Department of Mechanical and Aerospace Engineering

Utilizing Curtailed Wind Energy by the Deployment of Large Scale Storage Systems

Author: Kutlu Balci

Supervisor: Dr Andrew Grant

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Abstract

On the road towards low carbon energy supply systems, renewable energy deployment is increasing gradually all over the world. The UK is one of the leading countries in renewable generation capacity and wind powered generation presently forms the largest part of the total; abundant wind resources put the UK in a favourable position to achieve its targets. However, there is an existing and continuously growing problem with wind energy curtailment which gives it a bad reputation. There are significant payments made by National Grid to the wind farm operators to reduce their power outputs at specific times of high output and low demand.

One possible solution to minimize curtailment is the deployment of large scale storage systems. There are already utility scale storage pumped hydro storage (PHS) deployments in the UK, however they are not specifically designed to decrease curtailment. Key objectives of this study are to investigate the use of additional storage capacity to utilize present and future curtailed wind energy over the UK. In addition to PHS, other storage systems are investigated in terms of cost, technical specifications and applicability. Research into battery technology and expansion in the use of electric vehicles offer possibilities for utilizing presently discarded wind energy.

During the investigation, actual supply and demand data from 2015 have been used to build a model which simulates the curtailed wind energy with possible future increases in UK's energy supply and demand. From outcomes of the model it is possible to estimate how much storage capacity might be required to fully utilize curtailed wind energy. It is found that fairly moderate amounts of added storage capacity can have a dramatic effect: under the best scenarios, 100GWh of extra storage deployment by 2026 will mostly overcome the wind energy curtailment problem of the UK. But if immediate precautions are not taken, the problem will grow increasingly in the years ahead.

Acknowledgement

First of all, I would like to take this opportunity to thank my mum Muberra Balci and my dad Prof.Mustafa Balci for all their love, encouragement and continuous support throughout my life. I would also like to thank my beloved sisters, brothers and nephews for continuously motivating me with their support. I could not have done this course without them.

I am very grateful to my project supervisor Dr.Andrew Grant for his valuable advises, support and for his efforts to keep me focused on the most important aspects of the project.

I also appreciate for the information provided by Dr.Lee Moroney from Renewable Energy Foundation, Dr.David Evans from British Geological Survey and all my colleagues. Their support has helped me to form the significant parts of this dissertation.

Dedicated to those who lost their todays for our tomorrows during protection of democracy on 15th of July in Turkey

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1. Introduction

1.1 Background

Volatility in oil prices, rises in global temperature, dangerous air pollution, increases in electricity demand and the list goes on, so many incidents are happening to keep the significance of renewable energy generation on the agenda. Renewable energy targets are set by countries and the market is developing gradually. Solar and wind power, which are the most popular renewable sources, are classified as non-dispatchable sources, because their generation is intermittent which means when the weather is windy wind turbines generate energy; when the wind blows slower than required speed, the wind turbines stop generating electricity; similarly if there is cloud in front of the sun, power outputs of solar panels decrease significantly. Therefore, variable renewable sources (VRE) bring about an important challenge for the renewable energy world.

As mentioned, power outputs of wind farms are related with how windy the weather is. Sometimes wind can be slower than the required speed, and on some other days the speed of the wind can be so high that the turbines shut down their operation automatically to protect themselves. In case of inadequate wind speed, forecasting errors, power station breakdowns or any other unexpected events which lower the power output of the wind farm, the balance of electricity grid is met by backup generation. Conversely, on windy days, when there is a high electricity supply from wind farms, some of the operators are asked to stop generating or reduce output to prevent any fault or impact in the transmission network. There is a cost involved here, which is met by National Grid in the UK. Figure 1-1: Payments made to wind powered generation in UKshows the National Grid's constraint payments made to wind farms to reduce their outputs since the 2010-2011 financial years[1] (National Grid, 2016).

[1] Financial year starts on 5th April each year

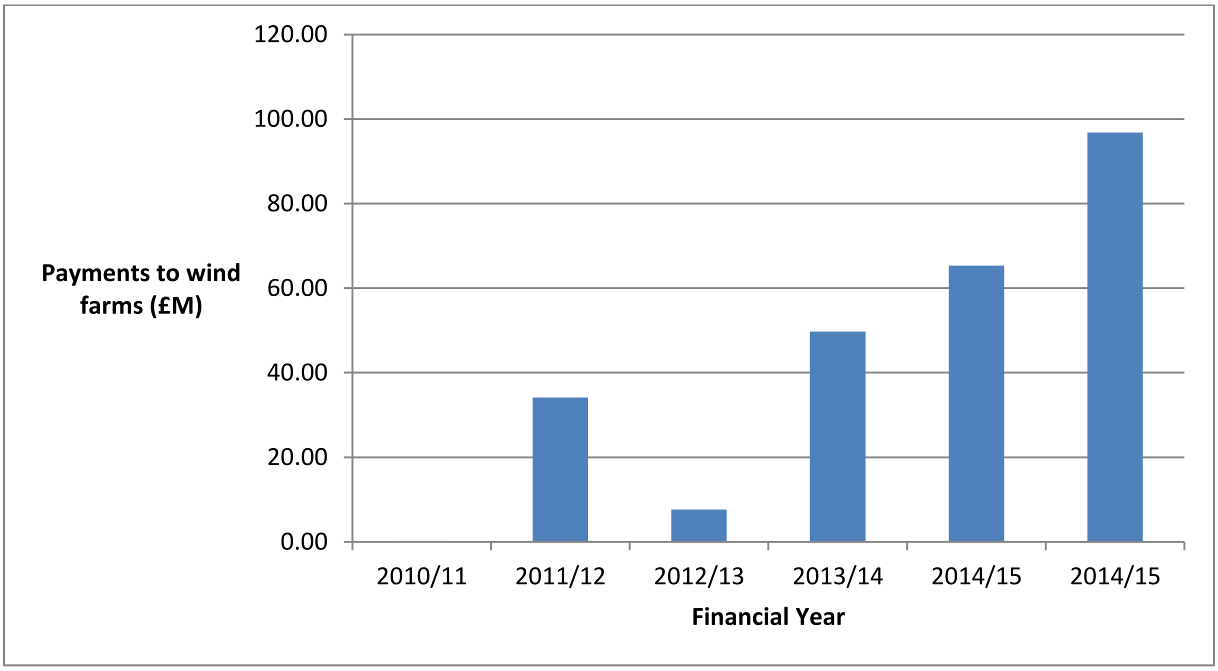


Figure 1-1: Payments made to wind powered generation in UK

As can be seen from the Figure 1-1: Payments made to wind powered generation in UK, there are considerable amount of payments made by National Grid to wind farm operators for reliable integration of wind farms output into the electricity grid. This process is one of the most significant and expensive operations that should be taken into account. If there are no new developments which help in balancing the grid, any increase in wind powered generation penetration into the grid will bring about greater costs of balancing mechanisms.

Utility Scale Electricity Storage Systems (ESSs) are possible options to utilize curtailed wind energy and decrease the related payments. Acceleration in VRE deployment and recent developments in electric vehicles boost the importance of storage systems. In this dissertation, effects of ESSs on utilizing curtailed wind energy will be investigated.

1.2 Project Objectives

- Analytical estimation of increase in demand, wind energy penetration and curtailment,
- Investigation of suitable types of utility scale storage systems for UK, and assessment of how much reserve capacity can be kept to utilize curtailed wind energy,
- To find out how electrical vehicles (EVs) can be effectively used to reduce the amount of curtailed wind energy,
- Based on variety of scenarios, to determine how far it is feasible to utilize curtailed wind energy with utility scale storage systems.

1.3 Project Scope

The project will focus on how to utilize the present and potential future curtailed wind energy and how to make wind power generation more reliable by the use of large scale storage systems. The dissertation will only focus on the UK national electricity grid and wind powered generation. Imports/exports of electricity and other electricity supply options will only be considered in software model.

Under variety of scenarios present and future wind powered generation and demand matching will be investigated. Cost analysis will be conducted to define how far it is possible to deploy ESSs. Finally, it is intended to present a range of feasible solutions which are acceptable in terms of utility, cost and physical possibility.

1.4 Methods

As a first step a literature review is undertaken to assess wind power characteristics in the UK and the curtailed wind energy in the UK is investigated. The second step includes a literature review of ESSs and the concept of electric vehicles. Third step consists of a software model based on the energy profile of UK in 2015, which will be used to estimate how much storage is required to utilize the present amount of curtailed wind energy and to supply reliable energy from wind powered generation. As a last step, different scenarios are investigated to observe the limits and possible storage requirements in future of wind powered generation in UK.

2. Literature Review

In order to achieve 2020 renewable energy targets, the renewable energy market in UK is expanding gradually. The leading actor of the UK's renewable market is wind power by far. UK is considered as the best location for wind power in Europe. However, it is ranked as 3rd in Europe and 6th in the World for cumulative installed capacity (DECC, 2011). In this part, forecasts for wind capacity and wind generation growth, projection of countrywide demand and comments on curtailed wind energy over UK wind farms will be conducted.

2.1 UK Wind Profile

2.1.1 UK Wind Capacity

Current data for wind power capacity in UK are as seen below (RenewableUK, 2016),

- Total UK Wind Power Capacity = **14,191 MW**
  - ❖ Onshore Wind Power Capacity = 9,073 MW – The total installed capacity of onshore wind farm (DECC,2016)
  - ❖ Offshore Wind Power Capacity = 5,118 MW – The total installed capacity of offshore wind farm (DECC,2016)
- Total under construction capacity = **3,577 MW**
- Consented Wind Projects' Total Capacity = **17,680 MW**
- Wind Projects in Planning Total Capacity = 8,590 MW
  - ❖ Total approved capacity = 21,257 MW
  - ❖ Total refused capacity = 11,129 MW

$$\frac{Total\ refused\ capacity}{Total\ refused\ capacity + Total\ approved\ capacity} = 0.34$$

  - ❖ So it can be estimated that in future 66% of "Planning Total Capacity" will be installed. After this calculation,
  - ❖ Amount of capacity which will be installed out of "Planning Total Capacity" = 8,590.535*0.66 = **5,670 MW**

According to data given above, Figure 2-1 shows the forecasted installed capacity in UK (MW),

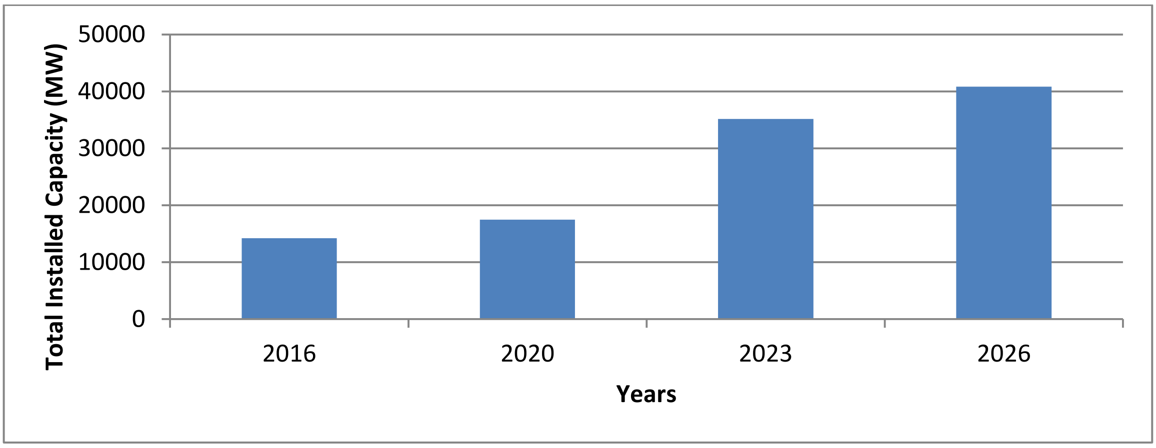


Figure 2-1: Forecasted installed capacity in UK

2.1.2 UK Average Wind Generation

Estimation for Energy Produced is made by RenewableUK which gives the result of 34,586,456 MWh (RenewableUK, 2016). However, the given value has been calculated by multiplication of the installed power capacity and the number of hours in a year. Then the installed capacity is multiplied by long-term average capacity factor for (onshore + offshore) wind (28.42%) which is defined by DECC.

The load factor can be defined as the actual annual power output of a turbine divided by its theoretical maximum output, so if a wind turbine's annual energy production is 10MWh, but when the capacity of the turbine is multiplied with total hours in a year equal to 40MWh, the load factor of the turbine would be 25%. While RenewableUK calculated the load factor, they took the average load factor values of the past five years using data provided by Digest of UK Energy Statistics (DUKES). The load factors calculated by RenewableUK are as follows;

- Onshore wind - 25.74%
- Offshore wind- 34.88%
- Average load factor for all wind (onshore + offshore) - 28.42%

However, the real values for 2015 wind energy data are as seen in below (DECC, 2016),

- UK Energy Produced from wind power in 2015 is 40.4 TWh
    - Offshore wind 17.4 TWh
    - Onshore wind 23.0 TWh
    - Load Factors

2015	Q1	Q2	Q3	Q4	Average
Onshore	38.7%	25.0%	19.6%	36.7%	30.0%

Offshore	46.7%	33.4%	30.4%	50.9%	40.35%

Table 2-1: Load Factors of Onshore and Offshore Wind Turbines in UK, 2015

- Average load factor for all wind (onshore + offshore) - **35.89%**

By taking the real load factors in 2015, forecasted energy produced is as seen in Figure 2-2 below,

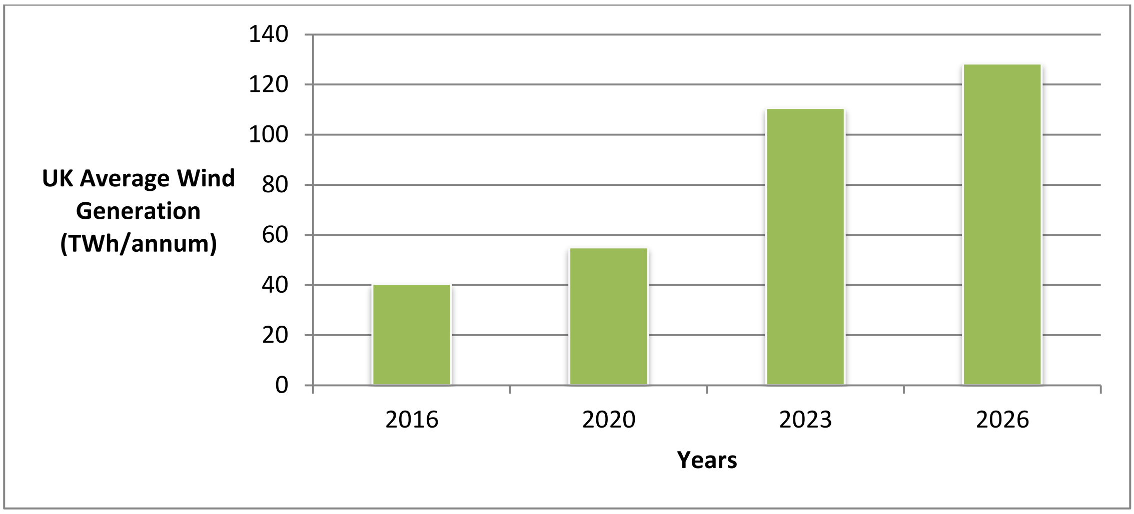


Figure 2-2: Forecasted average wing generation in UK

2.1.3 UK Wind Power-Demand Matching 2015

The grid data is recorded by National Grid, the data given in this part shows annual demand and wind penetration into the grid during the year 2015 (Gridwatch, 2016). Figure 2-3 shows the wind power and demand matching in UK throughout year 2015 and Table 2-2 shows some important data from the figure.

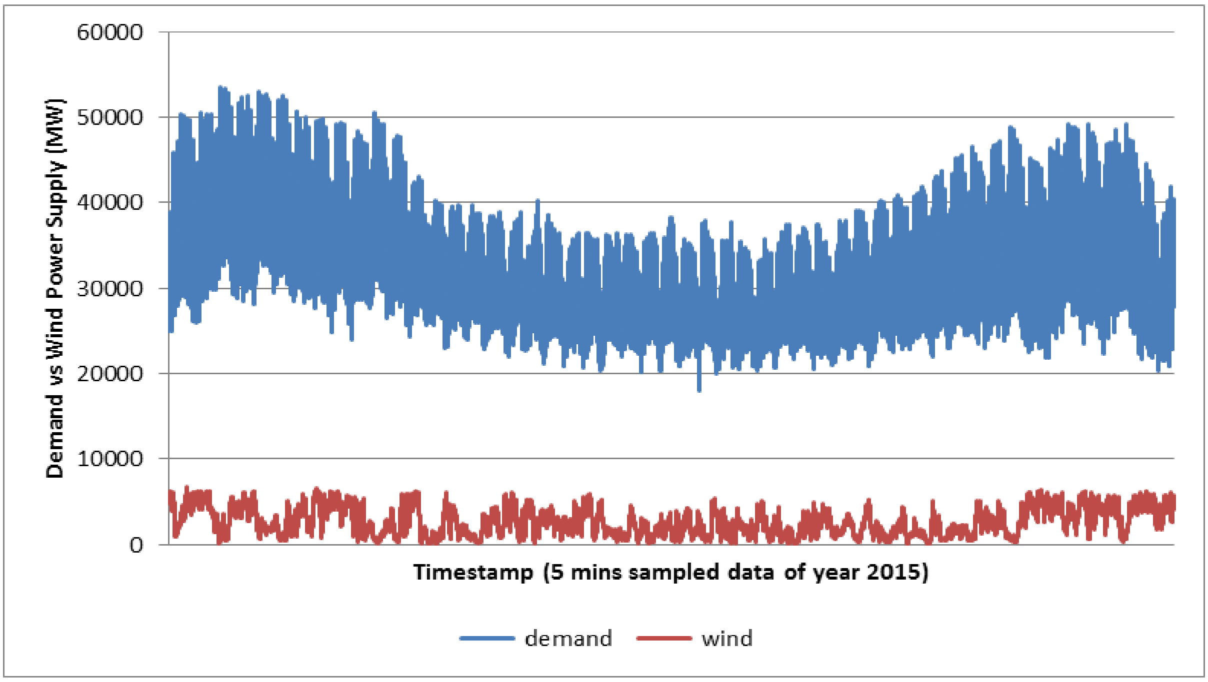


Figure 2-3: Demand and Wind Powered Generation matching of 2015

	Time Stamp (5mins Sampling)	Demand (MW)	Wind Supply (MW)
Max Demand	2015-01-19 17:30:07	53498	414
Max Wind Supply	2015-01-07 17:05:02	49702	6692
Min Demand	2015-07-12 04:45:02	18041	3369
Min Wind Supply	2015-04-08 01:50:02	27823	65
Average Demand	-	33104,0619	-
Average Supply	-	-	2670,21864
Wind / Demand Ratio	8,088%	-	-

Table 2-2: Facts about Wind Power-Demand Matching 2015, UK

As can be seen from the important figures, average wind power supply corresponds to **8%** of the average demand of UK. However, when minimum demand and max supply are considered together, it can be seen that a surplus wind power generation is possible when other non-dispatchable sources (nuclear, solar etc.) are considered. In such cases, wind farm operators are asked to reduce power generation, which gives rise to what is called curtailed wind energy. To compensate their loss, national grid makes payment to the wind operators.

2.1.4 UK Wind Power-Demand Matching Forecast

In order to forecast the future Wind Power-Demand Matching situation, the proper forecast of UK Demand plays vital role. As one of the “Future of Energy” documents, National Grid put different scenarios for future of electricity demand and transmission network in the latest “Electricity Ten Year Statement” (ETYS).

In this part of the dissertation, five different demand scenarios are taken into account. Four of them are defined by ETYS and other one (Balci's forecast) is defined by the author. The value for demand is shown at its peak day level, because peak day demand is critical for the systems' reinforcement analysis. Thus, for 2015 the demand value on the figure is 53.49GW.

The Grid Code defines National Demand as,

"The amount of electricity supplied from the transmission system plus that supplied by embedded large power stations, transmission losses, minus the demand taken by station transformers and pumped storage units. It does not include any Exports." (ETYS,2015)

Also, the definitions of scenarios (ETYS, 2015) are as seen in Table 2-3,

	Consumer Power	Gone Green	No Progression	Slow Progression	Balci's Forecast
Economic	Moderate growth	Moderate growth	Slower growth	Slower growth	Moderate growth
Political	Focus on indigenous security of supply and carbon reduction.	European harmonisation and long-term environmental energy policy certainty.	Inconsistent political statements and a lack of focus on environmental energy policies.	European harmonisation, focus on low cost environmental energy policies.	European harmonisation and long-term environmental energy and storage systems policy certainty.
Technological	High innovation focused on market and consumer needs. High levels of local generation and mixture of supply options.	Renewable and low carbon generation is high. Increased focus on green innovation.	Little innovation occurs in the energy sector with gas as the preferred choice for generation over low carbon.	Medium levels of innovation lead to a focus on a mixture of renewable and low carbon technologies.	Renewable and low carbon generation is high. EV penetration into market is growing. Increased focus on green innovation including smart grid and storage systems.
Social	Consumerism and quality of life drives behaviour and desire for 'going green', not a conscious decision	Society actively engaged in 'going green'	Society is cost conscious and focused on the here and now	Society is engaged in 'going green' but choices are limited by cost	Society actively engaged in 'going green'
Environmental	Long-term UK carbon and renewable ambition becomes more relaxed	New policy intervention ensuring all carbon and renewable targets are achieved	Reduced low carbon policy support and limited new interventions	New policy interventions are constrained by affordability	New policy intervention ensuring all carbon and renewable targets are achieved

Table 2-3: Definitions of demand scenarios

In the light of given scenario definitions, the UK demand forecast up to 2026 is as seen in Figure 2-4 below,

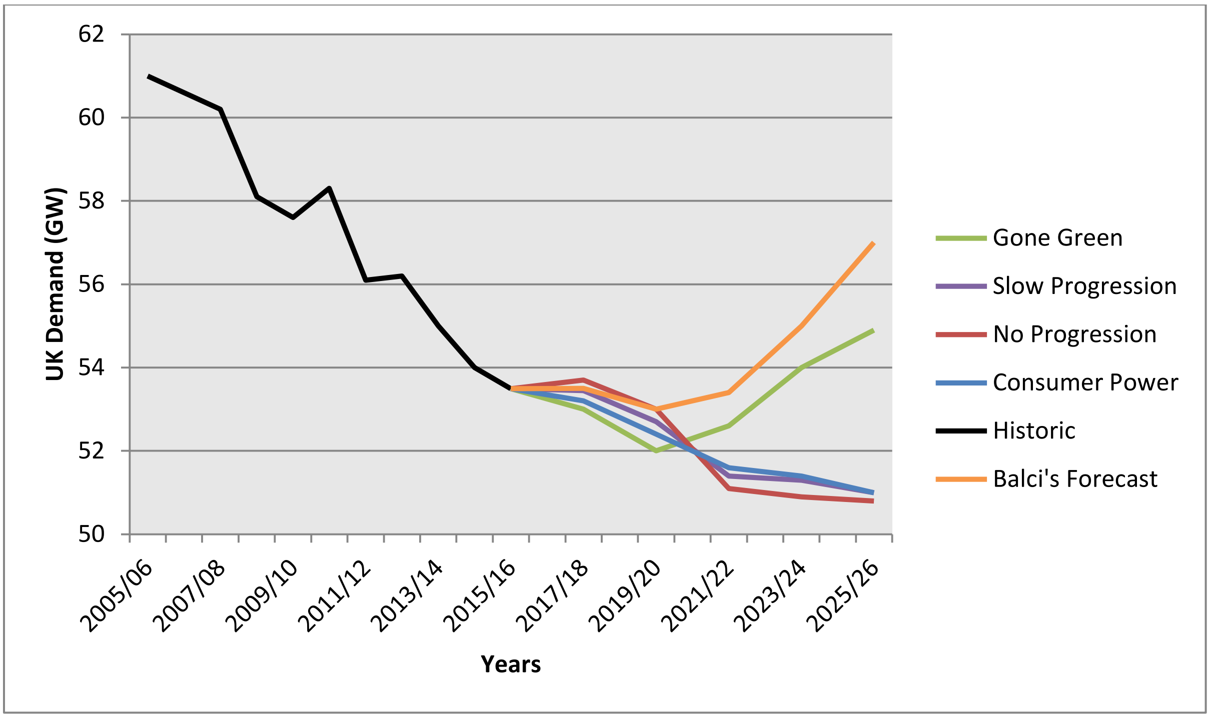


Figure 2-4: UK demand forecast for different scenarios

- **Gone Green:** Due to increase in energy efficiency and embedded generation demand falls in coming years. Then, the demand increases almost linearly towards 2025. This stems from the government policies resulting in decarbonised heat usage in residential and commercial sectors.
- **Slow Progression:** Decrease in demand is around 0.5% a year. This is caused by increasing levels of embedded generation, lower economic growth and lower increase in energy efficiency. Heat is decarbonised slowly, government misses the targets.
- **No Progression:** Decrease in demand due to energy-efficiency measures and embedded generation. It is expected to see an increase in demand after 2026 due to growth in population.
- **Consumer Power:** Similar profile to Slow Progression but for different reasons. Residential demand is high where embedded generation is the highest. Low gas prices encourage fuel switching and small scale CHP units are popular.
- **Balci's Forecast:** Similar profile to Gone Green scenario. Additionally, demand is higher due to increase in penetration of electric vehicles. Government policies related with large scale storage systems increase the electrification of heat, which causes the faster switch to decarbonised heat usage in residential and commercial sectors.

After defining demand forecast, the forecast of wind power penetration will be defined. In Figure 2-1, installed wind capacity forecast is shown, also in Part 2.1.2, typical load factors are argued. By taking average load factor as 30%, the wind power generation and demand matching is generated as seen in Figure 2-5.

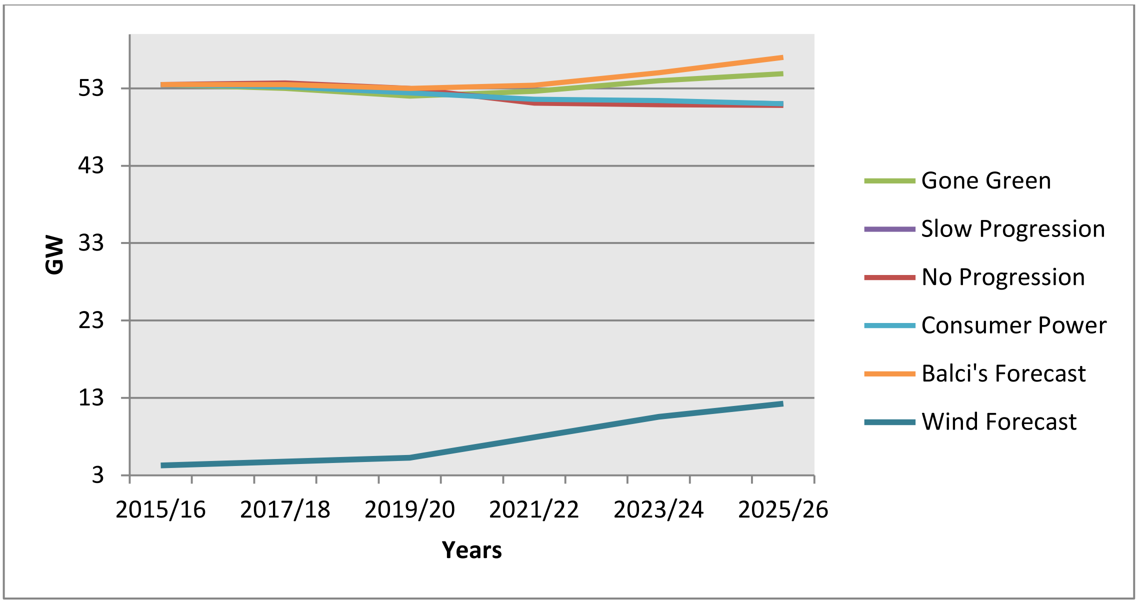


Figure 2-5: UK wind generation-demand matching forecast with different scenarios

Figure 2-6 shows the forecast of wind power generation and demand ratio,

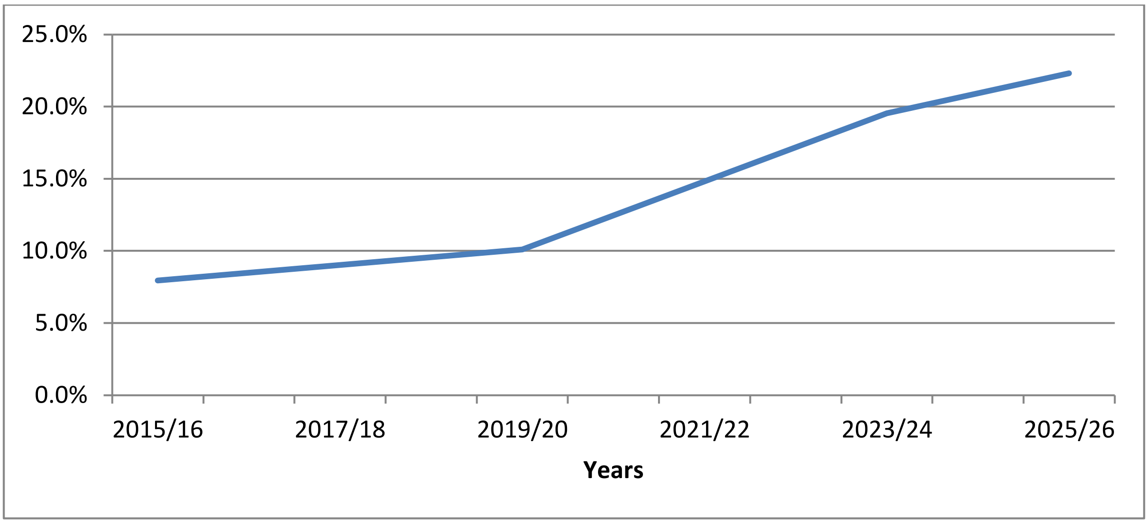


Figure 2-6: UK wind generation-demand ratio forecast

As can be seen from Figure 2-6 there is an obvious increase in wind supply to meet demand. It is forecasted that wind power generation will meet **10.1%** of demand in 2019/20, **19.5%** in 2023/24 and **22.3%** in 2025/26.[2]

2.1.5 UK Curtailed Wind Energy

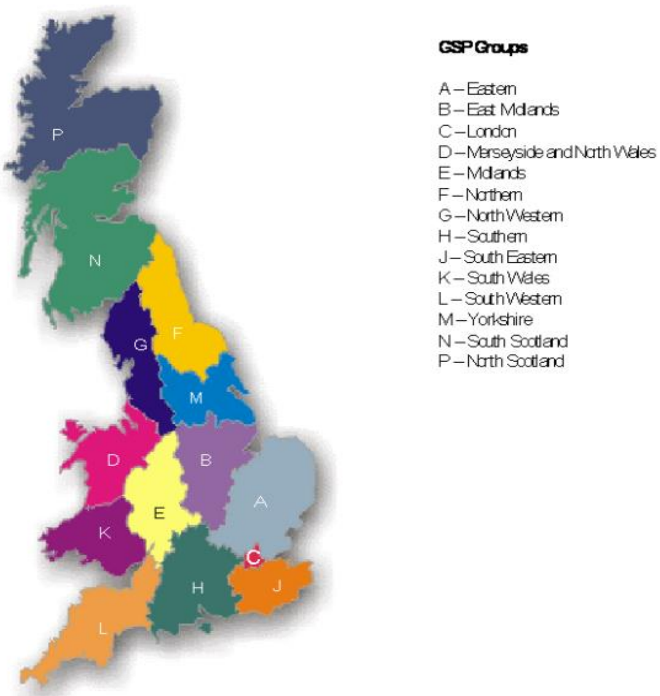
Curtailment of energy generation is generally observed in intermittent renewable sources like wind, solar and wave. Solar energy tends to form 'embedded generation' at local level and is well integrated into the distribution network. Wind is by far the most extensive new large-scale renewable energy resource in UK, for this reason only wind curtailment is examined. In this dissertation, wind curtailment is defined as involuntary reduction in the output of the wind farm from what it could produce in normal conditions.

Grid operators command wind generators to reduce their outputs for two main reasons; first to minimize transmission congestion and secondly to prevent penetration of oversupply into the grid. Transmission congestion generally occurs with wind farms that are located far from cities or towns. For those places generally transmission lines are weak, because the small local population required only comparatively weak transmission lines to be installed before the construction of wind farm. Thus, during the times of full capacity generations from the wind farm, they may be asked to reduce their output to prevent overload and any damage to the transmission system. In the other case, when the demand is low or base load generators' minimum generation thresholds are enough to cover demand, wind farms are asked to reduce their output to prevent oversupply because of frequency or voltage balance or interconnection issues. The oversupply curtailment generally occurs during night time when there is a substantial amount of wind resource available, but the demand is considerably lower than in daytime. Apart from these main curtailment reasons, there may be curtailments demanded due to environmental reasons such as birds and bats in migration, unusual meteorological conditions, etc. However, only the two main reasons for wind energy curtailment are taken into account in this study.

In order to understand curtailed wind energy in UK, as a first step 'Transmission and Distribution' system should be studied. The main duty of the transmission system in UK is to deliver generated electricity from large generation systems to the distribution networks.

[2] Gone Green demand scenario was taken as reference demand profile for ratio forecast, however when other demand scenarios are taken into consideration, ±1% of difference is observed for year 2026 and smaller for previous years

Transmission and distribution systems are connected at a point which is known as a 'Grid Supply Point' (GSP), so each distribution system is known as a GSP group. GSP groups and their distribution over regions is as shown in Map 2-1. Smaller power sources such as combined heat and power, solar power and some wind turbines (approximately one third of the total installed capacity) are connected to the Distribution Network, in other words the low voltage network. Roughly two thirds of the total installed wind capacity in UK consists of large wind farms and these are connected to the Transmission Network, i.e. the high voltage network. Nuclear, gas and coal fired power stations are other participants in the Transmission Network (Elexon, 2015). Transmission Network participants are members of a trading system of National Grid which is known as the 'Balancing Mechanism' (BM).



Map 2-1: GSP Groups over UK[3]

Curtailment of wind generation is arranged by the BM. As wind energy generation increases, curtailment is becoming more widespread. Curtailment affects the energy output of the wind farm therefore it affects the revenue and related financial liabilities of the wind farm. To compensate wind farms for losses caused by curtailment, National Grid makes payments to the wind farms. These payments are known as 'Constrained Payments'. National Grid have made constrained payments to the wind farms since 2010. Before that time, gas and coal

[3] Available from: https://www.mrasco.com/admin/documents/PPMIP%20by%20Supply%20Services%20Area%20%20Device%20Type%20v2%201.pdf

power stations might be called for output reduction. Renewable Energy Foundation (REF) records data from the BM which includes wind farm constraint payments and volume of constrained wind generation from 2010 to date. The data is sourced variously from Renewables Obligation Certificates, Renewable Energy Guarantees of Origin and in the case of some municipal waste generation, from Climate Change Levy Exemption Certificates (REF, 2015).

Table 2-4 shows the annual data of curtailed wind energy,

	Cost	Volume of Curtailed Wind Generation (MWh)	Average Price[4]
2011[5]	£12,826,756	58,708	£218
2012	£5,924,231	45,463	£130
2013	£32,707,351	379,817	£86
2014	£53,175,234	658,611	£81
2015	£90,494,271	1,274,165	£71

Table 2-4: Annual data of curtailed wind energy (REF,2015)

Figure 2-7 shows the volume of annual curtailed wind generation,

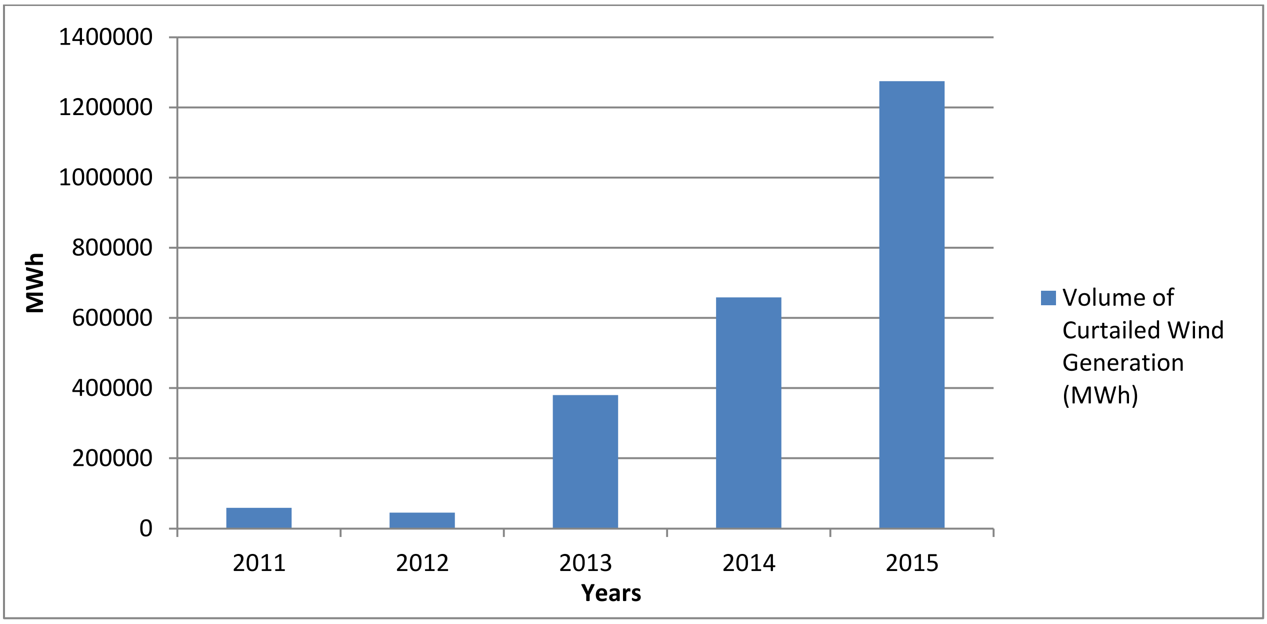


Figure 2-7: Volume of curtailed wind generation

Note that given constraint volumes and constraint payments only include the trades carried out as a part of the BM. There might be further constraints that are based on private contracts between National Grid and the generator which are not published or available to the public. As can be seen from Figure 2-7, the amount of curtailed wind generation has increased with

[4] Due to aggregation of data and rounding of calculated results there may be small apparent inconsistencies
[5] There are missing data (Months of Jan, Feb and Mar) for 2011

the increase in installed capacity. Table 2-5 shows the comparison of total produced wind energy and the volume of curtailed wind generation.

	Total Produced Wind Energy (GWh)	Volume of Curtailed Wind Energy (GWh)	Curtailment Ratio (%)
2011	15,816	59	0.4%
2012	19,519	45	0.2%
2013	28,124	380	1.4%
2014	31,535	659	2.1%
2015[6]	36,153	1,274	3.5%

Table 2-5: Comparison of produced vs curtailed wind energy

The ratio of volume of curtailed wind generation and produced wind energy varies over the years. Figure 2-8 shows the change in ratio of produced vs curtailed wind energy according to years.

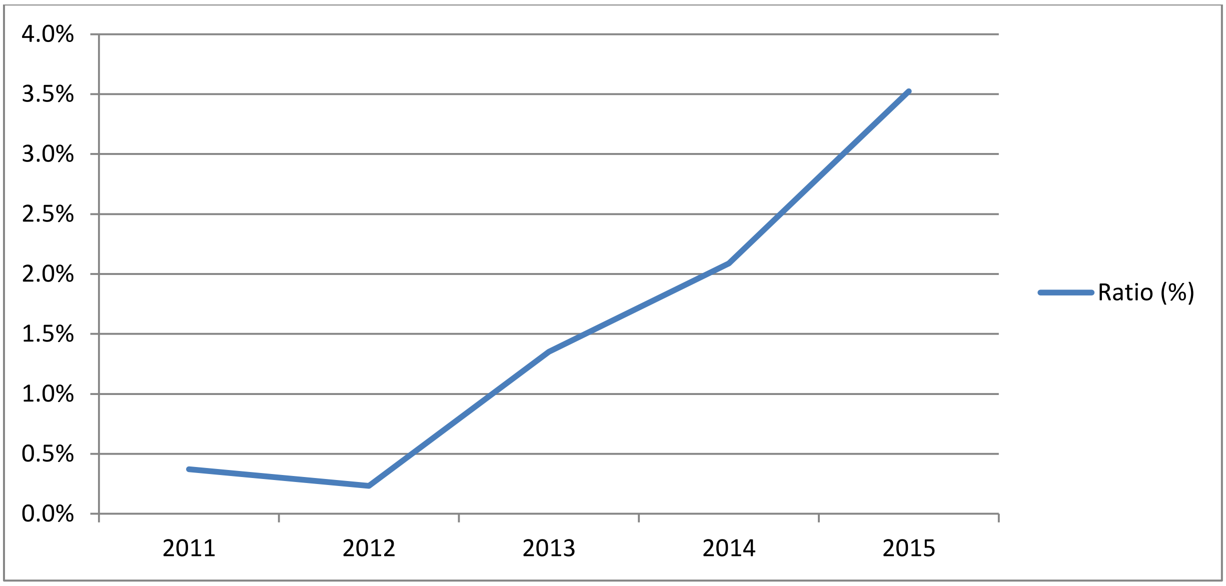
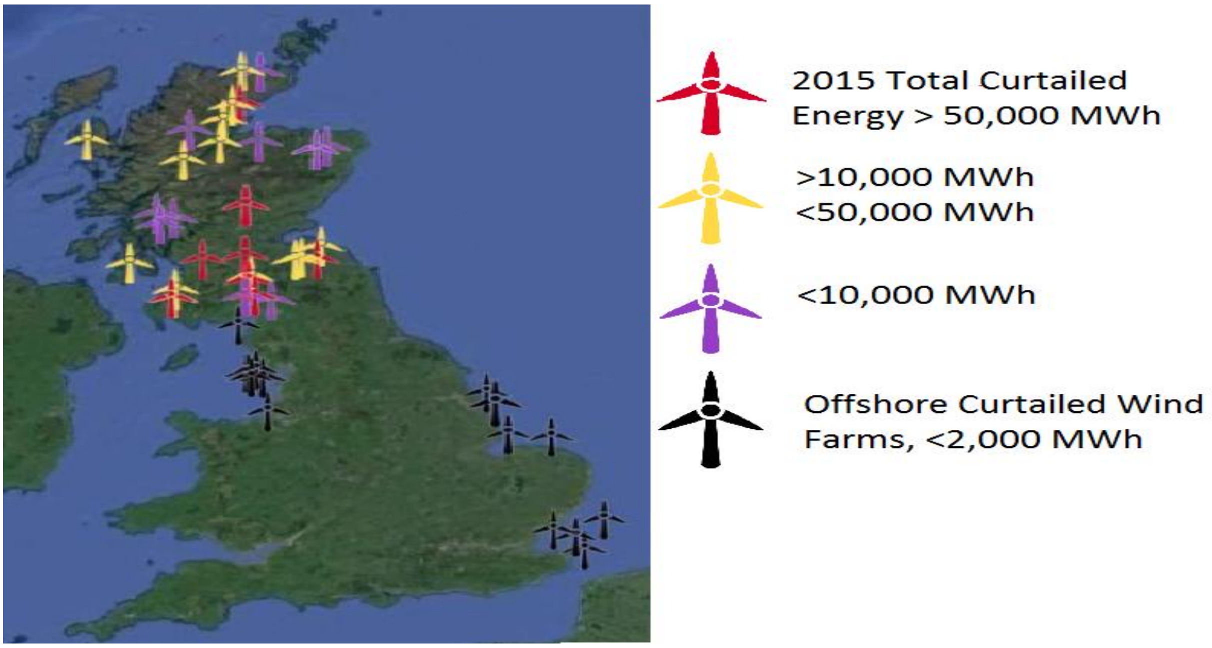


Figure 2-8: Ratio of Produced vs Curtailed wind energy

Figure 2-8 shows that the increase in wind energy penetration into the grid resulted in an increase in curtailed wind energy. The main point is that curtailed wind energy increases faster than the increase in capacity of generation, so it is seen as the increase in ratio. Future estimation of curtailment ratio is a challenging task, because supply and demand are two dynamic parameters which are also the main drivers of the curtailment. However, it is

[6] The result seen here is different from the one in Part 2.1.1, the reason is sources are using different resources while they are collecting data. Since it is published by DECC the most accurate result is the one in Part 2.1.1, however REF uses a wide range of sources which can be regarded as safe. The most noticeable part in this case is the ratio of Curtailed Wind Energy – Total Produced Wind Energy.

possible to make reasonable comments on the likely behaviour of the curtailment ratio in future. Map 2-2[7] shows the locations of the wind farms with curtailment,



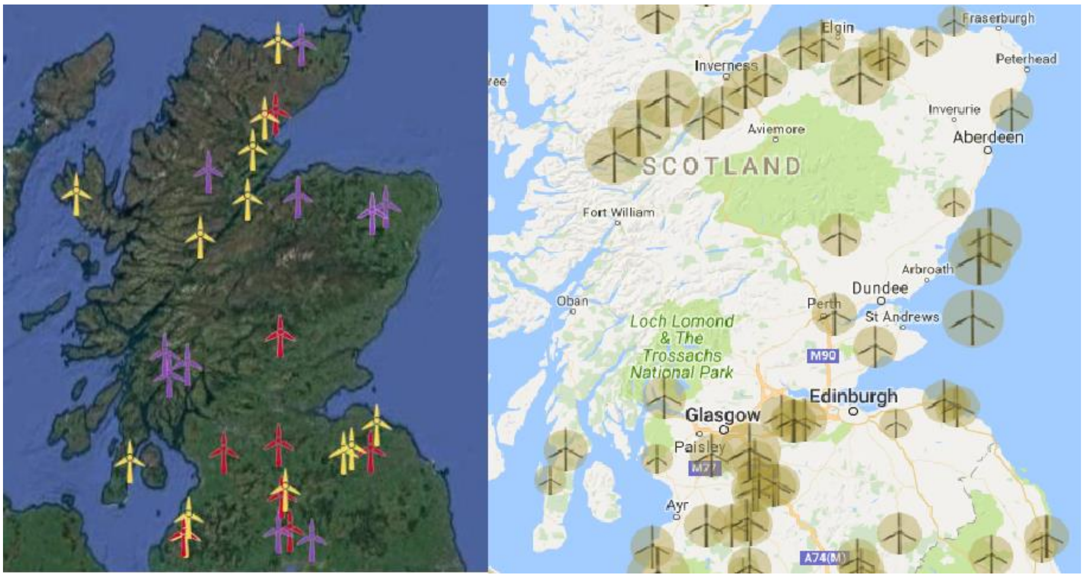
Map 2-2: Curtailed Wind Farms over UK - 2015

As can be seen from the Map 2-2, all the curtailed onshore wind farms are located in Scotland. Curtailed offshore wind farms are close to Eastern, East Midlands and Yorkshire GSPs, and in the west curtailed offshore wind farms are close to North Western and Merseyside and North Wales GSPs. The curtailment of each offshore wind farms are below 2,000MWh which are much lower in comparison with curtailment of onshore wind farms, therefore attention will be paid on curtailment of onshore wind farms. The main reason for the existence of curtailment over Scotland is that the grid interconnections between Scotland and England are insufficient to take the excess generated electricity. Although there is high wind potential, probably the highest in Europe, over Scotland, the demand is quite low. Thus, as noted above, during times of minimum demand the thresholds of base load generators are enough to cover demand and Scottish wind farms are asked to reduce their outputs, which results in curtailment. Some of the red labelled wind farms are located close to large centres of population and strong grid networks, so their heavy curtailment is surprising. The presence of substantial nuclear generation capacity in the region is perhaps the most significant factor.

To have an idea about how the curtailment might behave in future, wind farms which are under construction should be examined. In Map 2-3 the map on the left shows curtailed

[7] Due to commercial confidentiality the names of the wind farms and the exact amounts of curtailment can not be published in this study.

onshore wind farms over Scotland and the right-hand map[8] shows wind farms under construction.



Map 2-3: Curtailed Wind Farms and Wind Farms under construction over Scotland

As seen from Map2.3 there are considerable amount of wind farms under construction in similar locations to presently curtailed wind farms. Unless major changes are made to the way the network is managed, a significant increase in future curtailment of wind power seems likely.

How wind farms are distributed over the UK is an important criterion when looking at the planned increase in the capacity of wind farms over Scotland. According to 2014 data the distribution of onshore wind turbines are as seen in Table 2-6 below (The Guardian, 2014),

Region	Operational Turbines	Under Construction	Approved
East Midland	183	85	78
East of England	141	25	64
London	6	1	0
Mid Wales	389	0	63
North East	173	12	52
North Wales	100	0	42
North West	219	14	83
Northern Ireland	364	16	470
Scotland	2303	424	1144
South East	43	0	14
South Wales	98	94	64
South West	125	32	82
West Midlands	0	0	15
Yorkshire & Humber	194	43	88

Table 2-6: Onshore Turbines in UK (2014)

8 Capture of second map is taken from http://www.renewables-map.co.uk/

When the share of Scotland is calculated from the table above, its operational onshore wind turbines amount to 53.08% of the total; the share of under construction wind turbines in Scotland is 53.63% and the share of approved wind turbines in Scotland is 52.71%. Therefore when the distribution of onshore wind turbines over the UK is considered the share of Scotland can be assumed as about **53%**.

As forecasted in the previous part, it is expected that UK will have approximately 35GW of wind farm capacity by 2023, so according to assumptions made above, the wind farm capacity will be around 18GW over Scotland while it was around 6GW in 2015. Thus, the total capacity is expected to be tripled in coming years. If there will not be any significant grid expansion done, which requires significant working time and investment, the curtailment ratio is likely to keep increasing. Based on an assumption of linear growth, the curtailment ratio forecast is as seen in Figure 2-9 below.

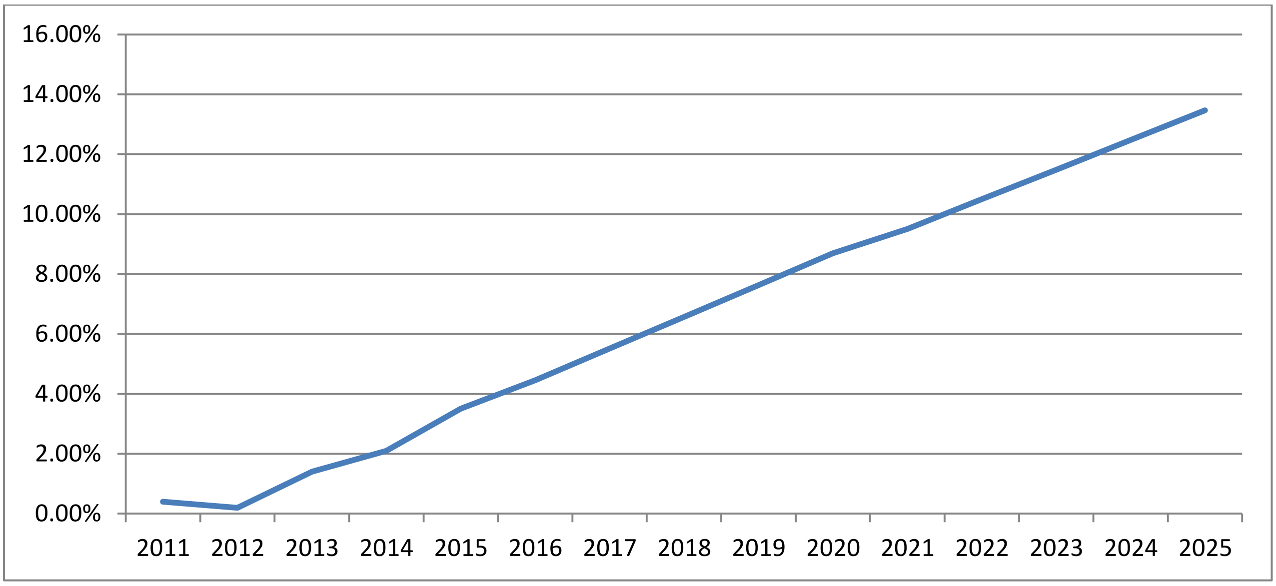


Figure 2-9: Curtailment Ratio Forecast according to gradual growing assumption

According to this forecast, the wind energy curtailment ratio will be 8.69% in year 2020 and it will reach 13.47% in the year 2025. If required precautions are not taken as soon as possible, there will be a huge loss of energy and related costs over the next decade. The mitigation of this problem is an immediate concern, and in this study a potential solution with the use of large scale storage systems and EV batteries will be investigated.

2.2 Utility Scale Storage Systems

In the road towards 100% renewable energy supply, intermittent sources play a vital role. However, intermittency brings about crucial problems for supply demand matching and the development of utility scale energy storage systems is an essential requirement for a successful future integrated energy supply system. The term of "Utility scale energy storage systems" stands for large capacity storage systems which can balance the grid in case of mismatching in supply and demand. Along with providing a secured energy supply, storage facilities may contribute to overall efficiency, transmission optimization, power quality and black-start functions. Also, given present energy market conditions in the UK, storage facilities might be regarded as a monetary resource derived by utility companies from arbitrage.

Currently, storage capacity on the electricity grid is mostly used to accumulate the energy production of less responsive and large capacity thermal power plants like nuclear and CCGT. ESSs on the grid store the generated electricity from thermal power plants at the times of low demand and re-dispatch it at times of peak demand (Barnes, 2008). It is obvious that such utility scale storage systems could be also used for intermittent renewable sources, so when there is generation and not enough demand the electricity will be stored and inversely when there is peak demand but not generation, the stored electricity will be dispatched to meet the demand. So with sufficient storage capacity, the reliability problem of intermittent sources could be overcome and also curtailment might be prevented. By the steady increase in storage capacity, the grid will evolve into something more suitable for future needs.

Obviously storage capacity on the grid is not enough at present for meeting peak demand at times of mismatch, so additional approaches are currently used, such as bringing gas-fired generators online. In the near future, other measures such as demand management using smart grids and differential pricing are likely to become more widespread. However, as intermittent renewable penetration increases over time, the importance of energy storage systems and the complimentary services that they can provide will become more prominent. These complementary services can be regarded as follows (AECOM, 2015),

- During periods of high value, ESSs have the ability to time-shift energy generation

- During the periods of network stress, they have a positive impact on network congestion
- ESSs increase grid capacity, so they allow penetration of renewable generators into existing infrastructure
- ESSs give the possibility of smoothing ramp rates
- They permit the deferral of network upgrade cost
- If there is enough storage available in the system, there is no need to reduce power output from generators, so ESSs allow generators to operate at high efficiencies

When considering all the benefits of utility scale storage systems the energy sector might get huge benefit from their expansion. In the following parts, different ESSs will be examined in terms of technology, cost and availability for UK.

2.2.1 Mechanical Energy Storage

Mechanical energy storage systems consist of the most mature technologies for utility scale storage systems. Pumped Hydro (PHS), Compressed Air Energy Storage (CAES) and Flywheels are the most well-known mechanical energy storage systems. In addition to these mature technologies, there are promising innovations like Liquid Air Energy Storage (LAES) which might be considered as the part of mechanical energy storage systems.

Pumped Hydro Storage (PHS)

PHS is the most mature technology for the utility scale storage market. Currently, it accounts for 99% of bulk storage capacity with 127,000MW across about 200 sites. (ESC, 2015)

Technology: PHS stores energy as potential of water with overall **efficiency up to 80-85%** (HEA, 2015). Basically during the times of low demand PHS takes electricity from the grid and pumps water from a lower reservoir to an upper reservoir and stores it to dispatch at times of peak demand (Figure 2-10). PHS uses turbines with the same concept as hydroelectric power stations, the most important technical distinction between PHS and hydroelectric power stations being limitation on the turbine type. Reaction turbines must be used in PHS, because they have the ability to work in reverse, and so function as pumps. So during high demands a reaction turbine works to turn a generator and during low demands the turbine works as pump. Impulse turbines, which are quite commonly used in hydro-electric systems, are unable to act as pumps when driven by a motor. The most well-known reaction turbines are Francis and Kaplan machines.

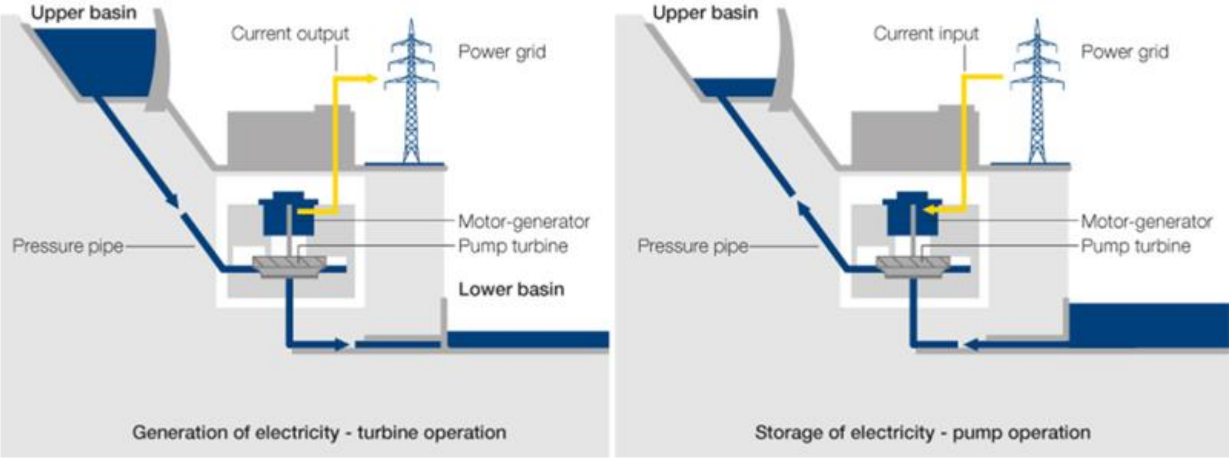


Figure 2-10: Schematic of PHS System (HEA, 2015)

Applicability to Utility Scale: PHS allows large scale storage of energy. The capacity of the storage is related directly to the size of the reservoir and its height above the lower reservoir or discharge point. As PHS is the dominant utility scale storage system in the world, so also in UK pumped hydro storage capacity accounts for 99.8% of all operational large scale storage systems[9]. Table 2.7 shows the existing pumped hydro storage systems in the UK (DOE, 2016).

Station	Rated Power (MW)	Duration at rated Power (HH:MM)	Status	Location	Energy Capacity (GWh)
Foyers Pumped Storage Power Station	300	21:00	Operational	Lochness, Scotland	6.3
Cruachan Power Station	440	22:00	Operational	Lochawe , Dalmally	9.68
Dinorwig Power Station	1728	05:00	Operational	Dinorwig , Wales	8.64
Ffestiniog Pumped Hydro Power Plant	360	06:00	Operational	Ffestiniog , Gwynedd	2.16

Table 2-7: Existing Pumped Hydro Storage in UK

Although PHS is the most available and mature technology for utility scale storage systems, the biggest challenge against the further deployment of PHS is that it requires special topography and large areas for reservoirs. Thus, PHS is not suitable for distributed generation and also it is a challenge to find suitable new sites.

[9] The list of large scale storage systems in UK is given in the Appenix A

However, it is important to point out a critical required topography distinction between PHS and hydro power stations. It is a bigger challenge to find suitable topography for hydro power stations, because it requires a height difference combined with a steady water supply (from gathered rainfall) to the upper reservoir; but for PHS there is no need to capture rain water, so the upper reservoir can be located in any region where a large volume may be held at high level. Once filled with water it can remain for a long time, especially for places with low amount of evaporation loss. Therefore, it is possible to find plenty of spaces to construct PHS systems in UK, although these will inevitably be in relatively mountainous regions.

Cost: Since it requires special topography, prices for PHS are highly project specific. Two types of costs will be taken into account, which are Capital Cost and Levelised Cost of Storage (LCOS). According to a research conducted by Lazard[10] **capital cost** of PHS in terms of energy varies between **213-313 $/kWh**[11] (Lazard, 2015) and according to IRENA report in 2014, **capital cost** of PHS in terms of power varies between **105-400 $/kW** (IRENA, 2014). According to IRENA report of 2012 **LCOS** of PHS varies between **0.05-0.15 $/kWh**[12] (IRENA, 2012) and Lazard states **LCOS** of PHS as varying between **0.188-0.274 $/kWh** (Lazard, 2015). Since the technology of PHS achieved its maturity before reference years, expectation for further cost reduction would not be so realistic. For future scenarios, **capital cost** of PHS will be taken as **210-310 $/kWh** and **LCOS** of PHS will be taken as **0.15-0.275 $/kWh.**

Compressed Air Energy Storage (CAES)

CAES is another moderately low cost, technically mature large scale storage technology with round trip efficiency between **70-89%** (CLCF, 2012). CAES emerged as a peak shaving option in 1970s, since then it is one of the most promising utility scale energy storage technologies suitable for long duration (Barnes, 2008).

Technology: CAES stores high-pressure air, then generates large quantities of energy from the stored air. As well as PHS, CAES is suitable for long duration utility scale storage system. CAES uses electricity during the times of low demand to compress and store the air in caverns or storage tanks. The system operates with similar methodology and uses similar cycles to gas turbines, although of course the compression and expansion occur at different

[10] https://www.lazard.com/
[11] Estimation is conducted for grid coupling applications
[12] Large applications (>200MW) are considered

times and independently (Figure 2-11). This is because, required electricity for compression is provided from different sources like the grid or coupled renewable generation during low demands, while during expansion the output of a gas turbine is used to generate electricity. In more conventional gas turbines, during the expansion stage, approximately two thirds of the output power runs the compressor (Barnes, 2008).

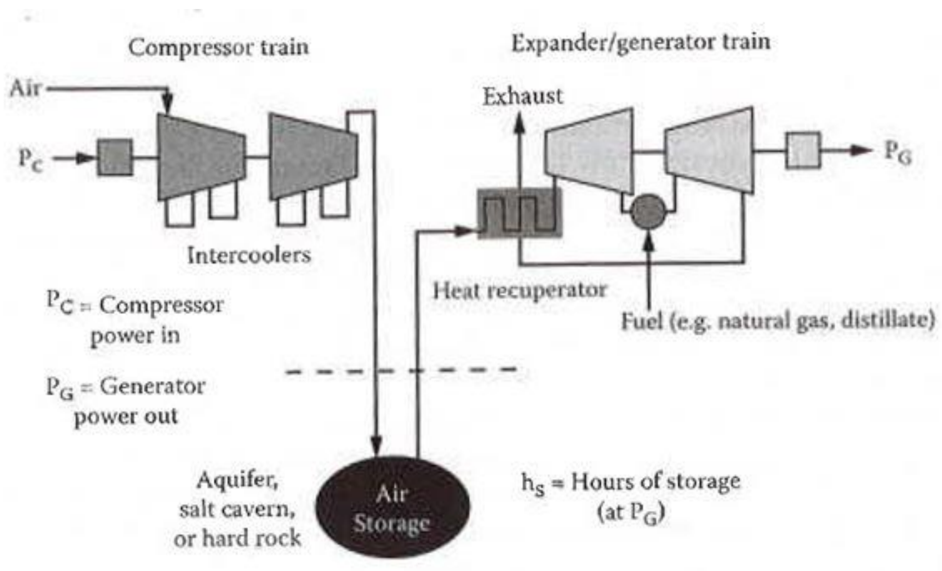


Figure 2-11: Schematic of CAES System (Barnes, 2008)

CAES can be applied to different types of geological structures. Potential structures are as follows (Plaat, 2004),

- Depleting oil/gas reservoirs
- Salt caverns
- Lined rock caverns
- Abandoned mines

Figure 2-12 shows the potential structures and typical durations for CAES scenarios. Figures in brackets represent the typical range in days for storage in that structure type,

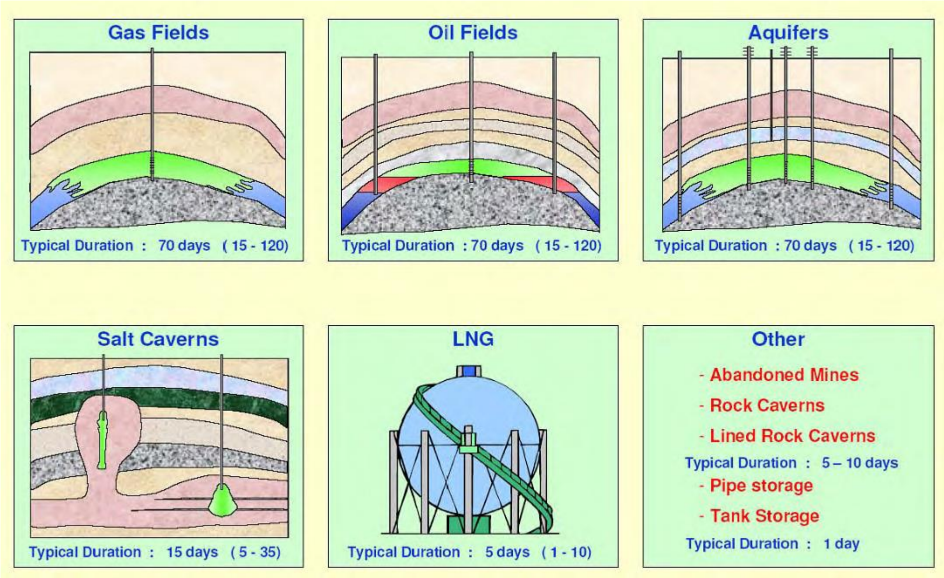
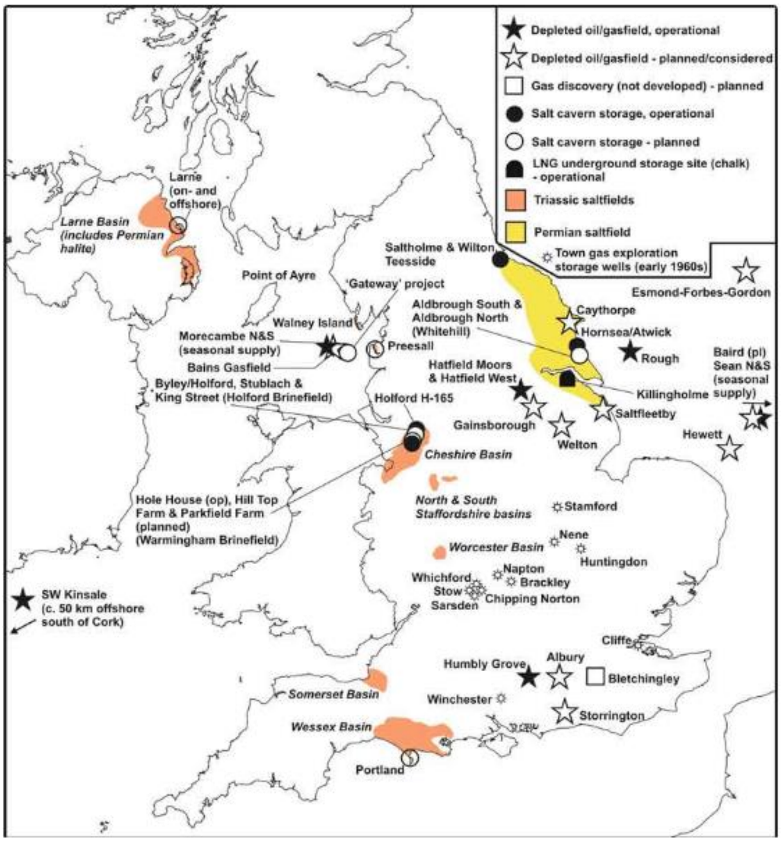


Figure 2-12: Potential CAES Structures (Plaat, 2004)

Applicability to Utility Scale: Although CAES is a mature technology for utility scale storage systems the technology has not been applied so widely in comparison with the PHS. Currently there is not an operational CAES in UK. However, the 330 MW Gaelectric Compressed Air Energy Storage has recently been announced. The project will be deployed in County Antrim, Northern Ireland and will be able to deliver power around 6 hours at rated power. The project will be the first deployed CAES system in the UK and $7.1M funding is allocated for the project (DOE, 2016).

On the other hand UK has considerable background in underground gas storage systems which have the similar logic and storing principles with CAES. There are seven operational underground gas storage facilities in the UK at Southern North Sea (offshore), East Yorkshire, Yorkshire, Weald, Cheshire. Map 2-4 shows the operational and proposed underground gas storage facilities in UK (BGS, 2015).



Map 2-4: Location map of the operational and proposed UGS facilities in the UK

As can be seen from the map there are various available locations for underground gas storage facilities in UK which also means there are various available places for CAES systems. Since CAES systems are currently not applied in the UK, the above map obviously shows that CAES systems can be possible strong future contenders to store electricity in UK. There are studies and experimental applications of CAES with artificial reservoirs, however they are unlikely to apply for large scale storage systems, therefore only CAES applications based on natural structures will be taken into account.

Cost: As well as PHS, CAES also requires special topography, thus prices for CAES are also project specific. According to IRENA report in 2012, **capital cost** of CAES varies between **0.80-9.00 $/W** and **LCOS** of CAES varies between **0.10-0.30 $/kWh** (IRENA, 2012). According to Center of Low Carbon Futures' LCOS of CAES varies between **2 to 120 $/kWh** (CLCF, 2012) and Lazard estimates the capital cost of CAES as **170$/kWh and LCOS of CAES as 0.192 $/kWh** (Lazard, 2015). There is considerable difference among the assumptions used, however IRENA assumed this price for large scale applications using ideal sites like natural underground caverns and applications which require ground in-vessel storage and CLCF assumed that price for more artificial and hard to build facilities and Lazard assumes costs for coupling transmission cases. All sources can be taken as reference for different case scenarios, however for future scenarios considered here, **capital cost** will be taken as **120-170$/kWh** and **LCOS** will be taken as **0.19-0.30 $/kWh**.

Flywheel Energy Storage System (FESS)

History of flywheel technology is a long one, with flywheels being used with rotating machinery from very early days. During the Industrial Revolution, James Watt used flywheel in steam engine (White, 1964). Today, flywheels might be used to store electrical energy for following functions (Molina, 2010),

- Standby Power Source
- Power Quality
- Load Levelling
- Peak Shaving
- Reactive Power Support
- Voltage Support

Technology: FESS stores electricity as rotational energy. FESS is charged and discharged through and integrated electrical machine which operates as a motor to accelerate the rotor, which is composed of high strength composite materials in an almost frictionless enclosure, or as a generator to produce power when it is required (Figure 2-13). Stored energy is released by slowing down the rotor and releasing a quick burst of energy. Energy is stored directly proportional with the mass of the flywheel, rotational speed and the radius of the disk by following formula,

$$E = 0{,}5 \times I \times \omega^2$$

Where,

'ω' is rotational speed

$I = k \times m \times r^2$; 'I' is moment of inertia, 'k' is internal constant, 'm' is mass of flywheel and 'r' is radius.

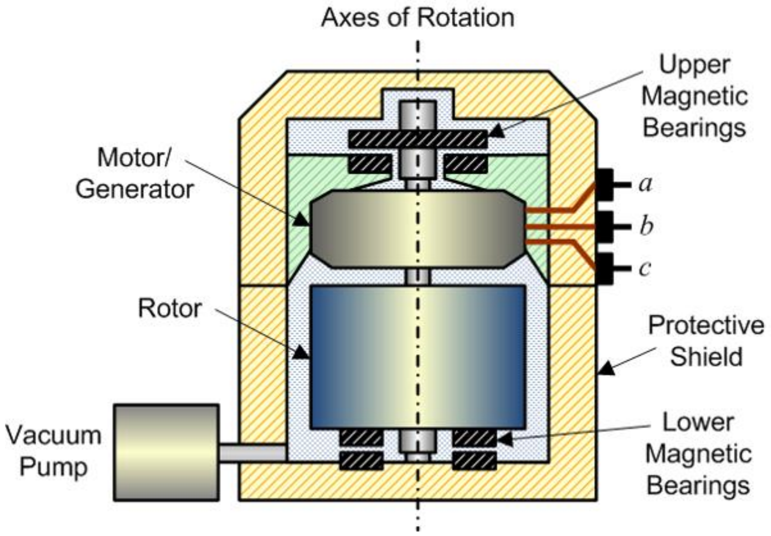


Figure 2-13: The structure of Flywheel model (Molina,2010)

Due to use of magnetic bearings which prevent contact of flywheel disk and stationary elements, FESS operates in an almost frictionless enclosure which brings about very low rotational losses. Also, since the system operates in vacuum, the rotor's aerodynamic resistance is greatly reduced. These features allow the system to reach efficiencies higher than 80% (Molina, 2010).

Applicability to Utility Scale: As big advantages over other types of storage technologies, FESS has the ability to rapid charge and discharge. Also, FESS requires little space in comparison with the other mechanical storage options. Maintenance requirement is lower than batteries, they are resistant to temperature fluctuations, and flywheels have a long life span which will not be shortened by hard use like a battery. Very compact units with high energy densities can be obtained by High-speed flywheels operating at 40000 rpm or more (Liu & Jiang, 2007).

Despite the given advantages, due to their low duration at rated power FESS is **not applicable as utility scale storage systems.** There is one operational large scale FESS deployed in Abingdon, Oxfordshire which has the capacity of 400MW with 50 seconds duration at rated power (See 104). Therefore it can be understood that, under today's circumstances, FESS cannot be used to complement a renewable supply source, but instead it can be used for peak shaving and similar functions given above.

Alternative Approaches to Mechanical Energy Storage Systems

Mechanical energy storage technologies can be regarded as perhaps the most promising types of storage technologies at present, in terms of utility scale storage systems. The technology develops gradually and new systems appear on the market. A few less mature systems are appearing as promising candidates to take part in a future utility scale ESS market, and perhaps the most promising one is Liquid Air Energy Storage (LAES) systems.

Liquid Air Energy Storage (LAES) stores air in the form of liquid in insulated and unpressurised vessels at very large scales. The system uses electricity to compress and cool air to -190^{0}C and liquefy it through expansion. During required times for energy production, the system is dispatched by being exposed to ambient temperatures which brings about rapid re-gasification and a 700-fold expansion in volume. The expansion is used to drive a turbine and create electricity (Highview Power, 2016).

Three main elements form the LAES system, which are charging system, storage system and discharging system. The charging system consists of compression, refrigeration and expansion stages; the storage system includes tank, warm thermal storage and cold thermal storage; and the discharge system involves compression, evaporation and expansion stages. Figure 2-14 shows the LAES cycle with stages mentioned above (Morgan et.al, 2015),

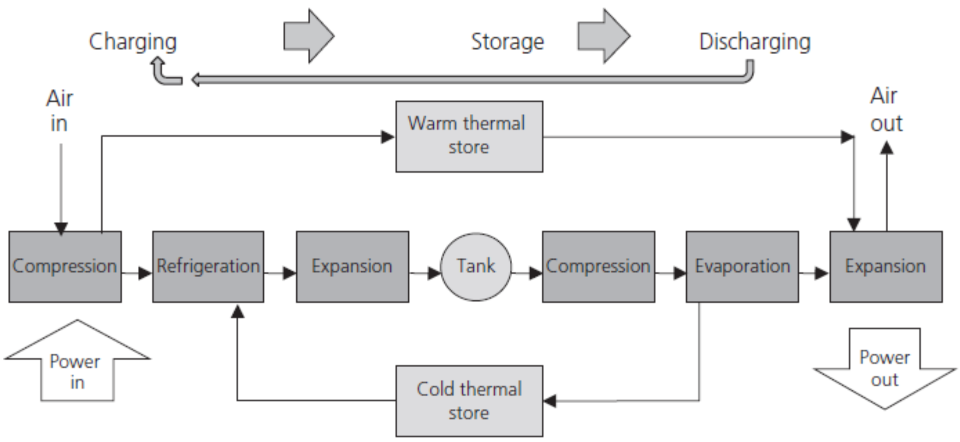


Figure 2-14: The LAES Cycle

As can be seen from the figure above, exhaust heat from the compression stage is used to warm the thermal store which is used in the expansion stage, and exhaust cold air from the evaporation stage is used to cool the cold thermal store which is used in the refrigeration stage; alternatively waste heat or cold from other processes can be used to increase the system's efficiency.

The most important advantage of LAES systems over other storage systems is LAES can store large scale energy without requiring special topography. Thus, unlike the PHS and CAES systems, LAES systems can be deployed anywhere. However, the round trip efficiency of LAES systems is between **45-55%** (Morgan et.al, 2015), which is lower than conventional PHS and CAES systems. It is expected LAES will be a competitive storage alternative when applications achieve above 50MW capacity and rated power duration of 2-20 hours. Currently, a system with 80MW power output has been developed, but not commercialized yet. This technology does not require special topography, so that can be deployed anywhere which causes a great advantage over other mechanical storage technologies (The Linde Group, 2016).

Since LAES systems are still in the development stage, the commercial cost of the system is only estimated. First-of-a-kind cost of 20MW/80MWh LAES system is **1,774 £/kW**; when the system is commercialized and become mature, the expected total specific cost is **995 £/kW** (Brett, 2014)**.** When LCOS of the system is considered, **250 £/kWh** which corresponds to **330 $/kWh**[13] is achieved.

The technology given above is still in the phase of development, so it needs time to commercially prove itself. Obviously, such developments in ESSs could bring about big advantages to the storage sector in terms of easy deployment and low cost.

2.2.2 Electrochemical Energy Storage -Batteries

Storing energy in an electrochemical medium is another commonly used type of storage systems. Electrochemical storage systems are generally known as "Batteries". Chemical reactions occur in batteries with two or more electrochemical cells which enable electron flow. Under this concept batteries can be used as storage systems. However, up to now they have not been suitable for large scale deployments, but increase in use of electric cars and consequent developments in battery technology have led to a rapid decrease in the cost of batteries. Figure 2-15 shows a worldwide forecast of battery storage capacity (MW) and annual revenue (USD) for utility-scale applications (Jaffe and Adamson, 2014).

[13] http://themoneyconverter.com/GBP/BBD.aspx - 23rd July 2016

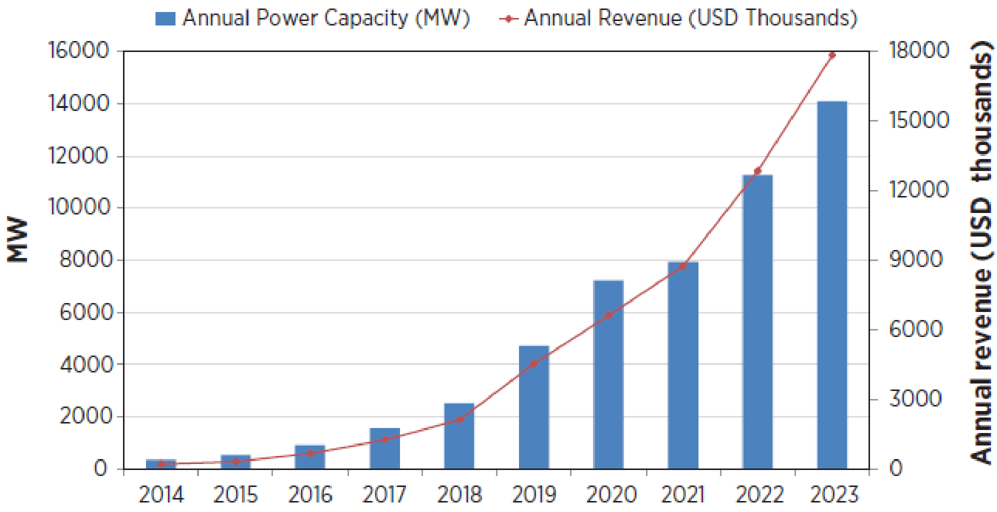


Figure 2-15: Worldwide forecast of battery storage capacity (MW) and annual revenue (USD) for utility-scale applications

As can be seen from the figure, a steady increase in the deployment of utility-scale batteries applications is forecast. The further decrease in the cost of the batteries will make it feasible to use batteries as large scale storage systems, thus batteries can be regarded as a potential utility scale storage type to (among other things) decrease the amount of curtailed wind power in UK.

Four types of batteries are leading the current battery storage market: these are Lead Acid Batteries, Lithium-Ion Batteries, Sodium Sulphur Batteries and Flow Batteries.

Lead Acid Batteries: Lead acid batteries are the oldest type of rechargeable batteries which store energy by using a reversible reaction between lead plates and dilute sulphuric acid (REUK, 2014). A typical lead acid battery schematic is as seen in Figure 2-16,

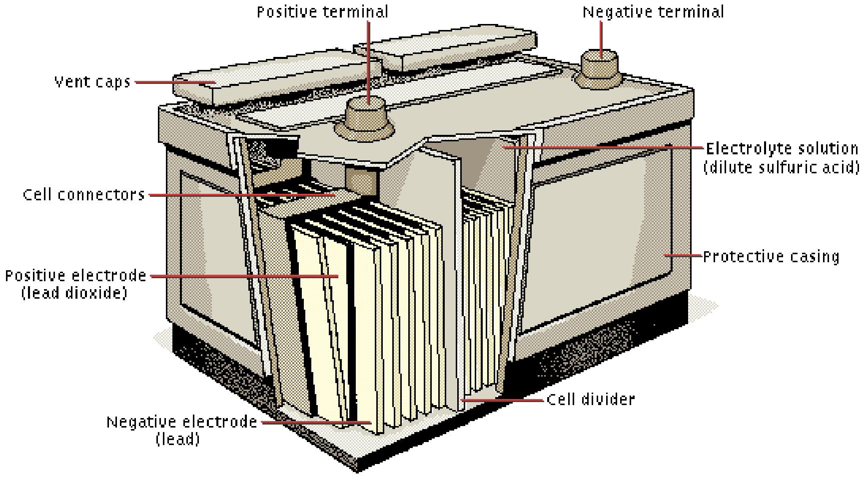


Figure 2-16: Lead acid battery structure (REUK, 2014)

Due to its low cost, lead acid batteries are used in various types of applications including vehicles, auxiliary off-grid power supply systems, grid stabilization or grid support. Also these types of batteries are extensively deployed to support renewable generation, for example around 50,000 solar home systems coupled to batteries had been deployed between 1995 and 2009 in Morocco. In Bangladesh 3.5 million solar home systems coupled to batteries have been deployed up to now (IRENA, 2015).

As stated, the manufacturing costs are low and technology is not complicated for lead acid batteries, however there are some challenges for deployment at large. Such batteries are slow to charge, have a limited number of cycles, cannot be discharged completely, have low energy-to-weight and low energy-to-volume ratios. In order to make lead acid battery chemistry technologically more feasible for grid balancing, lead-carbon electrodes are designed to combine high energy density with high specific power. Lead-carbon technology, which is also named as advanced lead-acid technology, mainly aims at extension of cycle life durability and specific power (Cole JF, 1995). The comparison of critical data for Conventional and Advanced Lead-acid batteries is seen in Table2-8 below (Garcia,2013),

	Conventional Lead-Acid Battery	Advanced Lead-Acid Battery
Power Range(MW)	1-50	1-50
Storage Duration	2h-4h	1min-8h
Cycles	1000-5000	4500-10000
Operating Life (years)	3-15	5-15
Efficiency (%)	70-90	90-94
Energy Density (Wh/kg) / (Wh/L)	25-50 / 40	up to 280 / 100

Table 2-8: Comparison of conventional and advanced lead-acid batteries

As seen from the table, Advanced Lead-Acid batteries are more applicable for utility scale storage systems than Conventional batteries. However, lead-carbon technology is still costly for large-scale deployment. According to AECOM, **2014 capital cost** of advanced lead acid batteries is **$600/kWh,** it is forecasted that capital cost of advanced lead acid batteries will be **$550/kWh in 2017** and **$500/kWh** in **2020** (AECOM, 2015). According to a research conducted by Lazard[14] 2015 capital cost of advanced lead acid batteries is between **553-1937 $/kWh** when it is coupled with a transmission system which is required when it is applied as grid-scale storage system. Also, Lazard forecast that by **2020** there will be 24% reduction in capital cost of advanced lead acid batteries, driven by engineering and design improvements and reduction in lead requirements. Therefore it is forecast that in 2020 the capital cost of advanced lead acid batteries will be **420-1470 $/kWh** (Lazard, 2015).

Li-ion Batteries: Li-ion batteries emerged in the early 1990s to replace nickel-metal batteries, which at that time represented the industry standards for portable electronic devices. Li-ion batteries consist of three tightly spiralled sheets which serve as positive electrode, negative electrode and separator surrounded by a liquid electrolyte inside of a cylindrical metal casing (Figure 2-17). The positive electrode is generally chosen as lithium cobalt oxide ($LiCoO_2$) and the negative electrode is chosen as graphite (C_6) (Scott and Lee, 2008)

Li-ion batteries are mostly used in cell phones, computers, MP3 players and other similar consumer electronic appliances. However, Li-ion batteries have also recently dominated the most recent EVs in development. It seems that developments in the EV sector will lead to a considerable growth in Li-ion market, from today's turnover of $11bn to $60bn by 2020 (Nexeon, 2016). The features that make Li-ion batteries a potential market leader are as follows (BatteryUniversity, 2010),

- High energy densities which makes these batteries potentially applicable at large scales
- Low maintenance, low self-discharge rate and absence of battery memory effect
- Specialty cells can provide very high current
- Lighter than other rechargeable batteries
- Reduced toxic landfill compared to lead, therefore environmentally beneficial.

[14] https://www.lazard.com/

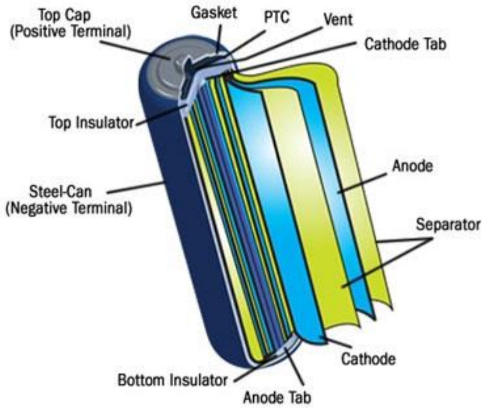


Figure 2-17: Li-ion battery structure (HSW, 2006)

Li-ion batteries have developed into a family with a variety of members, each with different characteristics. **Lithium Nickel Manganese Cobalt Oxide** and Lithium **Lithium Nickel Cobalt Aluminium** are perhaps the most promising li-ion types of batteries for large scale deployment. Due to their higher energy density, and longer life cycles they can be applied to EVs and grid scale storage systems. **Lithium Iron Phosphate** (Li-phosphate) is another member of the Li-ion family with lower energy density than normal Li-ion cells, but offering a longer life cycle with higher safety and it is environmentally friendly in comparison with other Li-ion batteries. Due to its safety and scalability to large applications, there are currently 24 utility scale Li-phosphate applications[15] operating in US. **Lithium Titanate** batteries may also be applied as large scale storage systems, and offer very promising cycle life. Their biggest challenge against Li-titan is their relatively low time duration at rated power (DOE, 2016).

There are other types of lithium batteries which are promising and increasing their market shares in niche applications. However they have limited load capabilities, short life span and low thermal capability, so they are not applicable for large scale deployment. **Lithium Manganese Oxide** and **Lithium Cobalt Oxide** are among these, although they offer high energy density, they are not suitable for large-scale deployments. Instead they are mostly used in electronic appliances.

Table 2-9 shows the overview of Li-ion batteries according to different combinations of lithium,

[15] Li-ion applications are listed in a different category. There are 118 li-ion applications are deployed currently in the US at utility scale.

	Energy Density (Wh/kg)	Cycle Life	Large Application Scalability	2014 price ($/kWh)	Price Forecast 2017 ($/kWh)	Price Forecast 2020 ($/kWh)
Lihtium Nickel Manganese Cobalt Oxide	120-140	800-2000	Yes	550-750	500	300
Lithium Nickel Cobalt Aluminium	120-160	800-5000	Yes	320-380	280	180
Lithium Iron Phosphate	85-105	200-2000	Yes	550-850	430	440
Lithium Titanate	80-95	2000-25000	Yes	800-2200	650	600
Lithium Manganese Oxide	140-180	800-2000	No	450-700	300	245
Lithium Cobalt Oxide	140-200	300-800	No	250-500	210	210

Table 2-9 Li-ion subcategory characteristics (IRENA, 2015)

There are 6 large scale (> than 1MW) li-ion battery systems deployed over UK in various places. Further decreases in prices of li-ion batteries as anticipated may lead larger scale deployment of the systems, and especially it might turn out to be the most promising battery type for grid-scale storage. However, there are two main challenges that need to be overcome. The first one is obviously cost reduction and the second one is improving duration at rated power. Average duration at rated power for large scale li-ion battery systems deployed in UK is presently only 1 hour (See 104).

Latest investments in EV battery systems are working to reduce the price of li-ion batteries significantly. According to Larsh Johnson, the chief technology officer of Stem, the company is paying 70 percent less for lithium-ion batteries than it was 18 months ago (GTM, 2016). AECOM reveals that, 2014 capital cost of li-ion batteries is **$550/kWh**. It is forecasted that capital cost of li-ion batteries will be **$300/kWh in 2017** and **$200/kWh** in **2020** (AECOM, 2015). According to Lazard, when it is coupled with transmission system, 2015 capital cost of li-ion batteries is between **422-1075 $/kWh**. Also, Lazard forecasts that by **2020** there will be **47%** reduction in the capital cost of li-ion batteries which is driven by increased manufacturing scale, reduction in required high cost materials and improvements in battery chemistry and design. Therefore it is forecast that in 2020 the capital cost of the li-ion batteries will be **223-570 $/kWh** (Lazard, 2015).

Sodium Sulphur Batteries (NaS): As one of the most effective battery type for large scale storage systems, sodium sulphur batteries offer the long duration of power supply at rated power with efficiency of **%70-90**. NaS batteries have already existing integrations with renewable technologies, so their performance is well known.

Sulphur is the active material in the positive electrode and sodium is the active material in the negative electrode, based on β-alumina ceramic. The basic cell structure and electrochemistry of the NaS cell are as seen in Figure 2-18 below (NGK, 2016),

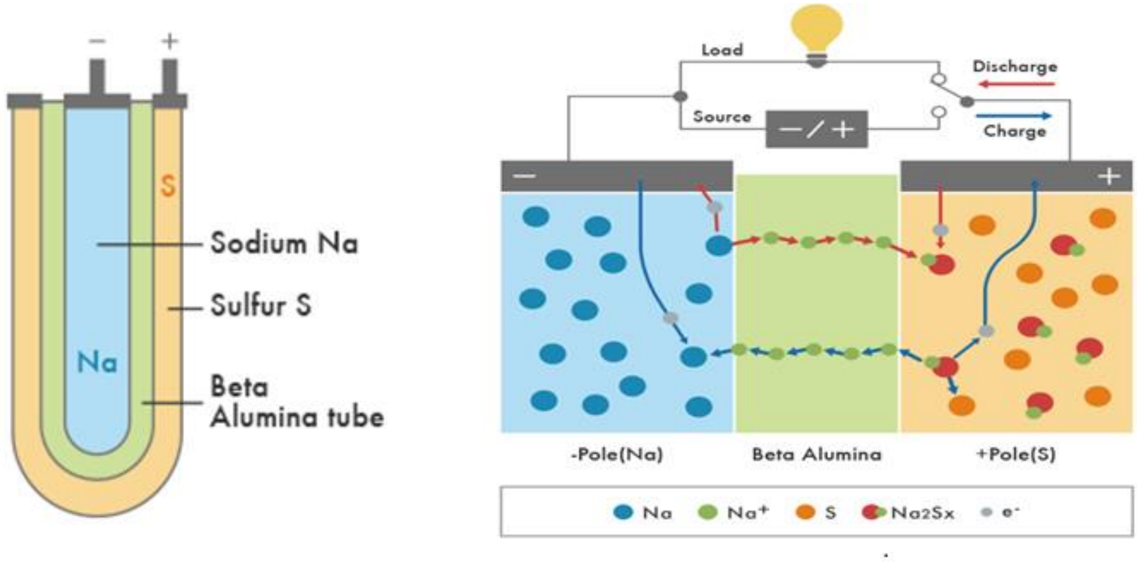


Figure 2-18: NaS Battery Cell and Electron-ion Motion during Charge and Discharge

In order to keep all the active electrode materials in a molten state and ensure ionic conductivity through the beta alumina interface, cells must be operated at sufficiently high temperature (270 to 350^{0}C). Operation at high temperature brings about serious safety problems especially when applied in large scales. Despite the temperature risk, NaS batteries are offering following advantages (Scott and Lee, 2008),

- NaS is the most effective battery type in terms of duration at rated power. Some of them offer 7 hours of supply at rated power,
- Since it offers a good power density, NaS systems can be compact and do not require as much space as other battery technologies,
- NaS systems respond very quickly, some of them store and deliver electric energy within one millisecond
- Long life span, up to 15 years

According to Scott and Lee, one of the main advantages of NaS systems is potential low cost relative to other technologies which stems from inexpensive raw materials. However, AECOM's forecast shows that **capital cost** of sodium sulphur batteries will be **$535/kWh in**

2017 and **$500/kWh** in **2020** where it was **$535/kWh in 2014 (AECOM,2014).** According to Lazard's report capital cost of sulphur batteries varies between **449-1367 $/kWh** when it is coupled with transmission system (Lazard, 2015). Lack of interest from the automotive industry (largely because of the requirement for high-temperature operation) means that costs are not falling as rapidly as for other types.

Flow Batteries: Another well-known and promising type of rechargeable battery is flow battery. Flow batteries' working principle is similar to conventional battery types mentioned above, so two chemical components which are separated by a membrane provide rechargeability. The most important advantage of flow batteries is that by replacing the electrolyte liquid they can be instantly recharged while recovering the spent material for re-energization at the same time (ESA, 2015). General structure of flow batteries is as seen in Figure 2-19.

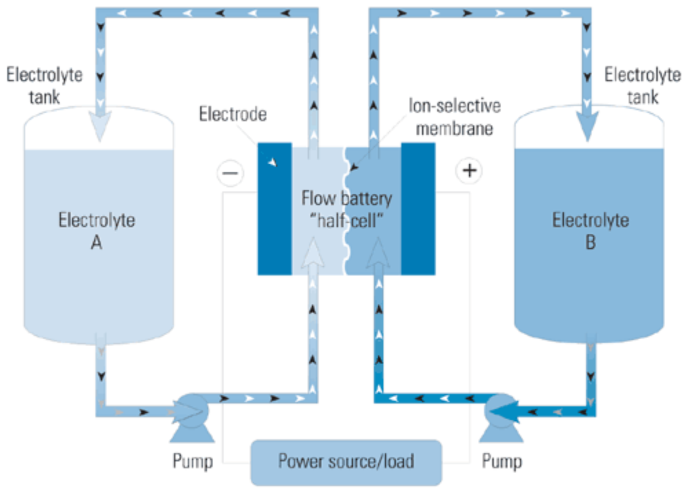


Figure 2-19: Structure of Flow Batteries (Peltier,2010)

Redox flow batteries (RFB) are the most important sub-category of flow batteries. The word "Redox" refers to words reduction and oxidation. By oxidation reaction an electron is released from the anode side of the battery during discharge. The electron moves through an external circuit towards the cathode side of the battery, and is accepted by reduction reaction. During charging, the direction of current is reversed. RFBs are divided into two types, the first one is named as "True Redox Flow Batteries" in which all the chemical species are active in storing energy and the second one is named as "Hybrid Redox Flow Batteries" in which at least one of the chemical species is plated as solid during the charging process. Vanadium Redox Flow Battery is the most applied "True RFB" and Zinc-Bromine Flow Battery is the most well-known for "Hybrid RFB" (Nguyen and Savinell, 2010).

In comparison with other true RFBs, Vanadium RFB provides a higher cell voltage which brings about higher power and energy density. However, the most significant challenge is caused by this higher voltage which puts more chemical stress on the materials used in the membranes and cell electrodes. Most vanadium RFBs are proposed as being attached to power plants to balance electrical grids. The zinc-bromine battery uses electrodes which do not take part in the electrochemical reactions but only serve as substrates for the reactions. As a result of this process, there is no material deterioration from continuous cycling activity. During their lifetime, flow batteries routinely deliver more 100% discharge cycles than other battery technologies (DOE, 2012).

The main **advantages** of vanadium RFBs are as follows,

- RFB offers high energy efficiencies
- RFB can discharge power for up to 12 hours
- Responds very quickly
- Potentially can store large amounts of energy in simple designs
- Can be operated at increased current densities
- Due to perfect electrochemical reversibility, it offers a long life cycle

And the main **disadvantages**/challenges are as seen below,

- Lower energy densities than other battery types which require more space to deploy and increase the related costs,
- Due to high amount of heat release, it may require the assistance of air conditioning systems which result in considerable energy losses, but with careful design the heat may be put to good use
- Standby current drain brings about extra power loss

As stated above, due to its low energy density flow batteries cost more than other battery types. **2014 LCOS** of flow batteries is **680 $/kWh**, however it is expected that on-going research and developments will significantly reduce this. Forecasted LCOS prices of flow batteries are **550 $/kWh in 2017** and **350 $/kWh** in **2020** (AECOM, 2015). According to Lazard, when it is coupled with a transmission system, 2015 capital cost of flow batteries is **324-970 $/kWh**. Also, Lazard forecasts that **until 2020** there will be **38%** reduction in capital cost driven by reduction in high cost materials, improved manufacturing and design and reduced time for manufacturing. Therefore it is forecast that in 2020 the **capital cost** of flow batteries will be **200-600 $/kWh** (Lazard, 2015).

Alternative Approaches to Electrochemical Energy Storage Systems

A variety of batteries with different characteristics play important roles in the storage market. The most common and well developed types of them are explained above. However technologies are not limited to those mentioned; there are promising innovations in batteries with different characteristics which can potentially be deployed for large scale storage.

Magnesium Batteries: Since the materials required by batteries are finite, it is important to increase the variety of battery types. As electrical vehicle development continues, companies are looking for new technologies which can be a good alternative to Li-ion batteries. Magnesium has been regarded for some time as a potential material for batteries. However, early studies revealed that simple salt electrolytes which are used in Li-ion batteries cannot be used in magnesium systems, because they passivate the magnesium metal surface (Gregory, et.al, 1990).

What makes magnesium an alternative promising material is its ionic structure. Magnesium ions have a plus two charge, while lithium ions have single positive charges. Thus in principle, magnesium ions could provide twice the electrical current of lithium ions. However, an outcome of this advantage is that the ions' motion slows down. The researchers of one of the leading vehicle companies (Toyota) have been working on magnesium as an alternative material for batteries (Figure 2-20). Toyota Research institute in North America (TRINA) has recently announced that they have developed an electrolyte based on a simple magnesium mono-carbonrate salt (MMC) for magnesium batteries. This overcomes the biggest challenge against development of magnesium batteries but for further improvements, high-oxidative stability is vital, especially for large scale applications (Mohtadi et.al, 2015). If this can be achieved, a new era for battery storage systems may begin.

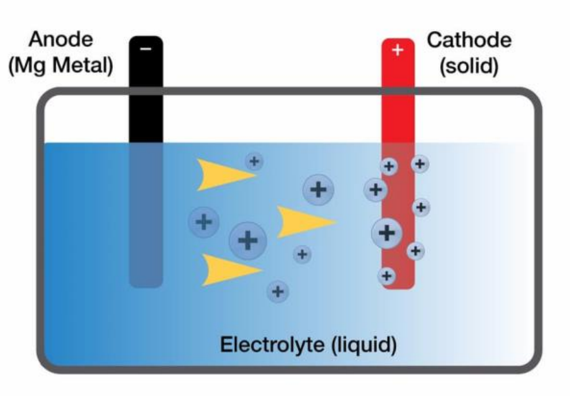


Figure 2-20: Magnesium Battery Structure (Mohtadi et.al, 2015)

Magnesium is the fifth most abundant element in the world, also it is non-dendritic (Aurbach, 2003). Such batteries are expected to be cheaper and they are also expected to have longer life cycle. Also, magnesium is more energy dense than lithium, because in order to make Li-ion batteries safer, lithium is embedded into graphite rods which reduces the density of the battery (Turpen, 2016). So magnesium offers great promise and potential application in EVs is spurring progress. If such batteries can be produced cheaply at large scale there is the prospect of cheap battery storage to complement renewable energy sources, and a significant step forward would then occur.

Overview of Batteries

Electrochemical energy storage systems are presently subject to intensive research; costs are falling steadily and the introduction of new materials opens up the possibility of further dramatic cost reductions in the future. Table 2-10 shows the technical overview of batteries mentioned above,

	Energy Efficiency	Discharge Duration	Cycle Life	Operating Life(Years)	Maturity	Energy Density(Wh/kg) / (Wh/L)
Conventional Lead Acid Batteries	70-90%	2hr - 4hr	1000-5000	3 - 15	Mature	25-50 / 40
Advanced Lead Acid Batteries	90-94%	1min – 8hr	4500-10000	5 - 15	Demonstration	up to 280 / 100

Li-ion Batteries (typical)	85-95%	1min – 8hr	1000-10000	5 - 15	Demonstration / Early Commercial	80-200 / 230 (400 Wh/L is achieved in solid state)[16]
Sodium Sulphur Batteries	75-90%	1min – 8hr	2500-5000	5 - 15	Commercialized	100-250 / 150
Flow Batteries	65-85%	1min – 5hr	>10000	15 - 20	Demonstration / Early Commercial	25-35 / 25-35 (200 theoretical)

Table 2-10: Technical overview of batteries

As observed from Table 2-10, in terms of technical specifications Li-ion batteries seem presently like the most suitable battery type for large scale deployment. Energy efficiency and energy density are the outstanding features. Advanced lead acid batteries look promising but they are still in demonstration phase, so it will take time for them to prove themselves commercially. NaS batteries also look competitive with li-ion batteries, for fixed storage as distinct from automotive applications. Flow batteries offer significantly greater cycle and operating lifetimes when compared with li-ion. But, much lower energy density and lower discharge duration are considerable shortcomings. Cost comparison of competing battery types is vital. Table 2-11 shows the capital cost and levelized cost of storage (LCOS) overview of the batteries so far discussed.

	AECOM- 2014 Capital Cost / 2017 Projection / 2020 Projection ($/kWh)	**Lazard's - 2015 Capital Cost($/kWh)**	**Lazard's - 2020 Capital Cost Projection($/kWh)**	**Lazard's 2015 LCOS ($/kWh)**
Advanced Lead Acid Batteries	600/550/500	553-1937	420 - 1470 (24% reduce)	0.461-1.429
Li-ion Batteries (typical)	550/300/200	422-1075	223-570 (%47 reduce)	0.347-0.739
Sodium Sulphur Batteries	535/535/500	449-1367	-	0.396-1.079
Flow Batteries	680/550/350	324-970	200-600 (38% reduce)	0.29-0.892

Table 2-11: Cost overview of batteries

Table 2-11 consists of recent costs and forecasts for mentioned battery types from two different sources. AECOM's research is based on general applications of batteries, while

16 http://www.greenoptimistic.com/toyota-solid-state-lithium-ion-battery-hits-400-whl-20140616/#.V5oYQvkrKM8

Lazard's results are specifically for grid coupled batteries. Both sources are excluding site cost and Balance of Plant (BoP) cost. As it can be seen from the table, advanced lead acid batteries are the least feasible choice among batteries in terms of LCOS, although with a predicted 24% reduction in their capital cost, they will remain expensive in comparison with other types. Sodium sulphur batteries seem cost competitive in today's circumstances, however there is not expected to be much future reduction in their costs. This situation appears to take sodium sulphur batteries away from being the best option for large scale battery deployment.

2.2.3 Chemical Energy Storage

The last type of large scale storage which might be applicable for UK is chemical energy storage using the chemical mediums of Hydrogen or Methane. Scalability and applicability with a wide range of capacities are attractive sides of chemical energy storage systems, however low efficiency, comparatively high costs and safety concerns of the technology presently make them unattractive. However, their potential for use in vehicles, either as a direct substitute for liquid fuels or in fuel cells, is likely to encourage technical development.

Hydrogen Energy Storage: Hydrogen is the most abundant and the simplest element with great potential for use in energy systems. When hydrogen is combined chemically with oxygen, only heat and water are produced. So, hydrogen is a source of clean energy. The specific energy of hydrogen is 141kJ/g which is much higher than for gasoline (Prakash, 2011). There are two methods of using hydrogen as a storage medium and power source. It is possible to produce mechanical power from hydrogen by putting hydrogen into fuel cell or using hydrogen to run a gas turbine or other combustion engine. Since the cycle efficiency of running a gas turbine is less than fuel cell generation method, most research is concentrated in the latter area. For this dissertation, only electrical output is of interest, so just the hydrogen-fuel cell generation option will be taken into account.

A hydrogen storage kit consists of four main parts; electrolyser, compressor, storage tank and fuel cell. The first stage of the kit is for the electrolyser to split water into hydrogen and oxygen and the compressor then compresses the hydrogen into a storage tank. When there is a need of electricity, hydrogen is taken from the tank and put into fuel cell to generate electricity. Figure 2-21 shows the representation of a hydrogen kit.

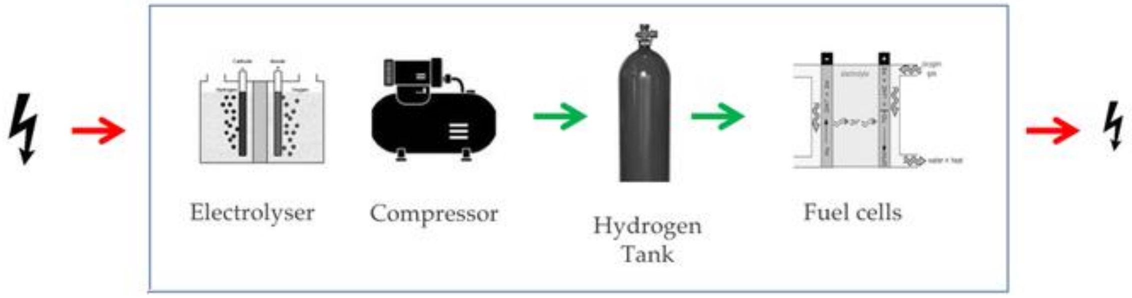


Figure 2-21: Representation of Hydrogen Storage Kit (H3P, 2016)

One of the biggest challenges in development of hydrogen storage systems is the loss of energy during the stages of the cycle. The main mechanisms for loss are as follows; heat loss from surroundings at electrolyser and fuel cell, chemical kinetics during activation polarisation, electrical resistance of cells, concentration effects, hydrogen escapes into the cell and auxiliary equipment losses. As the result of these, the total efficiency falls considerably and in today's circumstances the round trip efficiency is around 15-35% (Millet, 2015). Under best circumstances for future scenarios, it is estimated that overall round trip efficiency can achieve around 46% (H3P, 2016).

Another big challenge is the cost. Systems are still under development and there is some uncertainty about the cost of a hydrogen kit. The most recent research suggests a **capital cost** of around **1000 $/kWh** (Hogg, 2016). According to US Department of Energy the present **LCOS** of a hydrogen kit is **1.65 $/kWh** (Gardiner, 2014). Although there are considerable challenges, hydrogen storage systems offer a variety of advantages (Godula-Jopek, 2014);

- Hydrogen can be generated from an abundant source like water,
- Hydrogen can be stored separately from the point of generation,
- Desired amount can be stored in the forms of gas, liquid or metal hybrid,
- Scalable technology and long storage times are possible,
- Non-toxic
- Hydrogen offers multiple applications

Hydrogen storage systems can clearly be one of the alternative solutions for large scale storage systems, however in comparison with other types it is hard to claim that hydrogen will be preferable, mostly because of the high cost and low efficiency.

Methane Energy Storage: Methane can be produced as a carbon-neutral synthetic gas. Using methane as a storage medium is not a common type of application. There is only one example of large scale power to methane plant in the world, located in Germany with 6.3MW ETOGAS[17] plant. This technology is designed to combine carbon and hydrogen (Figure 2-22); the plant in Germany supplies carbon from a neighboring biogas plant in the form of CO_2, and H_2 is supplied from the electrolysis of H_2O. The process of electrolysing works with renewable energy generation, so the energy is conserved in the form of methane. However the plant produces amount of methane corresponds to 3MW while consuming 6MW of electricity, so round trip efficiency is around 50% without considering downstream losses (Andrews, 2015).

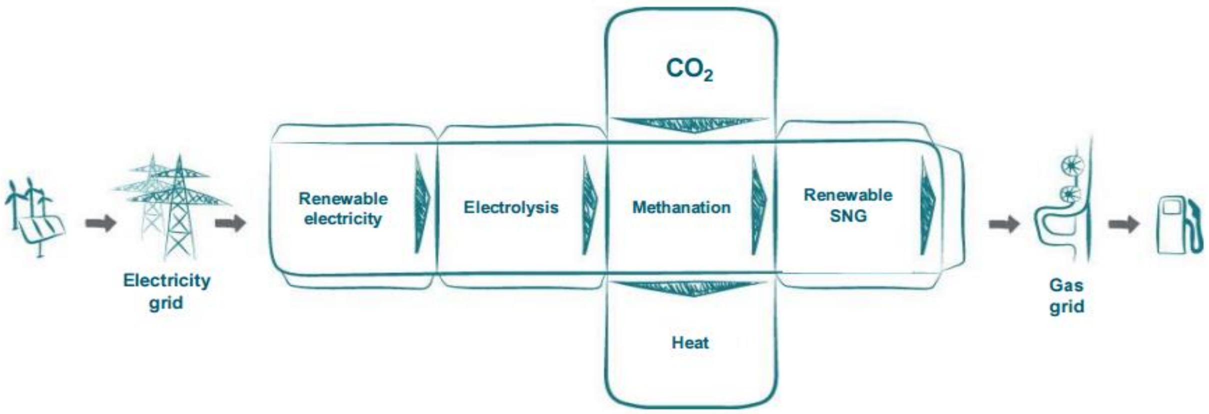


Figure 2-22: Schematic of Power-to-Methane Storage System (ETOGAS,2015)

As can be seen from Figure 2-22, stored methane can be either used as electricity, after conversion, or it can be combined with heat generation. However, further improvements and investments like pipeline, conversion mechanisms must be done which increases the cost of the system.

2.2.4 Comments on Utility Scale Storage Systems

It is crucial to provide a comparative overview of the systems discussed above to achieve a conclusion. Among mechanical energy storage systems, PHS and CAES are regarded as applicable storage systems for large scale deployment in UK. Although LAES system seems promising, it is still in an early development phase, while flywheel storage systems are not applicable as large scale storage system. For electrochemical energy storage systems a separate overview has been produced and li-ion batteries are stated as presently the best option for large scale deployment, although this may change in the future. The battery specifications to be used later in this dissertation are taken from data supplied for li-ion batteries. For chemical storage systems, hydrogen is more applicable at present than methane,

[17] http://etogas.com/fileadmin/documents/2015Q2r1_ETOGAS_company_presentation.pdf

because methane storage systems are still in an early development stage. Therefore, PHS, CAES, Battery and Hydrogen storage systems will be considered as applicable storage systems for inclusion in the simulations which follow. Table 2-12 and Table 2-13 show the overview of the utility scale storage systems discussed above based on author's inference by literature search.

	Energy Efficiency	Operating Life (Years)	Maturity	Capital Cost for Today / for 2020 ($/kWh)	LCOE Today ($/kWh)
PHS	80-85%	+20	Mature	210-310	0.15-0.275
CAES	70-89%	+20	Mature/Early Commercial	120-170	0.19-0.30
Battery	85-95%	5-15	Early Commercial	420-1000 / 220-570	0.34-0.74
Hydrogen	15-35%	-	Demonstration for large scale deployment	1000-20000	1.65

Table 2-12: Technical and cost overview of large scale storage systems

	Advantages	Disadvantages
PHS	• Most mature bulk storage • High efficiency	• Require specific topography • Further reduction in cost is not expected • Water requirement
CAES	• Allows bulk storage • High efficiency	• Require specific topography • Stages of storage should be controlled to prevent explosion
Battery	• Easy deployment regardless of geological structure, • Variety of types • Intensive R&D and industrial applications, so further reductions in cost and developments in technology are expected.	• Currently too expensive for large scales • Generally use limited resources • Some types can be toxic
Hydrogen	• Easy deployment regardless of geological structure, • Scalable, • Non-toxic, • Offers multiple applications, can be operated as combined heat and power plant	• High Cost, even with further reductions in cost might not be competitive • Low efficiency • Theoretically achievable efficiency limit is also low • Refill time of the systems is long, the cost of fast refill components are too expensive.

Table 2-13: Advantages and Disadvantages of different large scale storage systems

3. Electric Vehicles (EV) Storage

Electrical Vehicles (EVs[18]) are one of the most spoken topics in recent years. A few years ago the concept of an EV was regarded as something of a technological fad, but they have suddenly become so popular that even some of the developed countries set their policies to take account of EV technology. EVs are currently representing less than 1% of the new passenger cars' market. However this is now likely to change quickly (GEO, 2015). Therefore EVs will play an important role in any energy revolution and for sure battery systems will be an important part of this revolution. In this chapter, the background of the EV market and its future projections, the role of EV models to store curtailed energy and possible resulting outcomes will be discussed.

The main reason behind the political support for EVs is related with the ambitious emissions reduction targets of most countries. The transport sector plays a significant role in carbon emissions, accounting for 25% of the UK's CO_2 and other greenhouse gas emissions. (CCC, 2015) Even without political support, EVs are an attractive choice for the transportation sector. When the cost of driving on electric charge is compared with petrol or diesel fuels, electricity is a much cheaper option than conventional fuels, under present taxation regimes at least. Since the technology is newly developed, fully electric cars are presently more expensive than other vehicles. With continuing policy support and technological development, the rise in popularity of EVs is unavoidable. The energy storage sector can enjoy the benefit from decreased battery prices thanks to EVs, and have an impact on the levels of curtailed wind energy.

3.1 Background

The transport sector is witnessing a sales boom of EVs globally. Plug-in electric cars in the UK rose by more than 20,000% since 2010. Figure 3-1 shows the cumulative number of plug-in cars, vans and quadricyles licensed by local authorities in UK (OLEV and SMMT, 2016),

[18] The term EV includes automobiles, vans and quadricycles. Electric trains and similar vehicles are not taken into account.

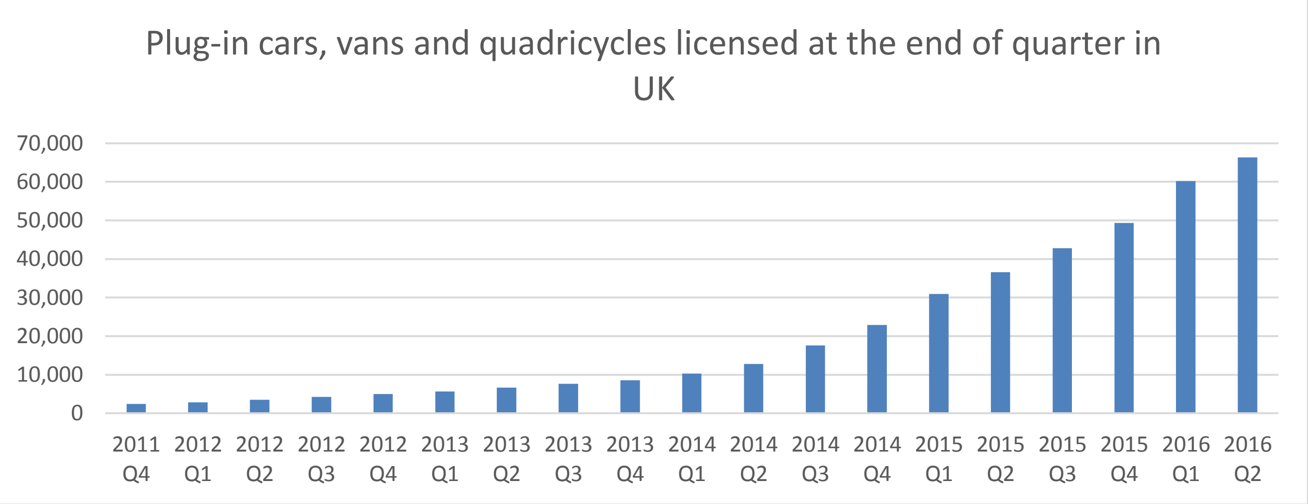


Figure 3-1: Plug-in cars, vans and quadricycles licensed at the end of quarter in UK

As can be seen from Figure 3-1, EV market in UK is developing fast and growth is likely to continue exponentially. Currently there are 66,296 registered EVs on the roads of the UK. When we consider the amount of storage capacity of all EV batteries, it corresponds to considerable amount of energy.

In today’s circumstances, the capacity of EV battery packs varies between 16kWh and 90kWhwith about 30kWh of average capacity (BatteryUniversity, 2016). So around **2 GWh** of storage capacity is available by EVs in the UK.

Obviously the development in EV technology will strive to increase the capacity of batteries that are used in EVs and the amount of EVs on the roads will increase as well. Therefore two sided growth will boost the total storage capacity provided by EVs.

According to a study conducted by World Energy Council, in order to reach 2020 EV targets, there will be 1.35M EV sales between 2014 and 2020 in the EU. Figure 3-2 shows the historic and projected EV sales to reach 2020 targets in the EU (WEC, 2016).

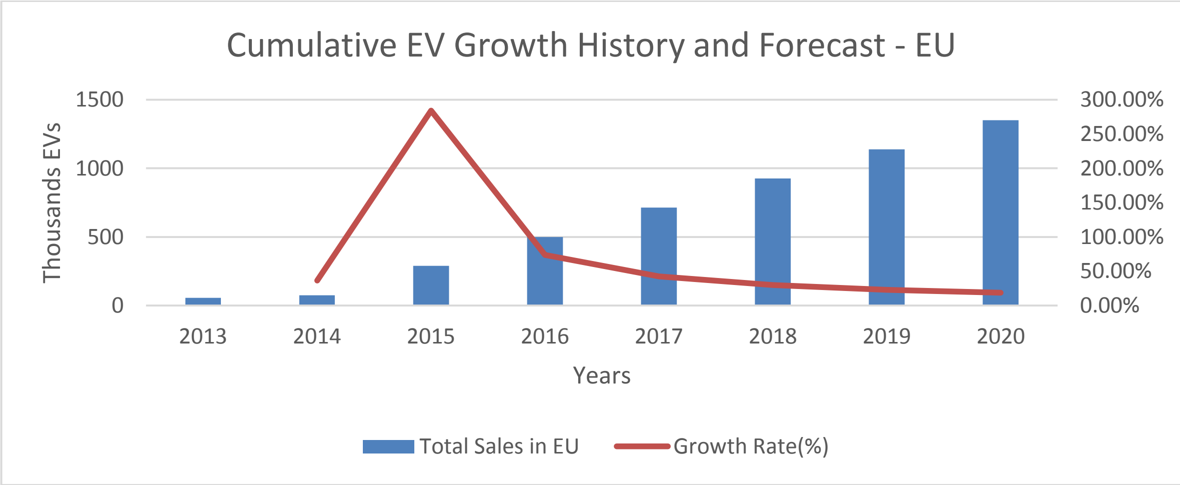


Figure 3-2: Historic and Projected EV sales to reach 2020 - EU

According to WEC's forecast between 2016-2020 the average annual growth rate will be 38% in the EU. UK energy and carbon policies are similar and compatible with the policies of EU, therefore it will be safe to apply same rates for UK's amount of licenced EV forecast. When the same annual rates are applied, the projected annual EV amount in UK is as seen in Figure 3-3 below,

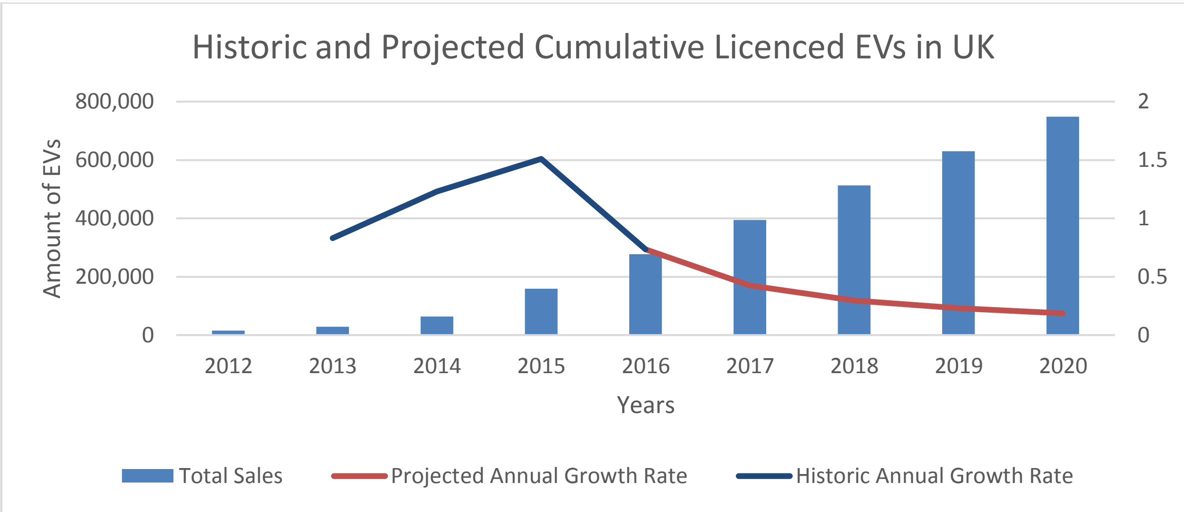


Figure 3-3: Historic and Projected EV sales in UK

According to projection, there will be around 750k licenced electric vehicles on the roads of UK. Although, there will be increase in average capacity of the EV batteries, let's assume there is not any development in average capacities of EV batteries, so the average capacity of EV batteries is 30kWh. According to projection and assumption, by 2020, even if there is not development in capacity of EV batteries, **22.5GWh** of storage capacity will be provided by EVs in UK. This can be regarded as the lower limit of battery storage projection, because no development of storage capacity is assumed. It is safe to assume 50% increase in average capacity of EV batteries, so by 2020 **33GWh** of storage capacity might be provided by EVs.

One of the vital things during the transition from fossil fuels to electricity usage in vehicles is the balance of the electricity network. During the development of EVs so far, one of the biggest concerns has been the long charging time of the batteries, however the Supercharger[19] system is able to charge 80% of the battery of a Tesla EV in half an hour, so this concern is likely to be overcome. But this might pose a serious danger for network. To reduce charging time more current must be drawn from the network in a specific time range. When the number of EVs is small, it may not affect the system seriously, but if EVs form a cluster and try to draw current simultaneously, then it may cause serious trouble. So, a particular research topic for EVs is generally based on understanding the dynamic of clustering of EVs. One of the outcomes of these researches was released by EA Technology's Ofgem funded project My Electric Avenue[20], where they found that when the 40-70% of local electricity network customers have EVs, 32% of networks will require intervention (MEA, 2015). In order to decrease the stress on the electric network and to decrease the risk of any fault in electricity distribution, it is important to develop alternative policy models where the EV batteries can be used as storage systems without harming the grid.

When curtailed wind energy is taken into account, EV batteries can be a storage alternative to utilize it. Modelling of the system is crucial part of the concept and a variety of operational models can be developed. The important point is keeping the cost reasonable while utilizing the curtailed wind energy and increasing the safety of grid.

3.2 Smart EVs

EVs can be an alternative storage system to balance the grid, if they are connected to a charging point at the right time. So how to find the right time is one of the main questions for EVs to help grid balancing. The concept of "Smart Grid" is an idea of electricity network in which power supply systems, power consumer appliances and distributed networks are interconnected by smart processing technologies. These smart processing technologies provide communication among the components of a network to manage supply and demand to increase energy efficiency and adapt intermittent power sources safely into the network. Demand management is a vital outcome of the concept of smart grid.

[19] www.tesla.com/supercharger
[20] myelectricavenue.info

Supply and demand matching is crucial for security of energy. Moreover, one of the biggest challenges against secured 100% renewable energy supply is possible mismatch between power generation from intermittent sources and demand. As noted, uncontrolled charging of a cluster of EVs can cause a serious problem, however if the charging of EVs can be delayed until the times of low energy demand, stress on the network is reduced, the electricity should be cheaper to buy and curtailed wind energy which is caused by energy surplus can be utilized. A smart EV which is compatible with smart grid can provide this service. Figure 3-4 shows the potential effects of Smart EVs on demand management.

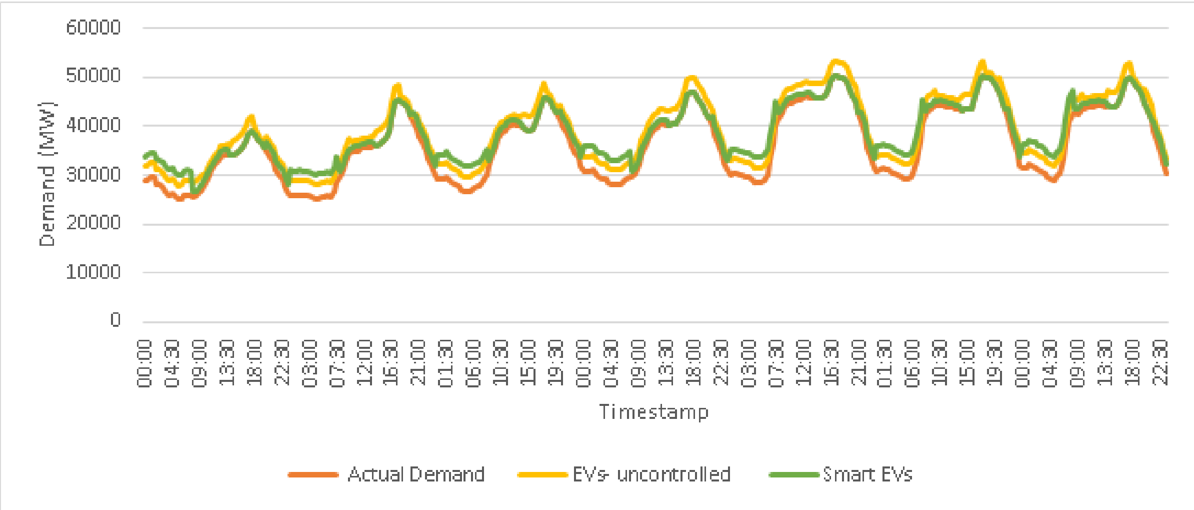


Figure 3-4: Potential Effects of Smart EVs on Demand Management

The Actual Demand data on the figure represents the electric demand data of the first week of 2015. For a future scenario, with the increase in number of EVs in place of today's fossil fuelled vehicles, the electric demand will increase. If the vehicles are charged in an uncontrolled manner, the demand in certain time ranges might be dangerous for the grid. The demand between 14:00 – 20:00 is generally observed as higher than for the rest of the day, which corresponds to working hours of most people. So, suppose that most of the employees of a factory own an electric car and during their working hours, they leave their cars as plugged-in, in order to charge them. When the already existing electrical demand of the factory can be a challenge for the grid for supply-demand matching, an extra load of a cluster of electric cars might put the grid into a risky position. When such a case is considered as country wide case, it is possible to observe a similar line with the EVs-uncontrolled (yellow) line. When the concept of smart EV works in integration with the smart grid system, the possible demand line can be as seen in the figure with Smart EVs (green) line. When smart EV line is compared with uncontrolled EVs' line, the gap between peak demand and the lowest demand is much higher in the uncontrolled EVs' case in which the amount of curtailed intermittent energy and related network stress will increase. The line representing Smart EVs is drawn by assuming that majority of the EVs are charged up during night time, when the demand is low. By doing that, it is possible to reduce the extreme points of demand and keep the peak demand unchanged from previous levels, despite the increased amount of EVs.

In addition to the advantages for utilities, demand management by smart grid brings about benefits for drivers. According to a smart grid project conducted by DIUS in Australia, when smart grid is used for EV charging demand management, drivers could save around $250 per year or around 50% on their charging cost based on the residential electricity tariffs (DIUS, 2013). There are a variety of projects under way and researches are being conducted all over the world, and in coming years it is expected to observe solid outputs from these studies.

Since the vehicle-to-grid (V2G) concept came into existence, modelling EVs as storage systems has become much more meaningful. UK's first V2G trial is conducted by popular car company Nissan and Italian power utility Enel. It is aimed to deploy 100 units of V2G, so by this project Nissan EVs will become mobile energy hubs. By these units, Nissan EV owners will be allowed to plug their EVs into the V2G systems, so owners will have opportunity to sell stored energy from their EV battery back to the National Grid (Nissan GB, 2016). When such units will be feasible for large deployment, a considerable amount of extra storage capacity will be in service of the grid network. According to a National Transport Survey conducted by DOT, around 80% of the vehicles are stationary during a typical day. Figure 3-5 shows the stationary vehicles during a typical day for the UK (DOT, 2009).

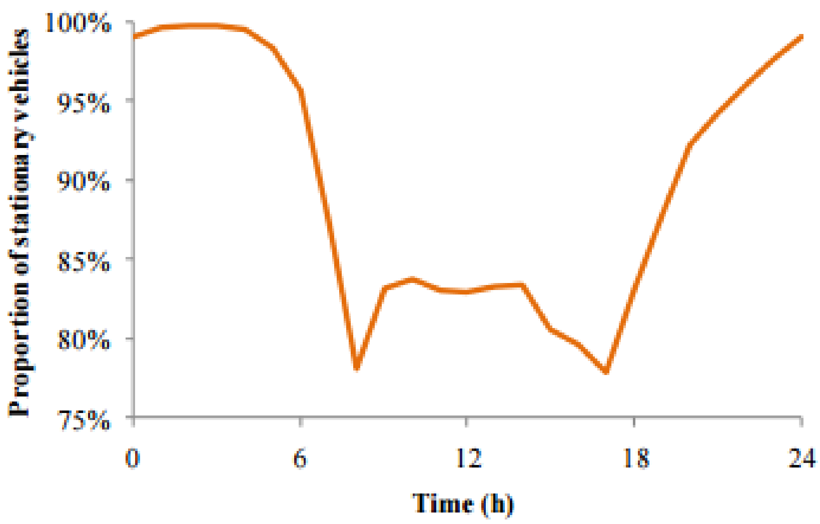


Figure 3-5: Stationary Vehicles during a typical day for the UK

It is clear that most of the time during a typical day, vehicles are doing nothing. For EVs which comply with V2G concept, while the vehicle is stationary the batteries can be charged for low cost during the times of low demand and the energy can be dispatched and sold back to the grid for high price during the times of high demand. All parties can get crucial benefit from such technology: the grid can call upon several GWh of storage capacity to balance the system and utilize the surplus energy, costly network reinforcements are cut down and EV drivers can enjoy the earnings from arbitrage. When V2G concept is assumed to be deployed country wide, according to forecasts there would be **1.6GWh** extra storage capacity provided by EVs during daytime and around **1.8GWh** during night time. When 2020 forecast for EV population is considered, there will be **18GWh** storage capacity during day time and **22GWh** storage capacity during night time provided by EVs without considering increase in average capacities of EV batteries.

3.3 Electric Road

Mitigation the risk of being stranded out of power during travel with an EV is one of the core research topics that the sector is working on. The quickest solution to the problem is instalment of frequent charging points, especially on highways. Although UK has thousands of chargers distributed over the country, the aim is to add plug-in chargers every 20 miles along highways. However, the primary development of plug-in charging networks will be in cities and towns (DOT, 2014). Plug-in chargers are beneficial to charge EVs conveniently while they are stationary, but to mitigate the risk of running out of power during long journeys there is a requirement for a strategic road network which uses electricity. As an alternative to plug-in charging solution, inductive charging which allows dynamic charging of EVs is a promising technology.

Induction charging, which is also known as Wireless Power Transfer (WPT), is based on the concept of electrostatic and magnetic induction, so it works on the same principle as a transformer. The system includes electric cables installed under the roads to generate electric field and a device under each car which will turn that electric field into electricity to charge the car. Figure 3-6 below shows the summary of an induction charging system for EVs (Highways England, 2015),

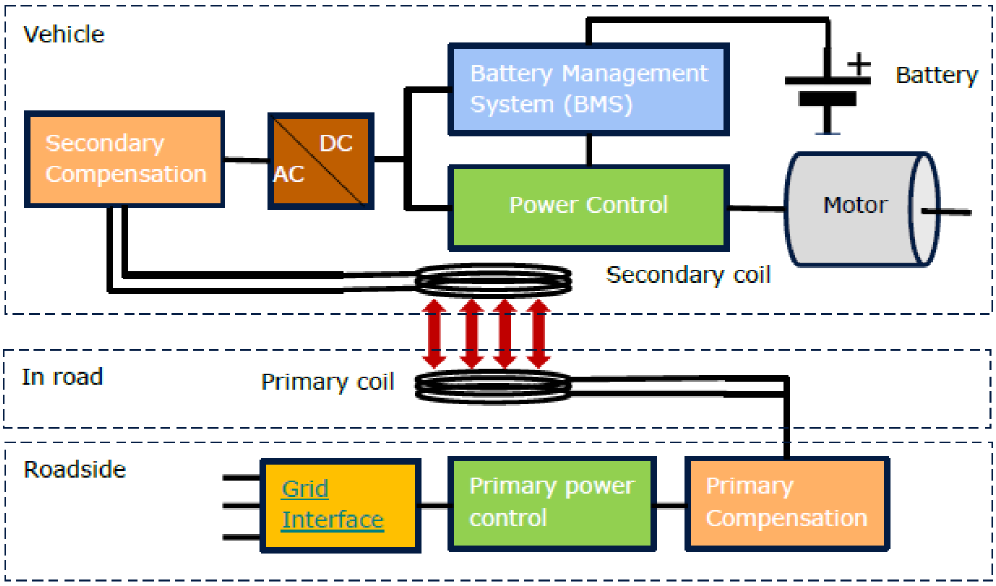


Figure 3-6: Working principle for induction charging of EVs

The first electrified road EV network opened in South Korea which consists of 15 miles of road in the city of Gumi. The road specifically is designed to charge electric buses. The gap between the road and the bus is 6.7-inch (165 mm) and the charging efficiency is 85% (Ahn, 2013). Thus, the technology looks applicable, and one of the results from the feasibility study conducted by the government states that people would be more likely to drive electric cars if induction charging roads were in place, especially if the charging networks spread off highways onto the regular roads (Highways England, 2015). Accordingly, EV sales might increase much more than forecasted values.

This system has potential to allow EV batteries to be used as an alternative storage system, so by similar logic to the smart EV concept, the electricity network will gain extra storage capacity to balance the grid when it is required. Also, the feasibility report states that, depending on the specific types, amount of EVs, the times of the day and the charging regime flexibility, there are some mechanisms to deliver additional financial benefits for EV fleet owners which are demand side response services, common distribution charging methodology, short term operating reserve (STOR), frequency response and frequency control by demand management (Highways England, 2015). In practice, this technology can only work in one direction, so V2G concept is not valid for electric road technology. However, this does not prevent use of EVs as large scale storage systems via this technology.

In the concept of a large scale storage system of EV batteries, such technology would be a milestone. In the smart EV concept, it is possible to charge stationary vehicles, but in this concept it is possible to charge the batteries while the vehicle is stationary or dynamic. There are operating wind farms with considerable amounts of curtailed energy installed next to highways. Therefore, such technology can be applied specifically for these wind farms. Turbines can be coupled with the road and with a power interface, and during the times of surplus energy, output from wind farm can be used to electrify the road. If different cabling infrastructure is applied between the road and the wind farm, curtailment caused by a weak transmission system can be prevented by this application. Figure3.7 shows how the systems can be adapted to utilize curtailed wind energy under the concept of electric road.

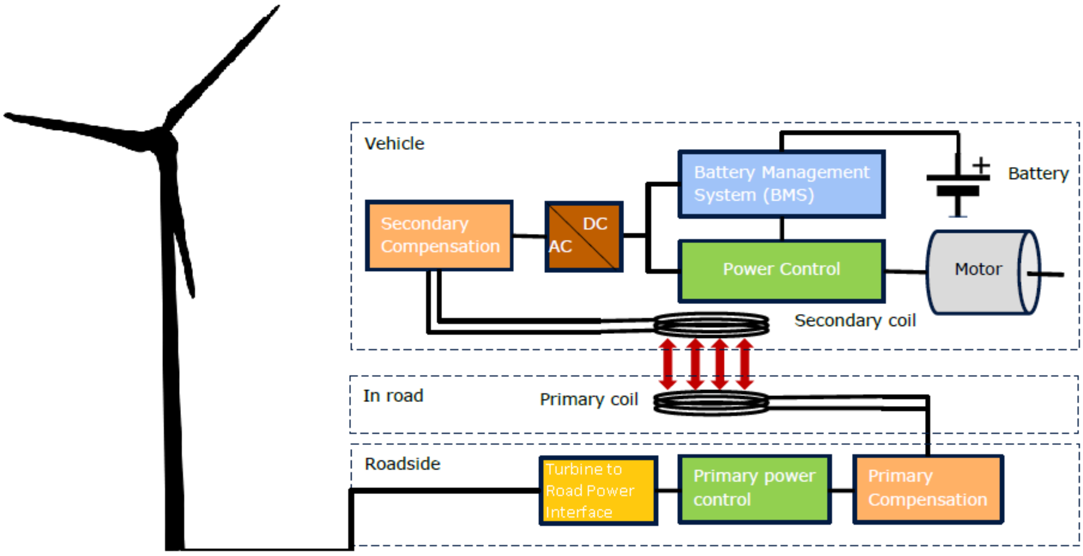


Figure 3-7: Utilizing curtailed wind power by electrifying the road

It will be seen from this chapter that it will be technologically possible to use EV batteries as additional storage systems to balance the grid and utilize curtailed wind energy. If the technologies mentioned above become sufficiently mature to use widely, by 2020 it is reasonable to claim that there will be additional 22.5GWh of storage capacity provided by EVs.

4. Software Model and Scenario Work

In order to conduct comparative performance and cost analysis and to observe the results from forecasted data in previous chapters a model in Excel has been developed. Based on these forecasted data and some other extreme cases, a number of scenarios have been investigated. In this chapter, first the software model will be described and then selected scenarios and the results will be presented.

4.1 Scenario Simulator

The scenario simulator is the principal software model of the project which has been developed in Excel. There are two versions based on different curtailment cases. Model1 is based on energy curtailment caused by predicted surplus and Model2 is based on a fixed curtailment ratio. A variety of scenarios based on different energy supply factors and different amounts of storage deployment have been investigated, chosen on the basis of reasonable forecasts and approaches. Any desired scenario can be applied in the Simulator which can be downloaded with the dissertation.

Model1:

In this model, 2015 half-hourly demand data is taken as the reference; the values can be changed by using the input factor coefficient in Simulator page. The 2015 data of energy supplies from coal power generators, nuclear power generators, wind farms, solar farms, biomass power plants, existing PHS systems, hydro power generators and other suppliers (oil, ocgt and interconnectors) are taken from Grid Watch. The CCGT output is then modelled according to demand and supply matching, so it is assumed that when there is energy deficit, it is compensated by CCGT systems.

Any energy surplus that is caused by mismatched supply and demand is considered as curtailed wind energy. There are two curtailment data columns available, which are before and after the deployment of additional storage systems. If there is a requirement for input to these additional storage systems, then the curtailed wind energy is distributed according to the coefficients of individual storage systems. If there is still surplus energy after distribution, it is noted as curtailed wind energy after additional storage.

As stated, it is possible to change data of suppliers from Simulator. The 2015 data for the listed supply systems may be multiplied by a factor given by user. Thus, if user inputs ’2’ into the wind cell in Simulator, then the model takes the 2015 wind energy supply multiplied by two and results are rearranged accordingly. The input will be noted as a coefficient factor. The decrease in CCGT use is then calculated as an output.

The main purpose of developing the first model is to observe the effect of changes in wind and other supply options on the curtailment caused by nationwide supply and demand mismatch and to observe the required amount of storage to utilize the curtailed wind energy.

Model2:

In Model2, wind energy curtailment is calculated by a fixed ratio. The user can input the desired ratio in Simulator, and also the wind supply data can be changed from Simulator based on the same coefficient factor logic as in Model1.

Model2 works based on a similar concept to Model1, the main difference being that the curtailment ratio before additional storage is arranged by a calculated coefficient. The deployment of storage systems and the distribution of curtailed wind energy are based on the same logic as Model1. To prevent confusion, the user is not allowed to change the factors of other energy supply options, so all factors except wind are arranged as one. Thus, only the wind factor and curtailment ratio can be changed.

The main purpose of developing the second model is to observe the effects of other causes of curtailment. In the first model only curtailment caused by mismatch of supply and demand can be observed, however as mentioned in previous chapters, curtailment can be caused by many other reasons. To observe the effects and requirements for extra storage capacity for a range of forecasted curtailment ratios and wind supplies, Model2 will be used.

Look-up tables are available for quick reference to different types of data. A variety of results and figures are shown on the Simulator page for the two different models.

4.2 Scenarios Investigated

4.2.1 Scenarios based on Model1

__Scenario1 & Scenario2__

	Demand	Wind	Coal	Nuclear	Solar	Biomass	Hydro	Other (Oil, OCGT, ICT)
S1	**1**	**3**	**1**	**1**	**1**	**1**	**1**	**1**
S2	**0.97**	**2.04**	**1**	**1**	**1**	**1**	**1**	**1**

Table 4-1: Demand & Supply factor coefficients for Scenario1 and Scenario2

For Scenario1 and Scenario2 coefficient factors for energy suppliers are kept the same except for Wind Energy. In Scenario1, 2026 forecasts (from Part 2.1.1) of installed capacity which produce **40.8GW** of wind supply are considered with no changes in other supply options and in demand, in comparison with 2015 values. In Scenario2, 2020 wind targets for UK are taken for the wind supply while other supply options are kept the same as 2015 values; the demand value is arranged according to 'Gone Green' Demand Scenario.

Scenario3 & Scenario4

	Demand	Wind	Coal	Nuclear	Solar	Biomass	Hydro	Other (Oil, OCGT, ICT)
S3	1	3	0	1	1	1	1	1
S4	1	5	0	1	1	1	1	1

Table 4-2: Demand & Supply factor coefficients for Scenario3 and Scenario4

For Scenarios3 and 4 the coefficient factors of coal were set to be zero, so coal free supply options are investigated. In Scenario3, the coefficient factor of the wind supply reflects the 2026 installed capacity forecast. In Scenario4, the factor of the wind supply is an extreme case which corresponds to **68GW** installed capacity. Factors of other energy suppliers and of demand are kept the same.

Scenario5 - Scenario7

	Demand	Wind	Coal	Nuclear	Solar	Biomass	Hydro	Other (Oil, OCGT, ICT)
S5	1.02	5	0	1	1	1	1	0
S6	1.02	7	0	1	1	1	1	0
S7	1.02	12	0	1	1	1	1	0

Table 4-3: Demand & Supply factor coefficients for Scenario5, Scenario6 and Scenario7

For Scenarios5, 6 and 7 the coefficient factors of coal and other (Oil, OCGT, ICT) were set to be zero; in other words, coal, oil, OCGT and import free supply options are investigated. In this case, the only supplier with carbon emission modelled is CCGT, so if the carbon free suppliers are enough to cover all demand, then carbon free energy is produced. For wind supply, extreme coefficient factors are taken. The coefficient factor 5 corresponds to **68GW** of installed capacity, factor 7 corresponds to **95GW** of installed capacity and factor 12 corresponds to **163GW**. The load factors of the wind turbines are left the same as 2015 values. The demands for these scenarios were set to the highest demand forecast in 'Gone Green' Demand Scenario which corresponds to **54.9GW** of peak demand.

Scenario8 & Scenario9

	Demand	Wind	Coal	Nuclear	Solar	Biomass	Hydro	Other (Oil, OCGT, ICT)
S8	1	12	0	0	1	1	1	0
S9	1	6	0	0	6	6	1	0

Table 4-4: Demand & Supply factor coefficients for Scenario8 and Scenario9

Scenario8 is the most extreme scenario in terms of wind supply. The coefficient factor 12 which corresponds to **163GW** of installed capacity is taken as input. Scenario9 reflects the case of similar development rates for wind, solar and biomass in terms of installed capacity. For both scenarios, with the exception of CCGT, the energy supply system is Coal, Nuclear, Oil, OCGT and ICT free, so completely based on renewable energy systems.

4.2.2 Scenarios based on Model2

Scenario10-Scenario12

	Wind	Ratio (%)
S10	2.58	3.5
S11	2.58	11.48
S12	5	13.47

Table 4-5: Demand & Supply factor coefficients for Scenario10, Scenario11 and Scenario12

Scenario10 is based on the 2023 wind forecast factor with 2015 curtailment ratio. So, it implies an improvement in transmission lines, so that despite more than doubled installed wind farm capacity the present curtailment ratio is protected.

Scenario 11 is based on the 2023 wind capacity forecast with a 2023 curtailment ratio forecast on the assumption that there is no significant development conducted in the electrical transmission system.

Scenario 12 is based on an extreme wind factor with a 2026 curtailment ratio forecast which is also the most extreme. Similar to Scenario11, it can happen if steps are not taken to upgrade the transmission system.

4.2.3 Storage Deployment Scenarios

The scenarios based on Model1 and Model2 will be run based on variety of storage scenarios and the results will be shown for each. The storage scenarios are as shown in the Table 4-6 with their explanations.

Storage Profiles	PHS (MWh)	CAES (MWh)	BATTERY (MWh)	EVs (MWh)	Total (MWh)	Explanation
SP1	10,000	10,000	0	0	**20,000**	10GWh storage from each mature technology,
SP2	10,000	10,000	17,500	22,500	**60,000**	EVs deployment forecast for 2020 by assuming no increase in capacity of the EV batteries
SP3	20,000	20,000	15,000	45,000	**100,000**	Storage with 1M EVs by assuming 50% increase in capacity of the EV batteries
SP4	0	0	0	225,000	**225,000**	Storage with 5M EVs by assuming 50% increase in capacity of the EV batteries
SP5	100,000	100,000	200,000	200,000	**600,000**	Extreme storage values. Assuming radical decrease in the batteries cost

Table 4-6: Storage deployment scenarios for Model1

In both models, it is assumed that the energy to be stored is the curtailed wind energy. Countless combination of storage systems can be generated; the chosen scenarios are based on some discussions about possible future developments.

4.3 Results

The investigated outputs of the model are as seen in below,

- **Average Wind Curtailment Ratio before Storage** returns the average ratio of curtailment before additional storage. So, for Model1 it means surplus energy over generated wind energy. For Model2 this parameter is defined as an input to the Simulator.
- **Half-Hourly Storage Requirement for Zero Curtailment (MWh)** returns the peak value of curtailed wind energy after additional storage. It gives the value of required storage capacity in every half an hour to store surplus energy. This value is important to observe requirement of storage capacity in the road of 100% renewable supply.
- **National Grid Payment for Curtailed Wind Energy before Additional Storage (M£)** returns the amount of payment made by National Grid to compensate loss of wind farms in proportion with the amount of curtailed wind energy. Please note that for S1-S3 since curtailment ratios before storages are lower than today’s rate, average price of 2011 is taken and for the rest of the scenarios average price of 2015 is taken as reference price per MWh.
- **Annual Total Energy Loss due to Storage Efficiency (GWh)** returns the amount of energy loss caused by efficiencies of storage systems. 85% efficiency has been taken

as reference efficiency value for all storage systems. The efficiency bands can be found in look-up tables in Simulator.

- **Average Wind Curtailment Ratio after Storage** returns the ratio of curtailment after additional storage. In both models, half hourly curtailed energy stored in available storage systems. However, when storage systems are completely filled, the excess energy is noted as curtailment after storage. The ratio returns surplus energy over generated wind energy.
- **Additional Utilized Wind Energy (GWh)** returns the difference between total curtailed wind energy before and after additional storage. The output gives total annual result.
- **Curtailed Wind Energy after Storage (GWh)** returns the amount of curtailed wind energy after additional storage deployment.
- **Amount of EVs (30kWh)** returns the number of EVs including 30kWh battery systems that correspond to EVs storage input.
- **Average Output of CCGT (MW)** returns the average output of back-up modelled CCGT. This output is important to observe the importance of storage systems in the context low carbon energy supply future. It is significant to note that average output of CCGT in 2015 is recorded as **9,587 MW.**
- **CCGT Decrease from 2015 (%)** reflects the percentage changes of average CCGT use between scenario parameters and 2015 CCGT data.
- **Total Benefit by Utilized Wind Energy (M£)** returns the value of saved money by utilizing curtailed wind energy by storage systems. Average payment of National Grid for constrained wind energy in 2015 is taken as reference benefit per MWh.
- **Average Wind Energy Supply Share** returns the wind energy share in energy supply system.
- **Average Renewable Energy Supply Share** returns the renewable energy share in energy supply system.

Scenario1&Scenario2

	Demand	Wind	Coal	Nuclear	Solar	Biomass	Hydro	Other (Oil, OCGT, ICT)
S1	1	3	1	1	1	1	1	1

Average Wind Curtailment Ratio Before Storage	Half-Hourly Storage Requirement for Zero Curtailment (MWh)	National Grid Payment For Curtailed Wind Energy Before Additional Storage (M£)	Annual Total Energy Loss due to storage efficiency (GWh)
3.18%	4,858	813	560

STORAGE (GWh)	20	60	100	225	600
Average Wind Curtailment Ratio After Storage	1.84%	1.20%	0.91%	0.52%	0.07%
Additional Utilized Wind Energy (GWh)	1,711	2,392	2,695	3,146	3,655
Curtailed Wind Energy After Storage (GWh)	2,021	1,340	1,037	586	76
Average Output of CCGT (MW)	4,826	4,635	4,554	4,447	4,325
CCGT Decrease from 2015 (%)	49.66%	51.65%	52.49%	53.61%	54.88%
Average Wind Energy Supply Share	23.36%	23.94%	24.18%	24.53%	24.93%
Average Renewable Energy Supply Share	31.73%	32.31%	32.55%	32.90%	33.30%
Amount of EVs (30kWh)	-	750,000	1,500,000	7,500,000	6,666,667
Total Benefit by Utilized Wind Energy (M£)	373	521	587	685	796

Table 4-7: Results for Scenario1

Wind curtailment ratio after storage shows that for Scenario1, the capacity of storage plays an important role. Thus the increase in storage capacity directly affects the amount of utilized wind energy. Figure 4-1 below shows the change in ratio with the increase in storage capacity.

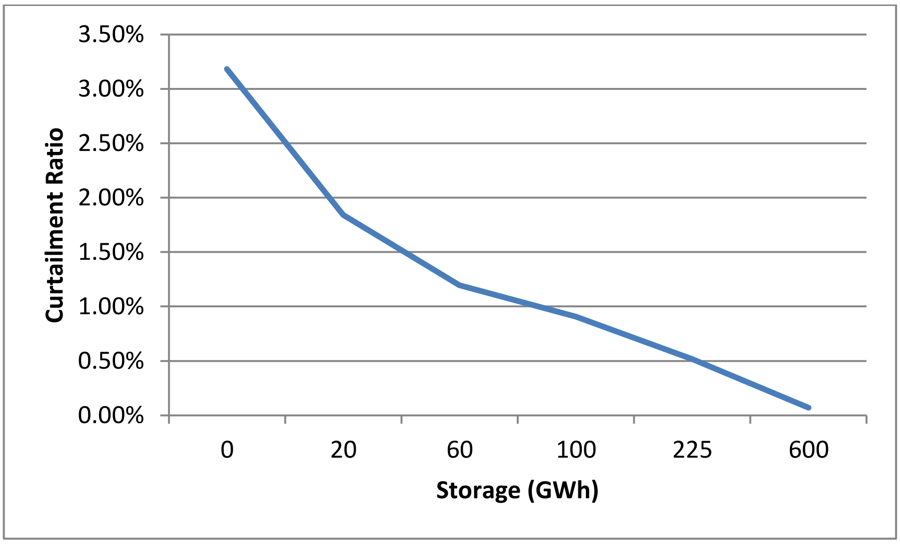


Figure 4-1: Wind Curtailment Ratio After Storage

As can be seen from the figure the ratio decreases in proportion with the increase in storage capacity. The maximum half-hourly storage requirement is **4858MWh,** however zero curtailed energy is achieved with around 600GWh of storage deployment, so approximately **120** times the half-hourly value will cover all storage requirements. This information could be used to forecast total storage requirements in similar scenarios. When total utilized wind energy is considered, it is observed that even with 20GWh of storage deployment **1711GWh** of extra wind energy will be utilized, reducing curtailment to around half its original value. Factor 3 for wind supply represents the **2026** forecast, so the results that are discussed above reveal the importance of an increase in storage deployment by this date.

Any increase in wind energy generation highly affects the modelled CCGT, so according to Scenario1 if the amount of wind generation is tripled from present levels with no difference in other generation options, the output of CCGT will decrease by around 50% from 2015 values. The effects of storage deployment on CCGT use are small but significant. Figure 4-2 shows the CCGT output decrease with changes in capacity of storage.

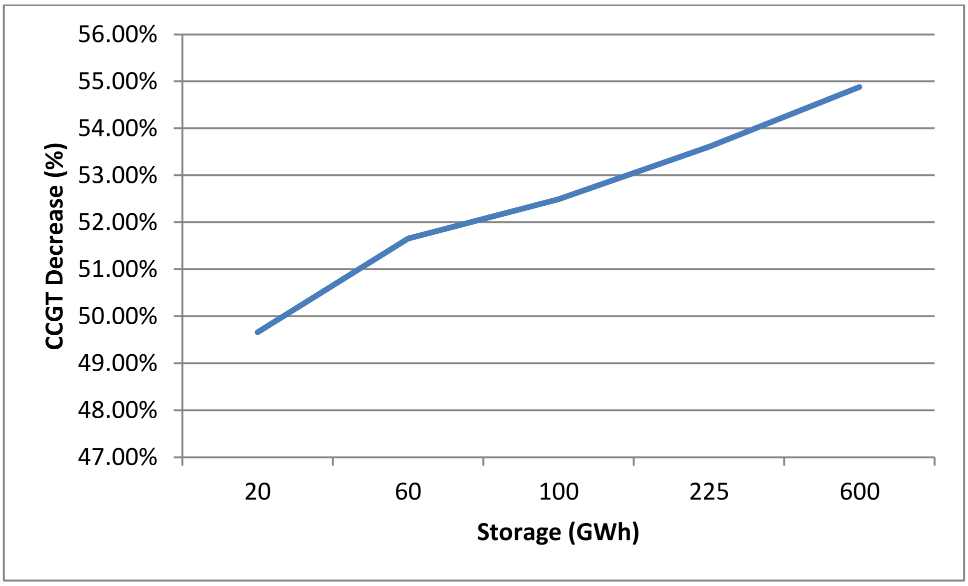


Figure 4-2: CCGT Decrease from 2015 (%)

In the road towards carbon free energy supply, an important criterion is the share of renewable energy systems in overall energy supply. In Scenario1, the wind energy supply varies between 23.36% and 24.93%, so it will increase proportionally with storage deployment. If the scenario described above happens, UK will supply around 24% of its electricity from wind sources. Storage deployment will not increase the renewable share greatly, but it will make renewable generation much more reliable.

Amount of EVs for different storage systems are based on the 30kWh EV batteries assumption, however the technological development in EV batteries will increase the average capacity of EV batteries, as it was stated 225GWh of EV battery deployment is assumed 50% increase in average capacity of EV batteries, which corresponds to 5M EVs.

	Demand	Wind	Coal	Nuclear	Solar	Biomass	Hydro	Other (Oil, OCGT, ICT)
S2	0.97	2.04	1	1	1	1	1	1

Average Wind Curtailment Ratio Before Storage	Half-Hourly Storage Requirement for Zero Curtailment (MWh)	National Grid Payment For Curtailed Wind Energy Before Additional Storage (M£)	Annual Total Energy Loss due to storage efficiency (GWh)
1.05%	2,386	192.1	132

STORAGE (GWh)	20	60	100	225	600
Average Wind Curtailment Ratio After Storage	0.22%	0.07%	0.00%	0.00%	0.00%
Additional Utilized Wind Energy (GWh)	713	832	879	882	882

Curtailed Wind Energy After Storage (GWh)	169	50	3	-	-
Average Output of CCGT (MW)	5,876	5,842	5,829	5,828	5,828
CCGT Decrease from 2015 (%)	38.71%	39.06%	39.20%	39.21%	39.21%
Total Benefit by Utilized Wind Energy (M£)	155	181.3	192	192.1	192.1
Average Wind Energy Supply Share	17.38%	17.48%	17.52%	17.52%	17.52%
Average Renewable Energy Supply Share	26.01%	26.11%	26.15%	26.15%	26.15%

Table 4-8: Results for Scenario2

Scenario2 is based on the 2020 forecast of UK government for demand and wind production, and if it is assumed other sources will be kept the same, the wind curtailment ratio caused by surplus energy is predicted to be **1.05%**. According to the above results, 20GWh of storage profile is enough to utilize most of the curtailed wind energy, decreasing the overall curtailment to **0.22%.** Further increase in storage capacity decreases the curtailment as expected, but quite slowly. It seems that until 2020 **20GWh** of storage investment would be enough to cover **most of the** requirement to utilize surplus wind energy. Based on the wind development forecast CCGT use is expected to decrease by around **38%** from 2015 levels and storage does not affect CCGT use very much.

Scenario3 & Scenario4

	Demand	Wind	Coal	Nuclear	Solar	Biomass	Hydro	Other (Oil, OCGT, ICT)
S3	**1**	**3**	**0**	**1**	**1**	**1**	**1**	**1**

Average Wind Curtailment Ratio Before Storage	Half-Hourly Storage Requirement for Zero Curtailment (MWh)	National Grid Payment For Curtailed Wind Energy Before Additional Storage (M£)	Annual Total Energy Loss due to storage efficiency (GWh)
0.26%	2,558	67.1	46

STORAGE (GWh)	20	60	100	225	600
Average Wind Curtailment Ratio After Storage	0.00%	0.00%	0.00%	0.00%	0.00%
Additional Utilized Wind Energy (GWh)	303	308	308	308	308

Curtailed Wind Energy After Storage (GWh)	5	-	-	-	-
Average Output of CCGT (MW)	12,760	12,758	12,758	12,758	12,758
CCGT Change from 2015 (%)	-33.09%	-33.08%	-33.08%	-33.08%	-33.08%
Total Benefit by Utilized Wind Energy (M£)	66.1	67.1	67.1	67.1	67.1
Average Wind Energy Supply Share	24.99%	24.99%	24.99%	24.99%	24.99%
Average Renewable Energy Supply Share	33.36%	33.36%	33.36%	33.36%	33.36%

Table 4-9: Results for Scenario3

Scenario 3 is based on coal free supply with a 2026 wind energy forecast. As can be seen from the table, the wind curtailment before additional storage is 0.26%, so there is very little surplus energy in the whole system. The surplus energy can be utilized fully with 20GWh of storage deployment.

The most important output that we can observe from Table4.4.3 is the change in use of CCGT. It shows that CCGT output increases by around **33%** from its 2015 values, and further increases in storage deployment does not change the value because all surplus wind energy would be already absorbed by 20GWh of storage. Wind energy share within other electric energy supply options is around **25%** and renewable share is **33.36%**.

	Demand	Wind	Coal	Nuclear	Solar	Biomass	Hydro	Other (Oil, OCGT, ICT)
S4	**1**	**5**	**0**	**1**	**1**	**1**	**1**	**1**

Average Wind Curtailment Ratio Before Storage	Half-Hourly Storage Requirement for Zero Curtailment (MWh)	National Grid Payment For Curtailed Wind Energy Before Additional Storage (M£)	Annual Total Energy Loss due to storage efficiency (GWh)
3.06%	8,338	424.9	898

STORAGE (GWh)	20	60	100	225	600
Average Wind Curtailment Ratio After Storage	2.22%	1.62%	1.32%	0.75%	0.36%
Additional Utilized Wind Energy (GWh)	2,088	3,080	3,617	4,631	5,362
Curtailed Wind Energy After Storage (GWh)	3,897	2,906	2,369	1,355	623

Average Output of CCGT (MW)	8,518	8,243	8,099	7,832	7,681
CCGT Decrease from 2015 (%)	11.15%	14.02%	15.52%	18.30%	19.88%
Total Benefit by Utilized Wind Energy (M£)	148.2	218.6	256.7	328.7	380.7
Average Wind Energy Supply Share	38.31%	39.19%	39.65%	40.52%	41.13%
Average Renewable Energy Supply Share	46.68%	47.56%	48.02%	48.89%	49.50%

Table 4-10: Results for Scenario4

Scenario4 is similar to Scenario3, but with a wind factor of five, which can be regarded as an extreme deployment. Wind curtailment ratio before storage is noted as **3.06%** which is quite similar to the actual 2015 curtailment ratio. The energy surplus in this case is quite high, so as expected the importance of storage is high as well. Figure 4-3 shows the changes in curtailment ratio with storage capacity.

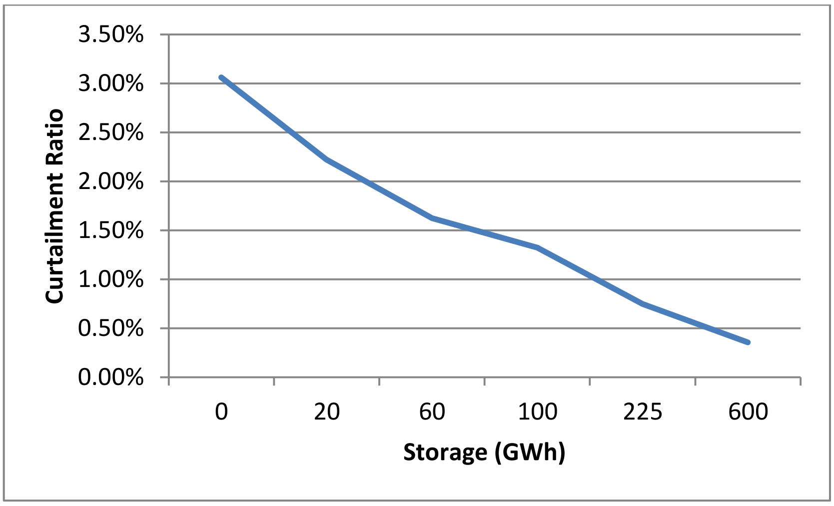


Figure 4-3: Wind Curtailment Ratio After Storage

As seen from the figure, there is a dramatic decrease in the curtailment ratio with increase in storage capacity. Even with the 600GWh of capacity, there remains **0.36%** of curtailment. By taking the calculation of storage requirement to cover all curtailed wind energy in Scenario1 into account, it is estimated that approximately **1000GWh** of storage is required for zero energy surplus throughout the year.

In contrast with Scenario3, there is a decrease in CCGT use. For 20GWh, the decrease is **11.15%** and for 600GWh the decrease is **19.88%,** so obviously the capacity of storage directly affects CCGT use. Wind energy share within other electric energy supply options is around **40%** and renewable share is around **48%**. They are quite close to each other, because wind energy is the massive part of renewable supply.

Scenario5 - Scenario7

	Demand	Wind	Coal	Nuclear	Solar	Biomass	Hydro	Other (Oil, OCGT, ICT)
S5	1.02	5	0	1	1	1	1	0

Average Wind Curtailment Ratio Before Storage	Half-Hourly Storage Requirement for Zero Curtailment (MWh)	National Grid Payment For Curtailed Wind Energy Before Additional Storage (M£)	Annual Total Energy Loss due to storage efficiency (GWh)
1.83%	7,160	259	547

STORAGE (GWh)	20	60	100	225	600
Average Wind Curtailment Ratio After Storage	1.15%	0.72%	0.51%	0.20%	0.08%
Additional Utilized Wind Energy (GWh)	1,592	2,346	2,767	3,305	3,519
Curtailed Wind Energy After Storage (GWh)	2,056	1,302	881	343	130
Average Output of CCGT (MW)	10.338	10.127	10.015	9.881	9.872
CCGT Decrease from 2015 (%)	-7.83%	-5.64%	-4.46%	-3.06%	-2.97%
Total Benefit by Utilized Wind Energy (M£)	113	166	196	234.6	249.8
Average Wind Energy Supply Share	39.07%	39.72%	40.08%	40.54%	40.72%
Average Renewable Energy Supply Share	47.27%	47.93%	48.28%	48.74%	48.92%

Table 4-11: Results for Scenario5

Scenario5 is based on the highest peak demand of the 'Gone Green' scenario and the electricity energy supply system is free from coal, OCGT, oil and interconnectors. Thus, export and import of electricity is not available in this scenario. As can be seen from the table, the wind curtailment before additional storage is **1.83%,** which can be almost completely removed by **600GWh** of storage deployment. In such a scenario, the deployment of storage systems has great strategic significance, because in this case the connection with the rest of the world is broken. The country can be regarded as an off-grid island, so there is a need for stored power to put online in case of an emergency. For this case, based on the required storage capacity calculation made in previous scenarios, there should be around **850GWh** of storage capacity for fully secured energy supply.

The use of CCGT increases by around **8%** from its 2015 values, but the storage deployment significantly changes the use of CCGT. Figure 4-4 shows the changes in use of CCGT with the increase in storage deployment for Scenario5.

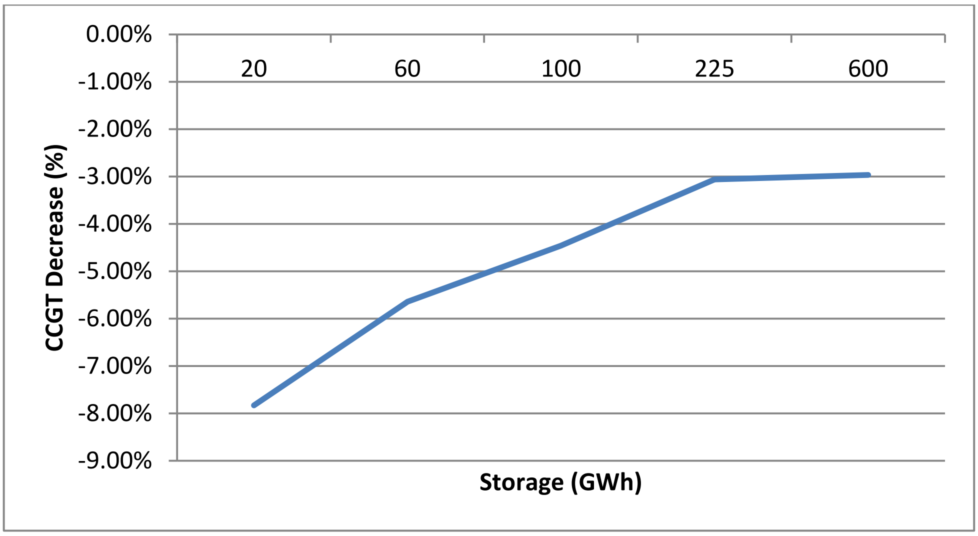


Figure 4-4: CCGT Decrease from 2015 (%)

There is a steady decrease in CCGT use with the increase in capacity of storage up to **225GWh**, after which there is almost no change. This stems from the lack of wind power generation to cover required demand; wind generation at factor five is not enough to decrease the CCGT use from 2015 values. Wind energy share within other electric energy supply options is around **40%** and the total renewable share is around **48%**. They are quite close to each other, because wind energy is the major part of renewable supply.

	Demand	Wind	Coal	Nuclear	Solar	Biomass	Hydro	Other (Oil, OCGT, ICT)
S6	**1.02**	**7**	**0**	**1**	**1**	**1**	**1**	**0**

Average Wind Curtailment Ratio Before Storage	Half-Hourly Storage Requirement for Zero Curtailment (MWh)	National Grid Payment For Curtailed Wind Energy Before Additional Storage (M£)	Annual Total Energy Loss due to storage efficiency (GWh)
5.41%	12,940	1,043	2,204

STORAGE (GWh)	20	60	100	225	600
Average Wind Curtailment Ratio After Storage	4.66%	4.06%	3.68%	2.97%	1.84%
Additional Utilized Wind Energy (GWh)	3,398	4,664	5,519	7,222	9,992
Curtailed Wind Energy After Storage (GWh)	11,293	10,027	9,173	7,470	4,700

Average Output of CCGT (MW)	7,539	7,200	6,966	6,511	5,801
CCGT Decrease from 2015 (%)	21.36%	24.89%	27.34%	32.08%	39.49%
Total Benefit by Utilized Wind Energy (M£)	241.2	331.1	391.8	512.7	709.4
Average Wind Energy Supply Share	48.31%	49.35%	50.06%	51.39%	53.56%
Average Renewable Energy Supply Share	56.51%	57.56%	58.26%	59.59%	61.76%

Table 4-12: Results for Scenario6

Scenario6 is based on a similar concept to Scenario5, but with the wind factor defined as seven, a more extreme deployment. The wind curtailment ratio caused by surplus energy is quite a bit higher than the actual 2015 results. The importance of storage deployment is again clearly seen in this case. The increase in total utilized energy is as seen in Figure 4-5.

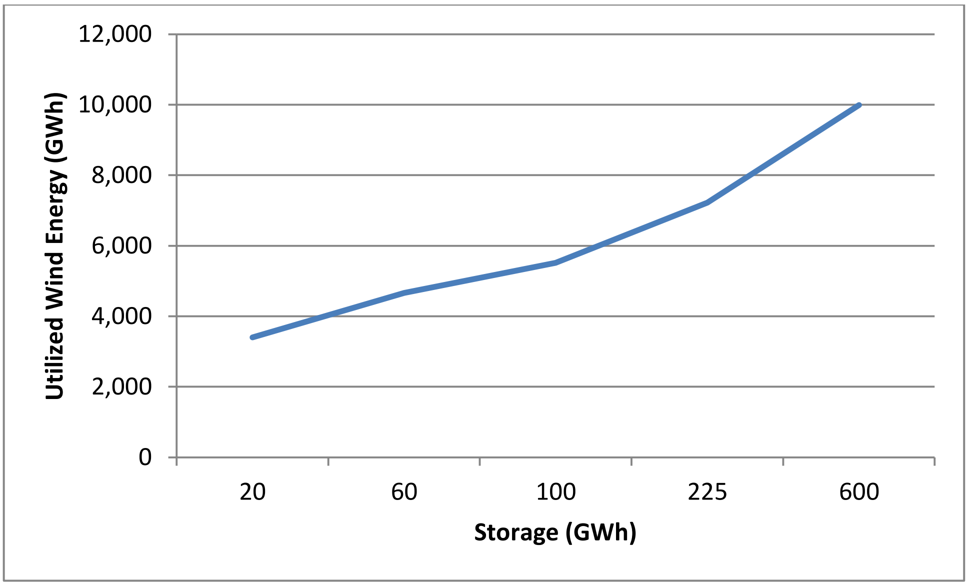


Figure 4-5: Utilized Wind Energy

The trend of growth in utilization reveals a requirement for more storage capacity than is provided here. Based on the required storage capacity calculation made in previous scenarios, there should be around **1550GWh** of storage capacity to utilize all the curtailed wind energy.

In contrast with Scenario5, there is a decrease in CCGT use. For 20GWh, the decrease is **21.36%** and for 600GWh the decrease is **39.49%**. Figure 4-6 shows the changes in use of CCGT with the increase in storage deployment for Scenario6.

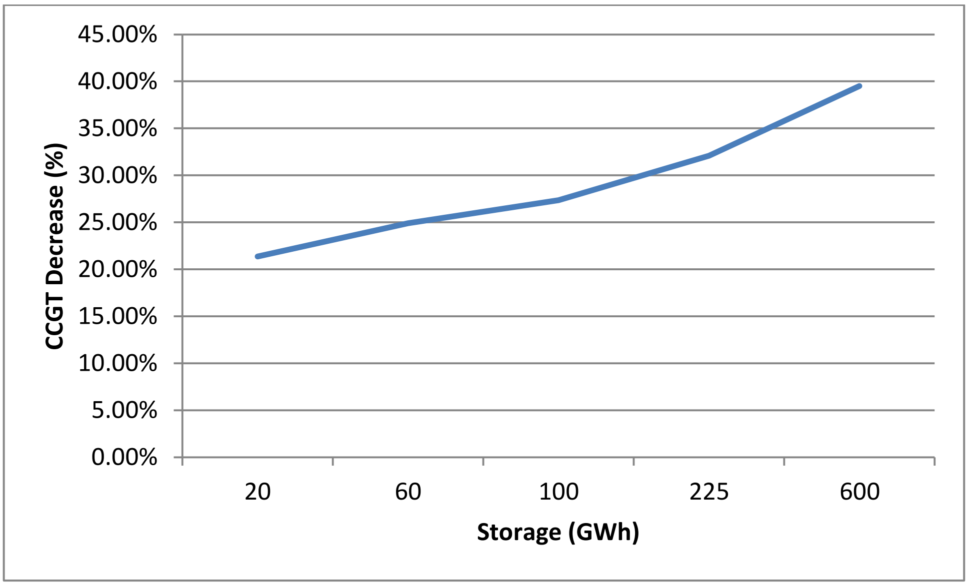


Figure 4-6: CCGT Decrease from 2015 (%)

Similar to Figure 4-5, the trend of decrease in CCGT use shows that it is likely to grow with further increase in storage capacity. Unlike Scenario5, there is abundant wind generation here, enough to cover more demand if more storage were deployed. Wind energy share within other electric energy supply options is around **50%** and renewable share is around **58%**.

	Demand	Wind	Coal	Nuclear	Solar	Biomass	Hydro	Other (Oil, OCGT, ICT)
S7	1.02	12	0	1	1	1	1	0

Average Wind Curtailment Ratio Before Storage	Half-Hourly Storage Requirement for Zero Curtailment (MWh)	National Grid Payment For Curtailed Wind Energy Before Additional Storage (M£)	Annual Total Energy Loss due to storage efficiency (GWh)
13.58%	27,480	4,079	8,619

STORAGE (GWh)	60	100	225	600	4000
Average Wind Curtailment Ratio After Storage	12.17%	11.80%	11.09%	10.03%	7.75%
Additional Utilized Wind Energy (GWh)	11,220	12,313	14,585	18,122	26,932
Curtailed Wind Energy After Storage (GWh)	46,240	45,148	42,876	39,338	30,528
Amount of EVs (30kWh)	750,000	1,500,000	7,500,000	6,666,667	16,666,667
Average Output of CCGT (MW)	3,763	3,480	2,874	1,953	-
CCGT Decrease from 2015 (%)	60.75%	63.70%	70.02%	79.62%	100.00%

Total Benefit by Utilized Wind Energy (M£)	796.6	874.2	1,035	1,286	1,912
Average Wind Energy Supply Share	63.81%	64.66%	66.46%	69.15%	75.45%
Average Renewable Energy Supply Share	72.02%	72.87%	74.67%	77.36%	83.65%

Table 4-13: Results for Scenario7

Scenario7 is similar Scenarios5 and 6, with the wind factor increased to 12, which can only be achieved with very aggressive deployment. There is a massive curtailment ratio before storage deployment of **13.58%** quite close to the curtailment forecast for 2026 which is **13.47%.** A special storage deployment case is applied for this scenario, with the right hand column showing the results for **4TWh** of storage deployment. This scenario is important to assess the possibility of carbon free energy supply for UK. Figure 4-7 shows the average output of CCGT after changes the capacity of storage.

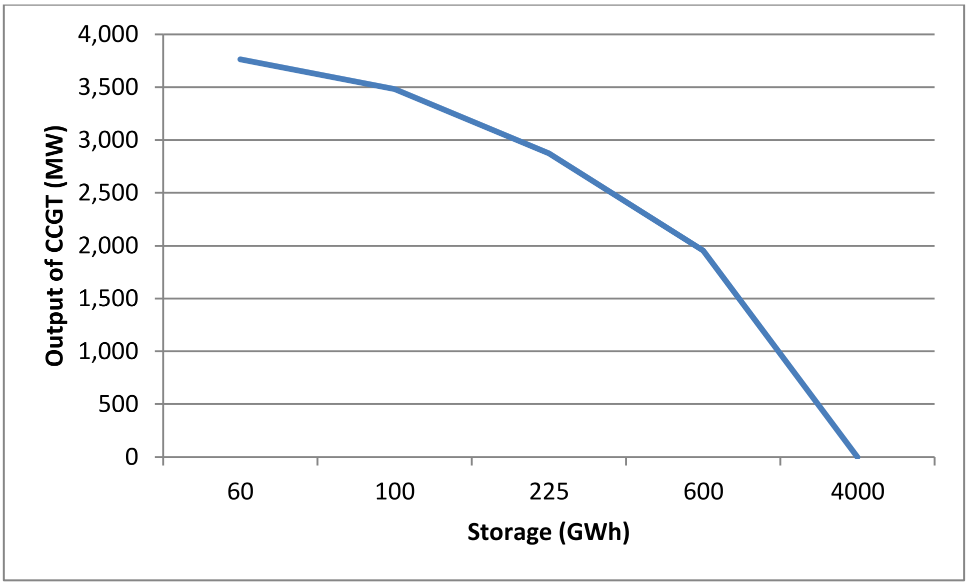


Figure 4-7: Average Output of CCGT (MW)

The most important output under this scenario is observing the possibilities for carbon free energy supply option for UK. With 4TWh of storage deployment, it is possible to achieve 100% carbon free electricity supply.

Even with such a huge deployment of storage, there is still **7.75%** of wind energy curtailment calculated. In the model we have achieved reliable carbon free supply and there is no need for extra storage to increase energy security. This means, 7.75% of generated energy will be just wasted. Although the scenario is based on ICT free supply, for such a scenario interconnectors should be strengthen to prevent waste of generated energy. In this scenario wind energy share within other electric energy supply options is around **75%** and renewable share is around **80%**.

Scenario8 & Scenario9

	Demand	Wind	Coal	Nuclear	Solar	Biomass	Hydro	Other (Oil, OCGT, ICT)
S8	1	12	0	0	1	1	1	0

Average Wind Curtailment Ratio Before Storage	Half-Hourly Storage Requirement for Zero Curtailment (MWh)	National Grid Payment For Curtailed Wind Energy Before Additional Storage (M£)	Annual Total Energy Loss due to storage efficiency (GWh)
9.07%	23,960	2,922	6,175

STORAGE (GWh)	60	100	225	600	22000
Average Wind Curtailment Ratio After Storage	7.98%	7.66%	6.91%	5.76%	0%
Additional Utilized Wind Energy (GWh)	8,740	9,851	12,516	16,791	41,167
Curtailed Wind Energy After Storage (GWh)	32,427	31,316	28,651	24,376	0
Average Output of CCGT (MW)	6,837	6,541	5,822	4,701	715
CCGT Decrease from 2015 (%)	28.68%	31.78%	39.28%	50.96%	92.54
Total Benefit by Utilized Wind Energy (M£)	620.5	699.4	888.6	1,192	2,922
Average Wind Energy Supply Share	75.49%	76.40%	78.52%	81.89%	94.96%
Average Renewable Energy Supply Share	83.86%	84.77%	86.89%	90.26%	98.33%

Table 4-14: Results for Scenario8

In Scenario8, nuclear, coal, OCGT, oil and ICT free energy supply system is modelled with wind factor of 12. The main purpose of this case is to observe if UK can rely only renewable generation which includes massive wind capacity. Like Scenario7 a special storage deployment case is applied for this scenario, the right hand column showing the results for the case of **22TWh** of storage deployment.

Although there is no nuclear generation, which is a strong driver of wind curtailment on specific sites, there is **9.07%** of curtailment ratio before additional storage. Figure 4-8 shows the wind curtailment ratio which varies with capacity of storage deployment.

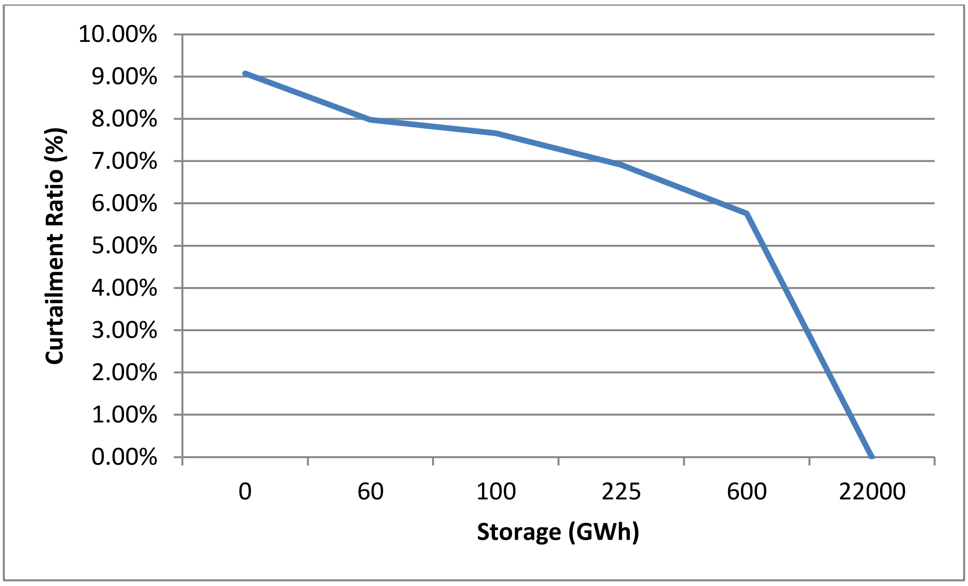


Figure 4-8: Wind Curtailment Ratio after Storage

As seen from the figure, by deployment of **22TWh** of storage it is possible to utilize all the curtailed energy. However, as seen from Table 4-14, the average output of CCGT for 22TWh of storage capacity is **715MW**; although it is **92.54%** less than 2015 values, it is not zero. It shows that under this scenario, it is not possible to achieve a totally carbon free energy supply. This is for the same reason as with Scenario5, which is lack of wind power generation to cover required demand. In this scenario the wind energy share within other electric energy supply options is around **94.96%** and renewable share is around **98.33%**.

	Demand	Wind	Coal	Nuclear	Solar	Biomass	Hydro	Other (Oil, OCGT, ICT)
S9	1	6	0	0	6	6	1	0

Average Wind Curtailment Ratio Before Storage	Half-Hourly Storage Requirement for Zero Curtailment (MWh)	National Grid Payment For Curtailed Wind Energy Before Additional Storage (M£)	Annual Total Energy Loss due to storage efficiency (GWh)
12.23%	22,786	1,276	2,697

STORAGE (GWh)	60	100	225	600	5380
Average Wind Curtailment Ratio After Storage	6.10%	5.22%	4.01%	2.55%	0.00%

Additional Utilized Wind Energy (GWh)	7,238	8,434	10,487	13,135	17,979
Curtailed Wind Energy After Storage (GWh)	10,741	9,544	7,492	4,844	-
Average Output of CCGT (MW)	5,661	5,322	4,768	4,090	3,393
CCGT Decrease from 2015 (%)	40.95%	44.49%	50.27%	57.34%	64.61%
Total Benefit by Utilized Wind Energy (M£)	513.8	598.8	744.5	932	1,276
Average Wind Energy Supply Share	41.55%	42.46%	44.09%	46.21%	49.98%
Average Renewable Energy Supply Share	84.78%	85.70%	87.32%	89.45%	93.22%

Table 4-15: Results for Scenario9

Scenario9 is based on Scenario8, but in this case distribution of renewable generation is different from previous cases with wind, solar and biomass factors are defined as six, which can perhaps be regarded as a more realistic and achievable deployment in comparison with Scenario8. Again a special storage deployment case is applied for this scenario, with the right hand column showing the results for the case of **5380GWh** of storage deployment.

In this case, there is **12.23%** of curtailment ratio before additional storage which is more than the previous case. Figure 4-9 shows the wind curtailment ratio which varies with capacity of storage deployment.

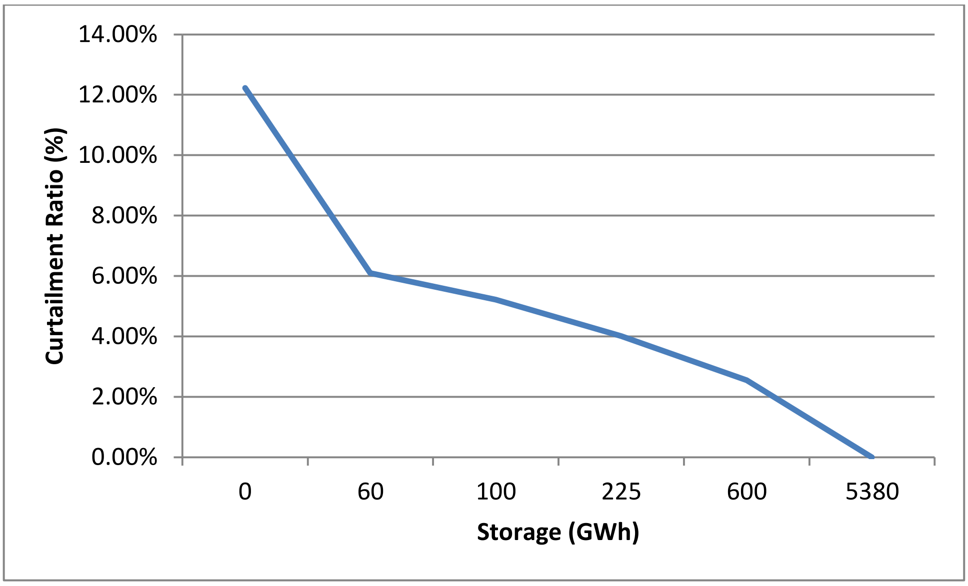


Figure 4-9: Wind Curtailment Ratio after Storage

As seen from the figure, by the deployment of **5380GWh** of storage it is possible to utilize all the curtailed energy. However, as seen from Table 4-15, the average output of CCGT for

5380GWh of storage capacity is **3,393MW**, which is much higher than in Scenario8. Biomass is a dispatchable source and solar energy output is quite low over UK, so despite zero curtailment, the output of the CCGT gets higher. In this scenario the wind energy share within other electric energy supply options is around **50%** and the renewable share is around **93%**.

Model2 Scenarios

Scenario10

	Wind	Average Wind Curtailment Ratio Before Storage (%)
S10	**2.58**	**3.5**

Half-Hourly Storage Requirement for Zero Curtailment (MWh)	National Grid Payment For Curtailed Wind Energy Before Additional Storage (M£)	Annual Total Energy Loss due to storage efficiency (GWh)
6,652	257	544

STORAGE (GWh)	20	60	100	225	500
Wind Curtailment Ratio After Storage	1.92%	0.95%	0.69%	0.29%	0.00%
Additional Utilized Wind Energy (GWh)	1,803	2,678	2,933	3,346	3,625
Curtailed Wind Energy After Storage (GWh)	1,823	947	693	279	-
Average Output of CCGT (MW)	10,527	10,280	10,206	10,091	10,012
Total Benefit by Utilized Wind Energy (M£)	127.9	189.9	208.1	237.3	257
Average Wind Energy Supply Share	19.98%	20.75%	20.95%	21.28%	21.49%
Average Renewable Energy Supply Share	28.35%	29.12%	29.32%	29.65%	29.86%

Table 4-16: Results for Scenario10

Scenario10 is based on 2023 wind forecast capacity factor with 2015 curtailment ratio. Using the methods of Model1, the average wind curtailment ratio before additional storage was **1.88%**, so for this scenario it can be assumed that more than half of the curtailment is caused by supply and demand mismatch and the rest by other issues. The **3.50%** wind curtailment can be completely utilized by **500GWh** of storage deployment. Figure 4-10 shows the changes in curtailment ratio with increase in storage capacity.

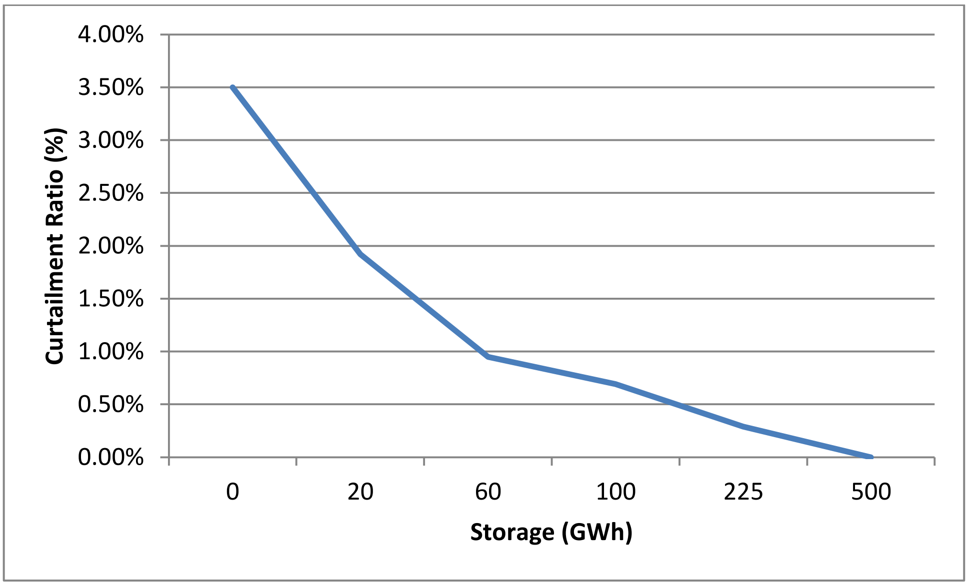


Figure 4-10: Wind Curtailment Ratio after Storage

It can be observed there is a steady decrease in curtailment ratio with the increase in storage capacity. Since the curtailment ratio is input manually it is not appropriate to compare modelled CCGT output values with the 2015 value. However, it is useful to observe the trend of CCGT output and Figure 4-11 shows this.

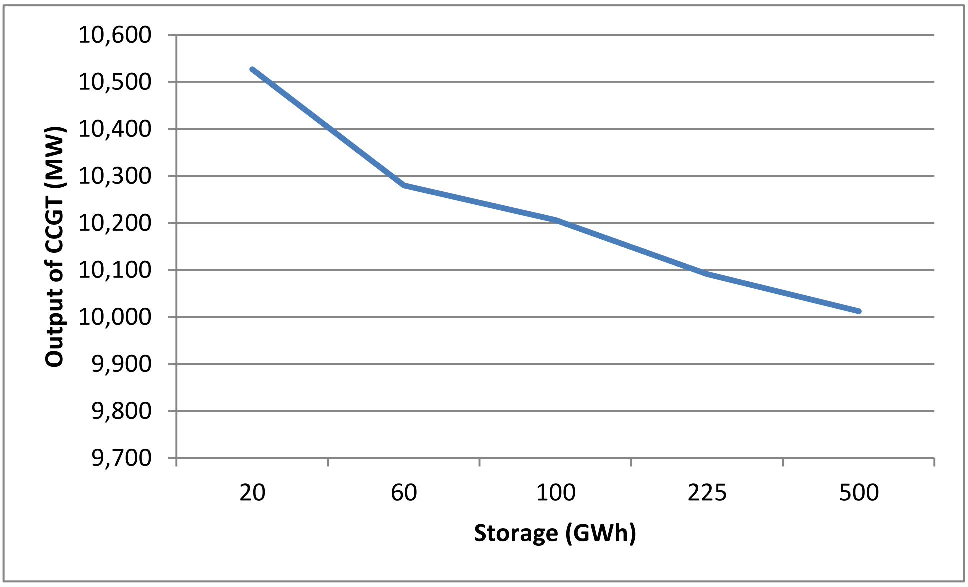


Figure 4-11: Average Output of CCGT (MW)

As can be seen, CCGT use decreases proportionally with the increase in storage capacity. However, even after utilizing all the curtailed wind energy, there is a considerable amount of use of CCGT which stems from a lack of wind power generation to cover required demand. Annual losses caused by the storage process are **544GWh,** 15% of all utilized energy, which is considerable. In this scenario the wind energy share within other electric energy supply options is around **21%** and the renewable share is around **29%**.

Scenario11

	Wind	Average Wind Curtailment Ratio Before Storage (%)
S11	**2.58**	**11.48**

Half-Hourly Storage Requirement for Zero Curtailment (MWh)	National Grid Payment For Curtailed Wind Energy Before Additional Storage (M£)	Annual Total Energy Loss due to storage efficiency (GWh)
21,818	843.1	1,781

STORAGE (GWh)	20	60	100	225	600	1650
Wind Curtailment Ratio After Storage	9.09%	6.52%	4.96%	2.88%	1.25%	0.00%
Additional Utilized Wind Energy (GWh)	3,531	5,694	7,080	9,018	10,640	11,871
Curtailed Wind Energy After Storage (GWh)	8,340	6,177	4,791	2,853	1,231	-
Average Output of CCGT (MW)	35,113	34,532	34,139	33,584	33,131	32,781
Total Benefit by Utilized Wind Energy (M£)	250.7	404.4	502.8	640.5	755.7	843.1
Average Wind Energy Supply Share	14.48%	16.36%	17.59%	19.25%	20.52%	21.49%
Average Renewable Energy Supply Share	22.85%	24.73%	25.96%	27.62%	28.89%	29.86%

Table 4-17: Results for Scenario11

Scenario 11 is based on the 2023 wind capacity forecast as in Scenario10, but in this case the curtailment ratio forecast for 2023 is applied. So, if the forecasted wind generation is installed and no precautions to prevent curtailment are taken it would not be surprising to observe results consistent with this scenario. As seen from the table, the wind curtailment before additional storage can be completely utilized by **1.65TWh** of extra storage deployment. Figure 4-12 shows the change in curtailment ratio with increase in storage capacity.

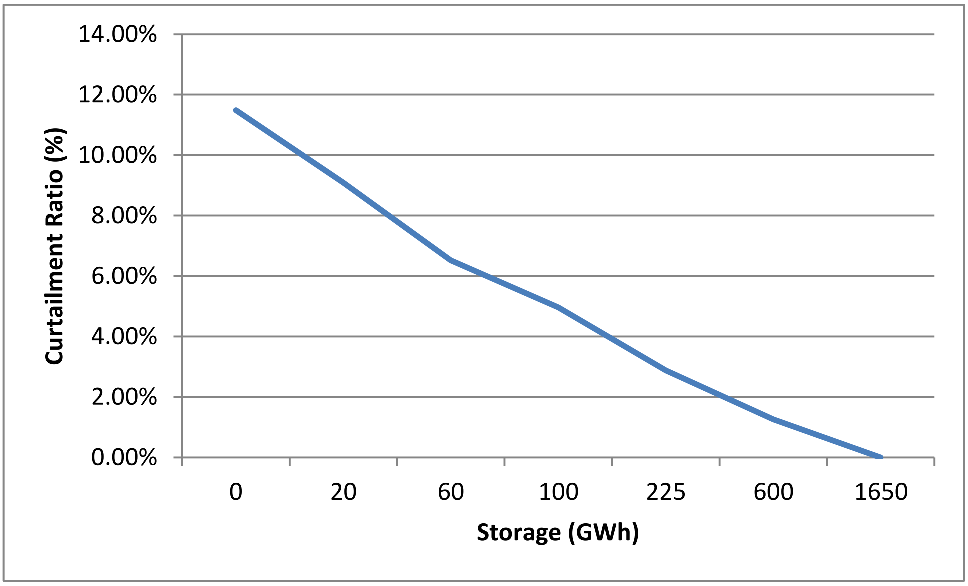


Figure 4-12: Wind Curtailment Ratio after Storage

For full utilization of curtailed energy huge storage capacity is required, but even with small storage capacity curtailment significant amount can be utilized. In this case, the importance of a cost-benefit analysis is clear. After deployment of 1.65TWh of storage it would be possible to utilize all the curtailed energy. However the deployment of this amount of capacity is likely to demand too much investment to be worthwhile.

Scenario12

	Wind	Average Wind Curtailment Ratio Before Storage (%)
S12	**5**	**13.47**

Half-Hourly Storage Requirement for Zero Curtailment (MWh)	National Grid Payment For Curtailed Wind Energy Before Additional Storage (M£)	Annual Total Energy Loss due to storage efficiency (GWh)
14,695	1,730	3,657

STORAGE (GWh)	600	2000	4000	8000	12000	13100
Wind Curtailment Ratio After Storage	7.43%	5.39%	4.35%	2.12%	0.32%	0.00%
Additional Utilized Wind Energy (GWh)	11,268	14,882	16,884	20,868	23,847	24,379
Curtailed Wind Energy After Storage (GWh)	13,111	9,497	7,495	3,510	531	-

Average Output of CCGT (MW)	2,233	1,433	1,157	611	65	-
Total Benefit by Utilized Wind Energy (M£)	799.9	1,056	1,198	1,481	1,692	1,730
Average Wind Energy Supply Share	32.04%	34.62%	36.08%	38.94%	41.20%	41.65%
Average Renewable Energy Supply Share	40.41%	42.99%	44.45%	47.31%	49.57%	50.02%

Table 4-18: Results for Scenario12

Scenario12 is based on extreme curtailment with extreme wind generation. Therefore, for this scenario the importance of storage systems is the highest of all scenarios. As seen from the table, the wind curtailment before additional storage can be completely utilized by **13.1TWh** of extra storage deployment. Figure 4-13 shows the change in curtailment ratio with increase in storage capacity.

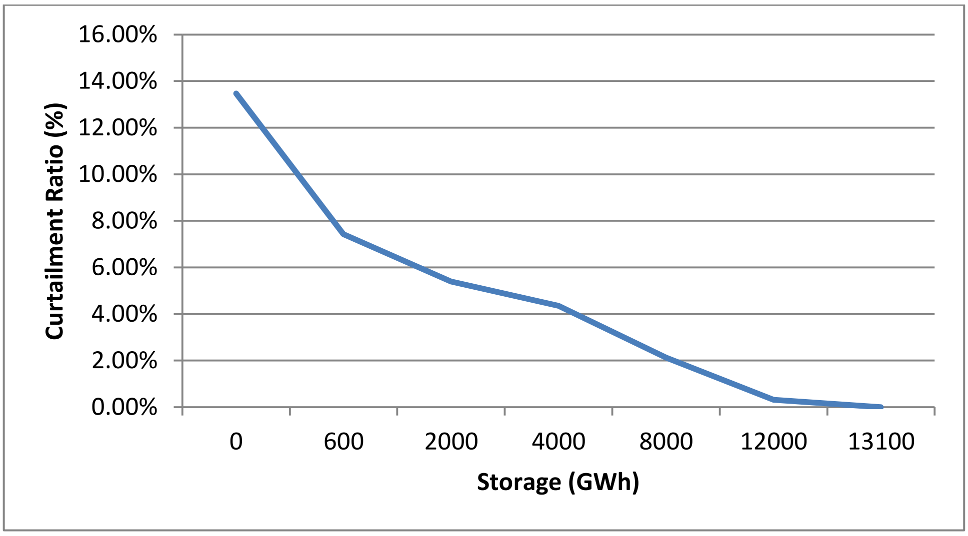


Figure 4-13: Wind Curtailment Ratio after Storage

As can be observed, **13.1 TWh** of storage capacity is required for full utilization, but with 12TWh almost all of the curtailed energy is absorbed. Figure 4-14 shows the change in CCGT use with the increase in storage capacity.

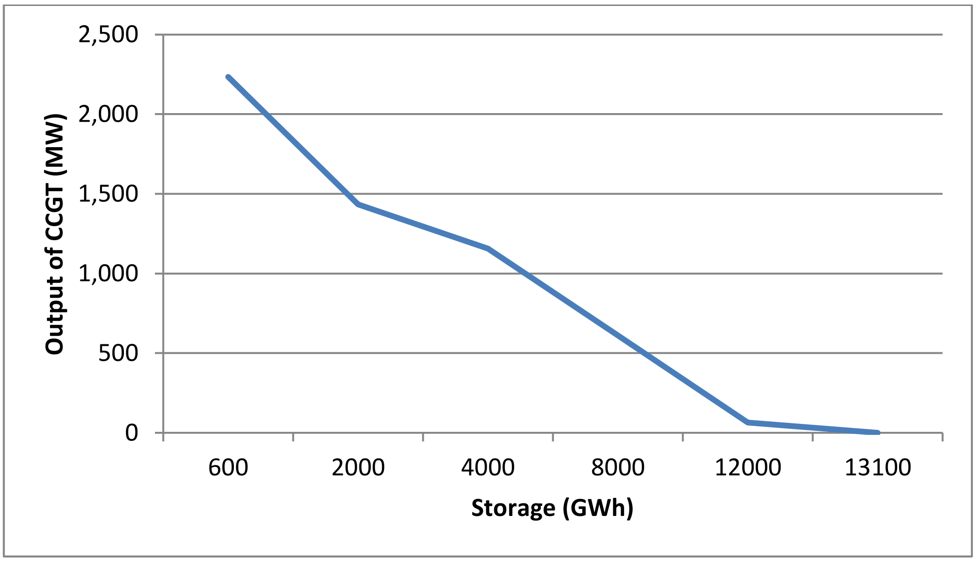


Figure 4-14: Average Output of CCGT (MW)

As observed from the figure above, under this scenario it is possible to avoid the use of CCGT with the help of storage systems. The CCGT figure follows a similar path to the figure of wind curtailment ratio. The importance of storage systems in the road towards a fully renewable energy supply is clearly illustrated by this scenario.

5. Discussion and Conclusion

5.1 Curtailment Profile

According to most forecasts and the outcomes of software models, it can be said that wind curtailment problem will become increasingly severe with the steady increase in wind farm installation, especially over Scotland where weak electricity networks will highly affect the curtailment ratio. Large-scale Energy Storage Systems (ESS) can play a major role in mitigating the problem.

In previous chapters, mostly the impacts of increases in wind turbine deployment are taken into account. In reality of course, future installation of power generators will not be restricted to wind farms. Since biomass and hydro power sources are dispatchable, expansion of these sources will not have an impact on energy curtailment ratios. Also, as mentioned in the second chapter, since solar farms in UK are mostly integrated into the distribution network, they will not have much impact on curtailment in the UK. But nuclear, which is non-dispatchable and has potential for deployment at very large scale can have direct impact to curtailment. Based on Model1 of the analytical software, Figure 5-1 shows the curtailment ratio before the provision of any additional storage, and shows values which rise steadily with an increase in nuclear energy generation. Demand and other energy suppliers' factors are as shown in Table 5-1. As in the analysis described in Chapter 4, the 'base-line' factor 1 quantities come from recorded 2015 data.

Demand	Wind	Coal	Nuclear	Solar	Biomass	Hydro	Other (Oil, OCGT, ICT)
1	2	1	x	1	1	1	1

Table 5-1: Energy suppliers' factors for nuclear deployment case

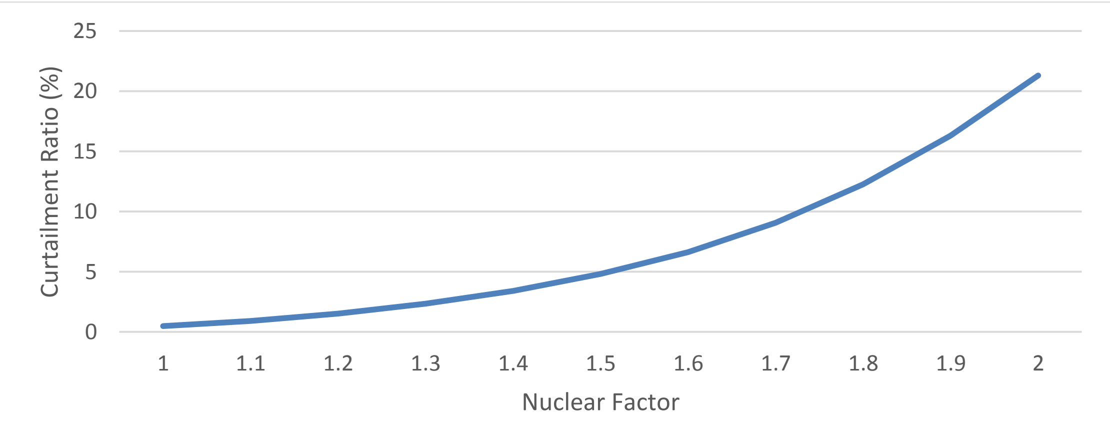


Figure 5-1: Curtailment ratio in accordance with the increase in nuclear generation

Clearly, one of the vital points arising from this is to pay attention in any co-development of nuclear power plants and wind farms. When nuclear plant and wind farms coexist in the same area, curtailment caused by energy surplus is almost inevitable. It can be reinforced by investigation of the curtailment map provided in the second chapter. The red turbines, which represent the most curtailed wind farms are in many cases located close to nuclear power stations. Wind farms and nuclear power plants might generally coexist in the same place with an intention that nuclear power can compensate for the intermittency of the wind farm, but this clearly does not work as planned. However, if storage systems were deployed properly and the capacity of them were enough to convert the wind farm into a dispatchable power source, then requirement to pair it with a more dependable source would disappear.

The capacity of transmission lines is another significant reason for curtailment. As previously stated, wind capacity in Scotland is big in comparison with the population and the generated electricity should ideally flow safely to England when there is not enough demand in Scotland. Therefore, reinforcement of the transmission infrastructure of the Scotland-England interface is vital. According to Electricity Networks Strategy Group's report in 2012, there are planned reinforcements for Scotland's transmission infrastructure, especially over Highlands, Western Isles, Orkney and Shetland (ENSG, 2012). For the Scotland-England interface, the transmission Boundary B6, currently has **2.2GW** capacity. Scottish Power is working to raise this boundary transfer capability from **4.4GW** to **6.6GW** by 2021. By the end of all planned reinforcement works, Scottish Power aims to increase overall transmission capacity from Scotland to England from 2.8GW up to 8.6GW (SP Transmission, 2013). This reinforcement can partially decrease the overall wind curtailment ratio, however the planned capacity of all new wind farm installations will be much more than the new transmission capacity, so the problem is likely to emerge again. Also curtailment problem caused by transmission infrastructure in some wind farms cannot be solved by reinforcement of transmission lines. For example, one of the main reasons of curtailment of Whitelee Wind Farm is due to 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 (Hoy, 2015). Although the curtailment can be reduced to some extent by reinforcement of the main transmission system, in many cases the problems with transmission are local ones and without action, the output cannot be completely utilized. The most effective way to utilize the curtailed wind energy of the any given wind farm is coupling with large scale storage systems.

5.2 Storage Deployment

As observed from the results, storage can play a vital role in utilization of curtailed energy and decrease in the use of CCGT. There is a significant outcome that should be taken into account here: the 'storage effect' has a decreasing trend, so a small amount of storage has a big impact on curtailment, however for full utilization of wind output a very considerable amount of storage capacity is required. Figure 5-2 shows the sensitivity analysis of Scenario4 to storage deployment.

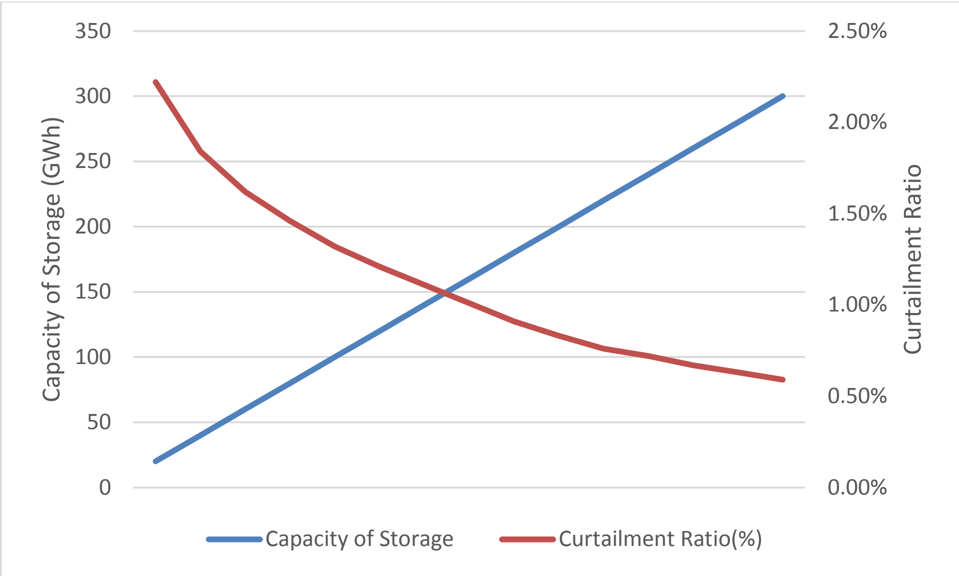


Figure 5-2: Curtailment Ratio vs Capacity of Storage for Scenario4

As seen from the figure above, with a linear increase in storage capacity the curtailment ratio is in a decreasing trend. This case is valid for all scenarios, so storage deployment should be based on a cost-benefit analysis. Regardless of efficiency and cost of the storage systems, it can be concluded that a small capacity of storage deployment is more cost effective larger deployments, in terms of the resulting amount of utilized energy.

Storage profiles that are used in the scenarios investigated are based on four types of storage. One of the main discussion points is about the potential capacity of storage types, especially those that require special topography.

According to a study conducted in 2013, the theoretical potential of PHS deployment over the UK is **6120GWh** and the realisable potential is **5292GWh** (Gimeno-Gutierrez and Lacal-Arantegui, 2013). When the Scenario8 is considered, which is based on only renewable electricity supply, 5292GWh of storage reduces the curtailment ratio from **9.07%** to **2.54%,** so a considerable amount of wind energy utilization can be met (potentially) simply by PHS deployment. As stated in the second chapter, UK currently has **26.78GWh** of PHS capacity, therefore there is still the potential of **5265GWh** of PHS instalment. Whether this is realistic is of course another question; there are major considerations over land use, environmental impact and cost.

There are only three CAES plants operating in the world and none of them is located in the UK. The research about CAES potential in the UK is currently being conducted by a consortium[21] which is funded by EPSRC and the results will be released in September 2016. As shown in **Map 2-4** the distribution of the possible underground storage sites in the UK are mainly located in parts of England and Northern Ireland. However, the big part of present and future curtailment is likely to be happening over Scotland. Therefore, CAES system is not in a strong option to utilize curtailed wind energy in the UK. In general, CAES systems have a good potential to be used as utility scale bulk storage, but require further development

As stated in the third chapter, EVs have the potential to be used as large scale storage systems. Theoretically all the EV cars on the road are available to charge and discharge, however practically it is not possible, because it will not be possible (or desirable!) to discharge a car while it is on the move. But as shown in Graph3.5, 80% of cars are stationary at any given time, and many of these could be connected and therefore available to the electricity network. For certain some car owners will not consider discharging their cars while parked a good idea.

However, this will not prevent using EV batteries to absorb curtailed wind power, as we are only considering energy flows in one direction. Assume that 60% of car owners do not want their cars while they are stationary, so even in this case **32%** of EVs can be used as large scale storage any time. As a result, for such an application of EV batteries, the amount of EVs required in the country should be tripled compared with the amount of EV outputs found in previous chapters. Therefore, when **Scenario1** is considered, it is safe to claim that, after advanced infrastructure is built, **15M** EVs are enough to utilize all the curtailed energy without requiring any other types of storage. Under this assumption, it can be said that, if EV charging technology allows using EV batteries as large scale storage system by 2020, **8GWh** of storage can be provided by EVs. But unfortunately it is not as simple as this; again the important point is the distribution of the EVs over the UK, especially the amount of EVs over the Highlands and big cities of Scotland which would act as the main input of utilizing curtailed wind energy by EVs.

[21] http://integratedenergystorage.org/

5.3 Cost

Cost of storage systems is perhaps the most controversial argument against wide scale storage deployment. So the benefit provided by storage systems must overcome the cost of them to make investments feasible. In the model presented so far, the only financial benefit is noted as the savings of National Grid payments. However decreases in gas and oil imports and reductions in carbon emission related costs are some other financial benefits of storage systems. The cost related values for storage profiles given in the chapter four are as seen in Table5-2.

STORAGE (GWh)	20	60	100	225	600
Total Energy Capital Cost of Storage (MIN) - 2015 (M£)	2,500	9,238	10,775	-	102,000
Total Energy Capital Cost of Storage (MAX) - 2015 (M£)	3,650	17,125	18,850	-	190,500
Total LCOS (MIN) - 2015	0.125	0.215	0.206	0.26	0.215
Total LCOS (MAX) - 2015	0.22	0.45	0.424	0.56	0.45
Total Energy Capital Cost of Storage (MIN) - 2020 (M£)	2,500	5,475	7,550	-	59,000
Total Energy Capital Cost of Storage (MAX) - 2020 (M£)	3,650	11,175	13,750	-	122,500

Table 5-2: Financial results for scenario profiles

Total minimum capital cost for 20GWh of storage deployment is calculated as **£2.5B** and in all scenarios the saving of National Grid payments by utilized wind energy is noted as the total benefit. In Scenario1 the total benefit from utilized wind energy by this same amount of storage is calculated as **£0,373B**. If such an investment is made, the return of investment (ROI) without considering the future value of money is **7 years**. If the investment is made by taking out loan with **6%** of annual interest rate by following formula, 'n' is found as **8.84** where 'n' represents the number of years for return of investment.

$$\frac{2.5 \cdot 0.06 \cdot (1.06)^n}{(1.06)^n - 1} = 0.373$$

Therefore, for such an investment, if credit is received from a bank with **6%** interest rate, it can be repaid in 9 years with only the savings from National Grid payments for curtailed wind energy. Also, based on Scenario1 the ROI for the maximum capital cost for storage profile1 is found as **10 years**. When other benefits of storage deployment are considered, such an investment can be regarded as highly profitable. It is important to note that **20GWh** storage profile is based on the mature types of storage. However, as discussed in previous chapters, those storage types require special topography, so they are not easy to deploy. Also, as stated above, CAES systems might not be an option for UK to utilize curtailed wind energy. It shows that the penetration of batteries into storage systems combination is highly important for future of storage deployment. As it can be seen, when other storage scenarios are considered, the capital investment cost increases because of the battery shares in combination. When the above financial calculation is applied for **SP2** in which **17.5GWh** of battery and **17.5GWh** EVs are added to the previous storage profile (SP1), the ROI is found as **18 years**. When the interest rate and future value of money are considered the return of investment would be later. Thus, although EVs do not have any impact on capital cost, for this case the return of investment is more than the lifetime of most of the batteries. But it is important to consider that the only benefit is taken as the savings of National Grid payments, so total benefits would be much more valuable than from this simple calculation. As stated in previous chapters, the most important benefit of batteries is that they can be deployed regardless of topography, water resource and location. A decrease in battery costs is vital for future storage systems deployment. **2020** capital cost for same storage profile is calculated as **£5.475B**, so after reduction in battery cost the ROI for the SP2 is **10.5 years** which is a reasonable duration for return of investment, especially when other benefits are taken into account.

For Scenario2, the total benefit from National Grid savings for 20GWh is **£155M**, while the total cost of constraint payments is **£192M**, so 20GWh of storage investment looks like the most economically feasible when compared with other storage options. For Scenario3 since there is not a big amount of curtailed energy, the benefits from National Grid payments are lower, however in such a case the benefits of storage deployment are quite high in terms of energy supply security, because storage systems have the ability to convert intermittent sources to reliable dispatchable sources.

For Scenario4, in which 2015 prices were taken into calculation, the total benefits from National Grid savings are vital points. The total payment made by National Grid is **£424.9M**, and it is possible to save **£380.7M** by 600GWh of storage deployment. However, the minimum capital cost for 600GWh SP is calculated as £102B, so if such an investment is made, the ROI is approximately **330 years** and when 2020 costs are taken the ROI is 1**54 years**. Therefore, for such a huge storage deployment any benefit by savings is not enough for feasible investment. For Scenario6 since there is a massive curtailment before storage, the payments from National Grid are huge but just like Scenario4, such a large amount of storage deployment requires high benefits to be feasible. For Scenario7, with 4TWh of storage deployment, it is possible to achieve 100% carbon free electricity supply. However, under today's circumstances this amount of storage requires £602.5B or the equivalent of 16.67 million EVs. Obviously, these values are massive, so such a scenario looks only theoretical or might happen in a few decades. But an important point is that battery storage could in future be separated from the availability of EVs. Present very intensive research into battery technology (largely driven by the automotive industry) might eventually lead to battery costs which make them attractive as fixed, local large-scale energy stores.

The most important cost related outcome of the scenarios investigated is that the amount of storage deployment should be investigated carefully. As shown in Figure 5-2, utilization of curtailment has a decreasing trend when the storage capacity increases linearly, and so does the cost. Figure 5-3 shows the capital cost of PHS deployment and total benefit for wind generation with factor three.

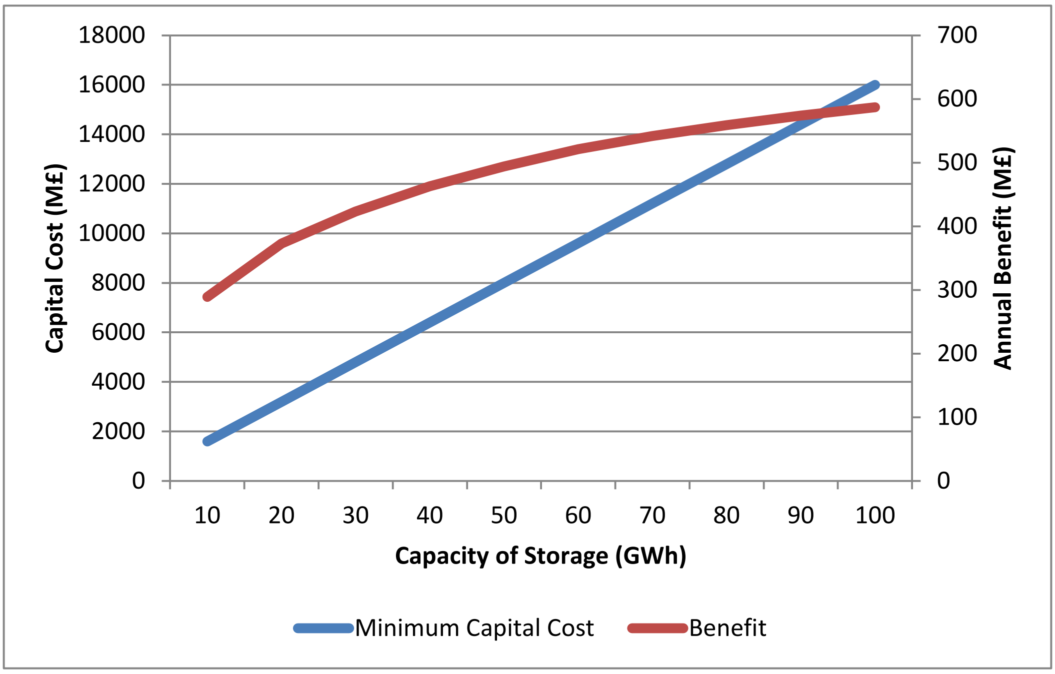


Figure 5-3: Capital Cost vs Benefit by National Grid Savings

As seen from the graph above, the decreasing trend of benefit and linearly increasing trend of capital cost should be carefully investigated. Therefore, optimum points for utilization and cost of storage should be defined in advance to make investments feasible. The ROI above **15 years** may not be regarded as feasible investment for storage. A further investigation can be related to an investigation of the more detailed financial benefits of storage systems and the realistic capacity of storage for a feasible investment.

The capital cost of energy storage systems will vary from **£90 to £770** per kWh and the upper bound of the cost is expected to decrease to around **£430** by 2020. LCOS of the storage systems shows that the most cost feasible storage type at present is PHS. But there is limited capacity for PHS development and PHS is highly location specific. Thus, it may not be possible to fully rely on PHS development to utilize curtailed wind energy. CAES is already a weak option for Scotland. So, the cost reduction in batteries is vital for utilizing future curtailed wind energy. As already stated, developments in the EV sector are promising for the future of battery costs.

6. Conclusion

The overarching goal of this dissertation has been to investigate the required storage deployment to utilize curtailed wind energy in the UK. The present UK wind profile has been investigated and the required forecasts have been conducted. A literature search for potential large scale storage systems and the developing concept of electric vehicles has been made. Based on these forecasts and the literature search, a variety of possible future scenarios have been generated. A software model has been developed based on Excel, and a number of defined scenarios have been run.

According to the present wind profile and forecasts for the UK, curtailment is already at unacceptable levels, and is likely to get worse. Curtailment generates bad publicity for the wind industry, useful energy is wasted and the related payments already reach surprisingly large amounts. Much of this curtailment takes place in Scotland, and plans to expand wind power here will only exacerbate the situation.

According to results presented here, large scale energy storage deployment can largely solve the curtailment problem. Moderate levels of storage deployment can have a significant impact, with further increases in capacity producing diminishing returns, so a vital point is to determine specific capacities to gain the optimum benefit. Given the present (and projected future) levels of payment for wind energy curtailment, the creation of extra storage capacity might be very cost-effective. More energy storage of course would confer other benefits not simply restricted to the management of wind energy.

One of the problems lies in predicting future wind curtailment, given the planned and possible future expansion of capacity. Improvements to grid infrastructure are likely and these will help, but many future wind developments will be in remote areas and full utilization of energy output will remain problematic. With any very significant expansion of wind energy exploitation (say to 5 times present levels), it seems that some level of curtailment will be an inevitable price that must be paid; the studies conducted here show that the complete elimination of curtailment requires unfeasibly large storage capacities.

In the near future, by **2023** around **100GWh** of extra storage deployment would keep the UK energy market relatively free from curtailment, with levels no greater than about 1% of total wind energy produced. But given the lead times required for any large-scale infrastructure projects, the situation is likely to get worse before it gets better.

Pumped hydraulic storage (PHS) remains the most suitable for the UK at large scale, but intensive work on electric vehicles (EVs) may bring the cost and performance of batteries to a level where they become competitive. There would then be the option of constructing distributed, local battery stores of varying size. But the presence of large numbers of EVs may also create storage (at no extra capital cost) to absorb surplus wind energy, and this is an enticing future prospect.

In conclusion, the author suggests that as an immediate step, nearby areas of wind farms over Scotland should be investigated for suitability to PHS construction, especially those areas that already suffer from energy curtailment. The possibility may soon arise for using EVs as storage systems; for this, infrastructure development is required and the required investment should be made as a matter of urgency.

7. Further Work

If time and available data had permitted, the following would have been added to the dissertation:

- Investigation of the required improvement in transmission infrastructure to utilize curtailed wind energy,
- Cost study of required infrastructure development to use EVs as large scale storage systems,
- Wind farm specific required capacity of storage to utilize all the curtailed wind energy,
- Investigation of the potential role of smart grids for decrease in curtailment.

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9. Appendix A

UK Storage Database (DOE, 2016)

Name	Rated Power (kW)	Duration at rated Power (HH:MM)	Type	Status	Paired Grid Resource	Location	Energy Capacity (kWh)
Foula Community Electricity Scheme	16	05:00	Lead-Acid Battery	Operational	19.2 kW PV Array, 15 kW hydro turbine	Isle of Faula, Scotland	80
Orkney Storage Park Project	2000	00:15	Lithium-ion Battery	Operational	N/A	Kirkwall, Orkney	500
Horse Island Microgrid Project	12	05:00	Lead-Acid Battery	Operational	18kW wind farm	Horse Island, Scotland	60
Foyers Pumped Storage Power Station	300000	21:00	Pumped Hydro Storage	Operational	Grid Interconnection , Transmission	Lochness, Scotland	6300000
Batwind Statoil	1000	01:00	Lithium-ion Battery	Announced	N/A	Peterhead, Aberdeenshire	1000
Isle of Rum Microgrid System	45	03:40	Lead-Acid Battery	Operational	45 kW hydro turbines, Back up Diesel generators	Isle of Rum, Scotland	165
Isle of Eigg Electrification Project	60	03:40	Lead-Acid Battery	Operational	32 kW PV system, 112 kW generation systems and a 24 kW wind farm	Isle of Eigg, Scotland	220
Isle of Muck Microgrid System	45	03:40	Lead-Acid Battery	Operational	Diesel Generator, 6 x 5 kW wind turbines, 33 kW PV array	Isle of Muck, Scotland	165
Cruachan Power Station	440000	22:00	Pumped Hydro Storage	Operational	Grid Interconnection , Transmission	Lochawe , Dalmally	9680000
Gigha Wind Farm Battery Project	100	12:00	Vanadium Redox Flow Battery	Contracted	Wind	Gigha, Scotland	1200
RedT-Southwest England	40	04:00	Vanadium Redox Flow Battery	Announced	N/A	United Kingdom	160

Northern Powergrid CLNR EES3-2	50	02:00	Lithium-ion Battery	Operational	Distribution Substation	Wooler Ramsey, Denwick	100
Northern Powergrid CLNR ESS2-2	100	02:00	Lithium-ion Battery	Operational	Distribution Substation	Wooler Ramsey, Denwick	200
330 MW - Gaelectric Compressed Air Energy Storage	330000	06:00	Compressed Air Storage	Announced	Renewables	County Antrim, Northern Ireland	1980000
AES Kilroot Advancion Energy Storage Array	10000	00:30	Lithium-ion Battery	Operational	Coal-Fired Generation Plant	Carrickfergus , Northern Ireland	5000
Northern Powergrid CLNR ESS3-1	50	02:00	Lithium-ion Battery	Operational	Distribution Substation	Rise Carr, Darlington	100
Northern Powergrid CLNR EES1	2500	02:00	Lithium-ion Battery	Operational	Distribution Substation	Rise Carr, Darlington	5000
Northern Powergrid CLNR ESS2-1	100	02:00	Lithium-ion Battery	Operational	Distribution Substation	Rise Carr, Darlington	200
Pre-Commercial Liquid Air Energy Storage Technology Demonstrator	5000	03:00	Liquid Air Energy Storage	Under Construction	Grid Interconnection , Primary Distribution	Bury , Lancashire	15000
Northern Powergrid CLNR ESS3-3	50	02:00	Lithium-ion Battery	Operational	Distribution Substation	Maltby , South Yorkshire	100
Dinorwig Power Station	1728000	05:00	Pumped Hydro Storage	Operational	Grid Interconnection , Transmission	Dinorwig , Wales	8640000
Ffestiniog Pumped Hydro Power Plant	360000	06:00	Pumped Hydro Storage	Operational	Grid Interconnection , Transmission	Ffestiniog , Gwynedd	2160000
Isentropic Demonstration Project	1400	04:00	Heat Thermal Storage	Announced	Grid Interconnection , Primary Distribution	Toton , Nottinghamshire	5600
EPSRC Grid Connected Energy Storage Research Demonstrator with WPD and Toshiba	2000	00:30	Lithium-ion Battery	Operational	11kV Substation	Wolverhampton , West Midlands	1000
ABB & UK Power Networks Energy Storage	200	01:00	Lithium-ion Battery	Operational	Grid Interconnection , Transmission	Hemsby , Norfolk	200

Installation							
WPD Falcon Project, GE Durathon	250	02:00	Sodium-nickel-chloride Battery	Operational	Grid Interconnection , Secondary Distribution	Milton Keynes , Buckinghamshire	500
Smarter Network Storage	6000	01:40	Lithium-ion Battery	Operational	Grid Interconnection , Primary Distribution	Leighton Buzzard , Bedfordshire	9960
EFDA JET Fusion Flywheel	400000	50 seconds	Flywheel	Operational	On Site Power	Abingdon , Oxfordshire	5555.556
250 kWh Berkshire Farm (Anesco UK)	250	01:00	Electro-Chemical	Operational	Renewables	Berkshire , England	250
5 kW / 40 kWh - redT Wokingham Development Facility	5	08:00	Vanadium Redox Flow Battery	Operational	Renewables	Wokingham , Berkshire	40
Slough Zero-Carbon Homes Community Energy Storage	75	01:00	Lithium-ion Battery	Operational	Renewables	Slough , Berkshire	75
Flat Holm Microgrid Project	5	05:00	Lead-Acid Battery	Operational	Back up Diesel Generator, 6 kW wind turbine, 2 solar arrays with ~8 kW output	Flat Holm Island , Wales	25
British Solar Renewables (BSR) and Western Power Distribution (WPD) Battery Storage Facility - RES	640	01:00	Electro-Chemical	Announced	1.5 MW solar park, at Copley Wood near Butleigh, Somerset	Butleigh , Somerset	640
Western Power Distribution-SomerSet	300	02:07	Lithium-ion Battery	Contracted	Renewables	Butleigh , Somerset	635
Slepe Farm: Solar + 250 kWh storage	598	00:30	Lithium-ion Battery	Operational	Solar PV	Dorset , England	299