179488	179488	179488	179488	179488	179488
Percentatage decrease in CCGT use from no storage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
CCGT Operation Reduction from 2014	-108.01%	-108.00%	-108.00%	-108.00%	-108.00%	-108.00%	-108.00%	-108.00%
Percentage Renewables Spilled	0%	0%	0%	0%	0%	0%	0%	0%
Total CO2 Saving compared to 2014 Emmisions (MtCO2e)	57.60	57.60	57.60	57.60	57.60	57.60	57.60	57.60
% of energy supply from renewables	20%	20%	120%	220%	320%	420%	520%	620%

Table 14 Appendix: Scenario 6 Results

Scenario 6		Wind	Nuclear	Solar	Hydro	Biomass	Coal	
	Factor increase to 2014's capacity:	1	0	6	1	1	0	
Storage Amount GWh	0	200	400	600	800	1000	1200	1400
CCGT Max Capacity Needed GW	42	42	42	42	42	42	42	42
CCGT Output over year GWh	155439	151118	151118	151118	151118	151118	151118	151118
Percentatage decrease in CCGT use from no storage	0.00%	2.78%	2.78%	2.78%	2.78%	2.78%	2.78%	2.78%
CCGT Operation Reduction from 2014	-80.13%	-75.13%	-75.13%	-75.13%	-75.13%	-75.13%	-75.13%	-75.13%
Percentage Renewables Spilled	5%	0%	0%	0%	0%	0%	0%	0%
Total CO2 Saving compared to 2014 Emmisions (MtCO2e)	65.96	67.46	67.46	67.46	67.46	67.46	67.46	67.46
% of energy supply from renewables	28%	30%	30%	30%	30%	30%	30%	30%

Table 15 Appendix: Scenario 7 Results

Scenario 7		Wind	Nuclear	Solar	Hydro	Biomass	Coal	
90GW Solar Capacity	Factor increase to 2014's capacity:	1	0	9	1	1	0	
Storage Amount GWh	0	200	400	600	800	1000	1200	1400
CCGT Max Capacity Needed GW	42	42	42	42	42	42	42	42
CCGT Output over year GWh	141446	123028	122621	122621	122621	122621	122621	122621
Percentatage decrease in CCGT use from no storage	0.00%	13.02%	13.31%	13.31%	13.31%	13.31%	13.31%	13.31%
CCGT Operation Reduction from 2014	-63.92%	-42.57%	-42.10%	-42.10%	-42.10%	-42.10%	-42.10%	-42.10%
Percentage Renewables Spilled	17%	0%	0%	0%	0%	0%	0%	0%
Total CO2 Saving compared to 2014 Emmisions (MtCO2e)	70.82	77.23	77.37	77.37	77.37	77.37	77.37	77.37
% of energy supply from renewables	33%	40%	40%	40%	40%	40%	40%	40%

Table 16 Appendix: Scenario 8 Results

Scenario 8		Wind	Nuclear	Solar	Hydro	Biomass	Coal	
120GW Solar Capacity	Factor increase to 2014's capacity:	1	0	12	1	1	0	
Storage Amount GWh	0	200	400	600	800	1000	1200	1400
CCGT Max Capacity Needed GW	42	42	42	42	42	42	42	42
CCGT Output over year GWh	132904	101509	97674	97095	96851	96648	96444	96251
Percentatage decrease in CCGT use from no storage	0.00%	23.62%	26.51%	26.94%	27.13%	27.28%	27.43%	27.58%
CCGT Operation Reduction from 2014	-54.02%	-17.64%	-13.19%	-12.52%	-12.24%	-12.00%	-11.77%	-11.54%
Percentage Renewables Spilled	27%	6%	3%	3%	3%	2%	2%	2%
Total CO2 Saving compared to 2014 Emmisions (MtCO2e)	73.79	84.71	86.04	86.24	86.33	86.40	86.47	86.54
% of energy supply from renewables	36%	46%	48%	48%	48%	48%	48%	48%

Table 17 Appendix: Scenario 9 Results

Scenario 9		Wind	Nuclear	Solar	Hydro	Biomass	Coal	
	Factor increase to 2014's capacity:	6	1	6	1	1	0	
Storage Amount GWh	0	200	400	600	800	1000	1200	1400
CCGT Max Capacity Needed GW	40	40	40	40	40	40	40	40
CCGT Output over year GWh	72203	55753	51816	49863	48647	47473	46645	46244
Percentatage decrease in CCGT use from no storage	0.00%	22.78%	28.24%	30.94%	32.63%	34.25%	35.40%	35.95%
CCGT Operation Reduction from 2014	16.33%	35.39%	39.95%	42.21%	43.62%	44.99%	45.94%	46.41%
Percentage Renewables Spilled	14%	5%	3%	2%	2%	1%	1%	0%
Total CO2 Saving compared to 2014 Emmisions (MtCO2e)	94.90	100.62	101.99	102.66	103.09	103.50	103.78	103.92
% of energy supply from renewables	56%	62%	63%	64%	64%	65%	65%	65%

Table 18 Appendix: Scenario 10 Results

Scenario 10		Wind	Nuclear	Solar	Hydro	Biomass	Coal	
	Factor increase to 2014's capacity:	4	2.17	3	1	1	0	
Storage Amount GWh	0	200	400	600	800	1000	1200	1400
CCGT Max Capacity Needed GW	33	33	33	33	33	33	33	33
CCGT Output over year GWh	59212	49879	48167	47594	47185	46893	46893	46893
Percentatage decrease in CCGT use from no storage	0.00%	15.76%	18.65%	19.62%	20.31%	20.81%	20.81%	20.81%
CCGT Operation Reduction from 2014	31.38%	42.20%	44.18%	44.84%	45.32%	45.66%	45.66%	45.66%
Percentage Renewables Spilled	10%	2%	1%	1%	0%	0%	0%	0%
Total CO2 Saving compared to 2014 Emmisions (MtCO2e)	99.41	102.66	103.25	103.45	103.60	103.70	103.70	103.70
% of energy supply from renewables	37%	40%	41%	41%	41%	41%	41%	41%

Table 19 Appendix: Scenario 11 Results

Scenario 11		Wind	Nuclear	Solar	Hydro	Biomass	Coal	
	Factor increase to 2014's capacity:	3.3	1	3	1	3	0.8	
Storage Amount GWh	0	100	200	300	400	500	600	700
CCGT Max Capacity Needed GW	27	27	27	27	27	27	27	27
CCGT Output over year GWh	49197	42690	41319	40544	40000	39722	39524	39524
Percentatage decrease in CCGT use from no storage	0.00%	13.23%	16.01%	17.59%	18.69%	19.26%	19.66%	19.66%
CCGT Operation Reduction from 2014	42.99%	50.53%	52.12%	53.02%	53.65%	53.97%	54.20%	54.20%
Percentage Renewables Spilled	8.05%	2.61%	1.48%	0.84%	0.39%	0.16%	0.00%	0.00%
Total CO2 Saving compared to 2014 Emmisions (MtCO2e)	30.90	33.16	33.64	33.90	34.09	34.19	34.26	34.26
% of energy supply from renewables	38.18%	40.44%	40.91%	41.18%	41.36%	41.46%	41.53%	41.53%

Table 20 Appendix: Scenario 12 Results

Scenario 12		Wind	Nuclear	Solar	Hydro	Biomass	Coal	
	Factor increase to 2014's capacity:	10	0	5.25	2.722	5	0	
Storage Amount GWh	0	200	400	600	800	1000	1200	1400
CCGT Max Capacity Needed GW	40	40	40	40	40	40	40	40
CCGT Output over year GWh	57560	42780	36961	33452	30765	28429	26730	25326
Percentatage decrease in CCGT use from no storage	0.00%	25.68%	35.79%	41.88%	46.55%	50.61%	53.56%	56.00%
CCGT Operation Reduction from 2014	33.30%	50.42%	57.17%	61.23%	64.35%	67.05%	69.02%	70.65%
Percentage Renewables Spilled	21%	17%	15%	14%	13%	12%	11%	11%
Total CO2 Saving compared to 2014 Emmisions (MtCO2e)	99.99	105.13	107.15	108.37	109.30	110.12	110.71	111.20
% of energy supply from renewables	81%	86%	88%	89%	90%	91%	91%	92%

Table 21 Appendix: Scenarios 13-15 Results

Scenario 13		Wind	Nuclear	Solar	Hydro	Biomass	Coal	Storage Required GWh
	Factor increase to 2014's capacity:	1	4.7	0	1	0	0	18500
Scenario 14		Wind	Nuclear	Solar	Hydro	Biomass	Coal	Storage Required GWh
	Factor increase to 2014's capacity:	5.2	2.17	2	2.722	5	0	9100
Scenario 15		Wind	Nuclear	Solar	Hydro	Biomass	Coal	Storage Required GWh
	Factor increase to 2014's capacity:	9.7	0	9	2.722	0	0	15000