Title: Technical Benefits of Energy Storage and Electricity Interconnections in Future GB Power Systems

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Highlights

1. A reference model of the 2012 GB electricity system was developed and validated.
2. Future scenarios for 2020 and 2030 were developed, based on industry data.
3. The maximum technically feasible wind penetration was calculated for each scenario.
4. Increasing interconnection and energy storage increases the maximum wind penetration.
5. Electricity system emissions can be reduced to $113gCO_2/kWh$.

Keywords

GB Energy System; Modelling; Simulation; Energy Storage; Interconnection; Maximum Wind Penetration

Abstract

There are concerns that the Great Britain (GB) electricity system may not be able to fully absorb increasing levels of variable renewables with consequent implications for emission reduction targets.[1] This study considers the technical benefits of additional energy storage and interconnections in future GB electricity systems. Initially a reference model of the GB electricity system was developed using the EnergyPLAN tool. The model was validated against actual data and was confirmed to accurately represent the GB electricity system. Subsequently, an analysis of four possible scenarios, for the years 2020 and 2030, has been performed and the maximum technically feasible wind penetration calculated. Finally, the level of interconnection and energy storage has been varied to assess the technical benefits to the operation of a 2030 GB electricity system. We conclude that increasing levels of interconnection and energy storage allows a further reduction in the primary energy supply and an increase in maximum technically feasible wind penetration, permitting the system emissions intensity to be reduced from 483gCO_2/kWh in 2012 to 113gCO_2/kWh in 2030. Increasing the levels of interconnection and energy storage will be fundamental to the delivery of a low carbon electricity system.

1. Introduction

As a result of the Climate Change Act 2008, the UK is required to reduce emissions by 80% on 1990 levels by 2050 [1]. Electricity generation accounts for 27% of the emissions in the UK. It is considered that in order to reduce emissions by 80% then the electricity system will have to be almost completely decarbonised [2] [3]. Also, European legislation requires the UK to reduce its emissions by 20% on 1990 levels by 2020, and for this reason the government has set targets for 40% of electricity to be generated by low carbon technologies by 2020 [4].

Beyond 2020 the UK is required to meet the targets set within the fourth carbon budget, a 50% emissions reduction on 1990 levels by 2025 [5]. To meet these targets the Climate Change Committee have stated that 30-40GW's of low carbon capacity needs to be added to the power system through the 2020's [6]. In 2012, renewables (11.3%) and nuclear (19%) contributed to 30.3% of the UK's electricity generation [7]. In order to meet the targets, it is expected that wind power will contribute to a significant proportion of the UK's low carbon electricity generation [4].

Wind is a variable and non-dispatchable technology that presents challenges to the power system. Wind penetration can be defined in both capacity (wind power capacity as a percentage of peak load

[1] While the decarbonisation targets consider the whole of the UK, the analysis within this study refers to the GB electricity system, which is owned and operated by National Grid Plc.

capacity) and energy (wind power generation as a percentage of demand) metrics [8]. Studies have shown that the technical and economic impacts of additional wind capacity on the power system are very system specific [9]. The impacts of increased wind penetration are a function of many factors; not least, wind resource, geographical aggregation of wind turbines, interconnections to neighbouring electricity systems and the integration of the electricity sector with other energy sectors, specifically heat and transport. Thus in the case of Denmark, a country with a significant wind penetration, the system has a high level of interconnection (Norway (1.04GW), Sweden (2.64GW) and Germany (2.38GW southbound 2.1GW northbound), large integration of heat and electricity (due to a high level of combined heat and power plants) and a strong wind resource [10]. In the case of GB, there is little integration between electricity and heat. While the GB system has a number of interconnectors (to France 2GW, Ireland 0.5GW and The Netherlands 1GW), relative to the size of the peak demand this is very small. In summary, relative to the Danish system, GB has a very rigid energy system.

As the level of wind capacity in the GB system increases, it will become increasingly important to ensure that the system remains resilient. As there is no certainty that periods of high electricity demand will coincide with periods of high wind, the power system will have to have a high level of dispatchable capacity and/or an increasing level of demand response. As Wilson et al. [11] suggest, a means of achieving this is to increase the level of energy storage within the power network. Wilson et al. [11] provide a review of the technology options and suggest that further research is required into the amount and location of energy storage that should be incorporated into the electricity grid.

In order to understand the requirements of interconnection and/or energy storage in a future GB high wind electricity system, a full analysis of the electricity system is required. Gross and Heptonstall [12] report that it is not adequate to analyse independent generators to understand the costs and impacts of intermittency. In 2010, Connolly et al. [13] presented a comprehensive review of the computer tools used for analysing the integration of renewable energy into various energy systems [13]. In this study, the EnergyPLAN tool has been employed. The deterministic, hourly simulation model optimises the operation of the system and allows for a choice of regulation strategies.

The tool is open source and has been used in a number of academic studies. Studies have considered large scale integration of renewable energy [14] [15] and [16], 100% renewable energy systems [17], [18] and [19] and the benefits of energy storage [20]. The tool has also been used to simulate both national and regional energy systems [21], [22] and [23] While EnergyPLAN has been used for a study of the GB system previously, the aim was to find the optimal level of wind generation, based on the total cost of the electricity supply [16].

Uniquely this study, specific to GB, considers an in depth analysis of a number of system structures in order to quantify the technical improvements that energy storage and interconnection can bring to a high wind GB power system in the years 2020 and 2030. The structure of this paper is as follows: in section 2 the methodology, data used and details of the energy storage and interconnection scenarios are discussed. Section 3 provides the results and a discussion, including an in-depth analysis of one of the scenarios and finally section 4 provides a conclusion.

2. Methodology

2.1. EnergyPLAN Advanced Systems Analysis Tool

The EnergyPLAN tool considers the three main energy sectors of an energy system: electricity, heat and transport. In GB, there is little integration between the three sectors and for this reason this study focusses solely on the electricity sector. In the future , to utilise renewable energy more effectively, GB will have to better integrate the energy system and it is expected that both the heat and transport sectors will become electrified [24]. In reality, to move to an entirely decarbonised electricity system then the whole energy system will have to change; smart technology to reduce demand peaks, electrification in the transport sector and energy demand reduction through increased efficiency and behavioural changes will be required to ensure that the UK meets its strict emission reduction targets and maintains a secure energy supply.

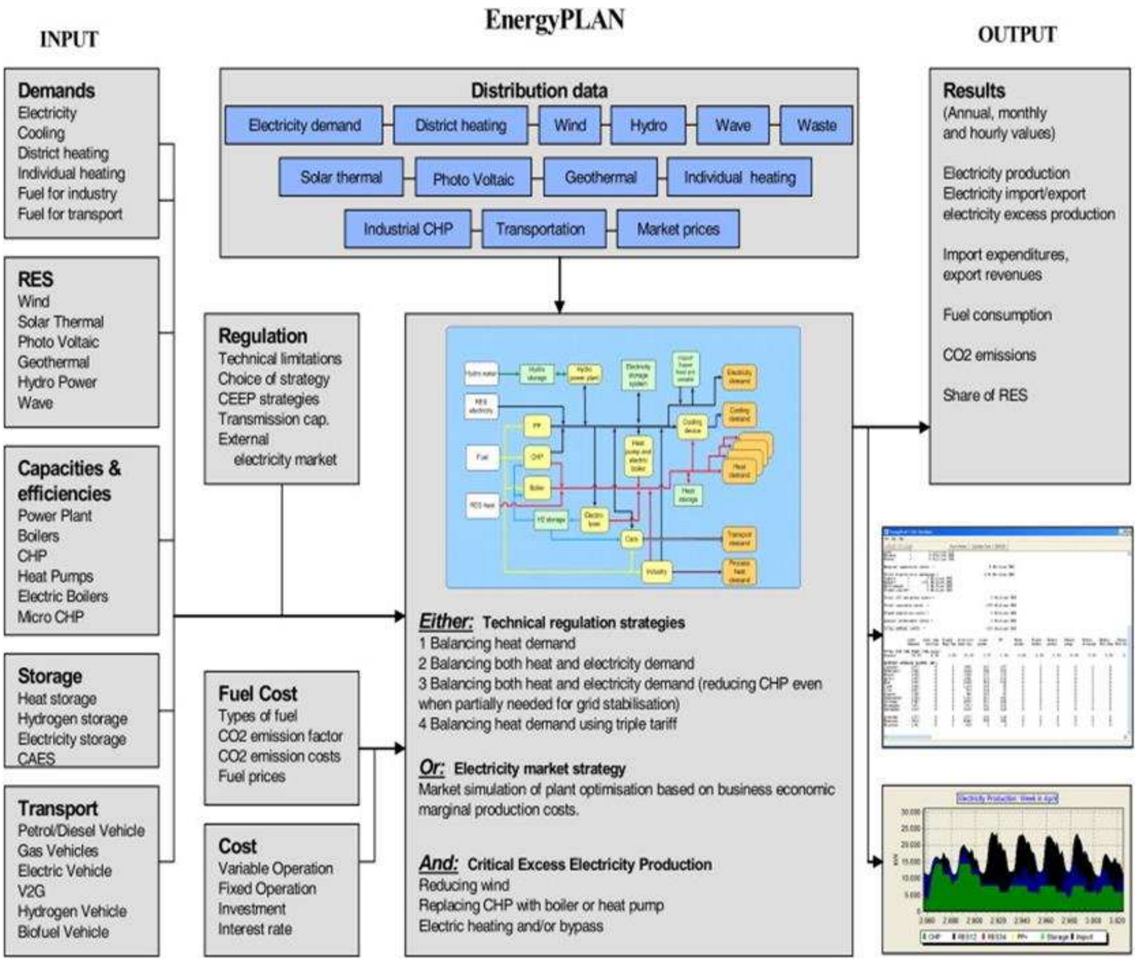

Figure 1 – Structure of the EnergyPLAN advanced energy system analysis tool [21].

A full user manual for the tool can be found in [25] and the overall tool structure is shown in Figure 1. There are many inputs that are required, including demand distributions, energy production distributions from renewable sources, generation capacities, efficiencies and a choice of regulation strategies.

2.2. Reference Model Data

The required model inputs are now briefly discussed. It should be noted that the EnergyPLAN tool requires many inputs and assumptions and thus it is vital to ensure that the model is validated against actual data. A description of the validation process can be found in [26]. The year 2012 was chosen as the reference model due the availability of recent and reliable data.

Electricity Demand: Actual hourly demand and supply data is available for the GB electricity system and thus requirements for assumptions are reduced. The first parameter to input is the electricity demand and the hourly demand was retrieved from National Grid and compared against [7], [27] and [28] [2,3]. The total annual demand [4] (less demand for Northern Ireland[5]) was retrieved from [7].

Hydropower: The hydropower distribution was obtained from [29]. The GB hydropower capacity has been relatively stable for many decades, and while it's relative energy contribution is small, it is critical to the balancing of the system [30].

Pumped Storage: GB has four major pump storage stations with a total storage capacity of 27.6GWh [31]. The power output, head, volume and energy stored for each of them can be found in [32]. At present, Scottish and Southern Electricity (SSE) are considering the construction of two plants in Scotland, Coire Glas and Balmacaan, and these would both have capacities between 300-600MW and would add a potential combined storage capacity of 60GWh to the GB system [33].

Nuclear: The planning and construction of new nuclear plants in GB is an extensive process. The potential extension in lifetime of the AGR reactors means that it is unlikely that the capacity will change significantly by 2020. Beyond 2020, it is exceptionally difficult to predict, due to the current issues for the funding of nuclear plants. For the 2030 scenarios, data is taken from reviewed scenarios.

Conventional Generation: Under the Large Combustion Plant Directive, the operation of unabated coal power plants is being significantly reduced and there are currently no plans for any unabated coal plants to be built [34]. While the coal capacity is reducing, the capacity of combined cycle gas turbine (CCGT) plants continues to increase in the UK. The government has suggested that up to 41GW may be operational in 2030 [35]. However, industry scenarios show a greater level of gas capacity in 2030 [27] [28].

Wind: The wind power time series for the year 2012 was obtained from [29]. The time series contains 8784 aggregated hourly output values for all wind farms in GB. A correction factor was applied to the data to reflect the increase in offshore wind that is expected in a high wind GB system. This factor takes into account the likelihood that many of the new wind

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[2] Note that the DECC figures include the whole of the UK (England, Scotland, Wales and Northern Ireland). National Grid is the system operator for GB (England, Wales and Scotland) and thus there is a difference between the figures. This study is concerned with the GB system (owned and operated by National Grid Plc.) and thus the system demand is the total UK demand minus the demand for Northern Ireland (including station loads, pumping demand and losses).

[3] Within the UK Future Scenarios Report, the total GB demand is listed as 328TWh for 2012. However, this does not include continental exports, pumping loads and station loads.

[4] In this study the demand refers to the total electricity demand and includes losses, pumping demand imports and station loads and net Imports.

[5] A value of 8TWh was subtracted for Northern Ireland, equal to the average generation for 2009, 2010 and 2011. The 2012 sub national statistics were unavailable at the time of publishing.

farms will be built offshore in locations that have a greater wind resource. The correction correlates to load factors of 0.262 and 0.352 for onshore and offshore wind, respectively, in line with the average load factors achieved in 2012 [36].

Interconnectors: GB has a number of existing interconnectors (France 2GW, Netherlands 1GW, Ireland 0.5GW) and further projects have been proposed to Norway, Belgium and France [37]. Interconnectors are discussed in more detail in section 2.4.1.

Solar PV: Given the greater load factor for wind, in each of the scenarios presented it is unlikely that solar would generate more than 15% of what wind generates in GB. Take an example of a high nuclear scenario (see Table 1), with 25GW of wind and 8GW solar. Using the 2012 load factors [36], 29% for wind and 10% for example, wind would generate 63.5TWh and solar 7Wh (or 11% of that of wind) in a year with 8760 hours. It is however, important to model solar as it is a form of variable renewable generation that can have an impact on critical excess electricity production (CEEP) and primary energy supply (PES). A time series of solar was obtained with the EnergyPLAN software.[6] The output was validated against [36].

2.3. Energy System Scenarios

After the reference model has been validated against actual data, a full technical system analysis can be completed. The scope of this study is to quantify the potential technical benefits that storage and interconnection can bring to electricity systems that have a high level of renewable penetration. Four scenarios (shown in Table 1) have been developed for the years 2020 and 2030, drawing on the National Grids own energy scenarios [27] [28];

- Scenario 1 (Slow Progression 2020): Uses assumptions from the National Grid slow progression scenario for the year 2020.
- Scenario 2 (Slow Progression 2030): Models the year 2030. The scenario uses a combination of the National Grid slow progression scenarios and some of the authors own interpretations for the year 2030.
- Scenario 3 (Gone Green 2030): Is a ‘gone green approach’. In this approach the system has a much greater level of wind energy in the electricity system.

[6] A number of solar time series for different years and different countries are available with the EnergyPLAN software. The sensitivity of these was checked to ensure that the series used was not critical to the results. In all cases the distributions had little impact on the overall results, due to the low solar capacity and low load factor in comparison to both wind. In 2012, solar also contributed less than 1% of total system demand.

- Scenario 4 (High Nuclear 2030): A scenario with increased demand and nuclear capacity. This scenario has a lower level of solar and wind than the gone green scenario .

	Slow Progression 2020	Slow Progression 2030	Gone Green 2030	High Nuclear 2030
Demand (TWh)	343	327	353	375
Unabated Gas (GW)	36.70	48.50	40.00	50.00
Unabated Coal (GW)	13.70	0	0	4.00
Biomass (GW)	5.00	5.00	4.20	5.00
CCS (GW)	0	0	4.60	0
Nuclear (GW)	9.00	9.30	12.70	20.00
Wind (GW)	17.60	34.40	57.00	25.00
Solar (GW)	3.40	6.10	15.80	8.00
Hydropower (GW)	1.55	1.55	1.55	1.55
Pumped Storage (GW)	2.74	3.94	3.94	3.94
Reservoir Storage Capacity (GWh)	29.30	89.30	89.30	89.3
Interconnector (GW)	5.20	8.40	7.10	8.00
Total Plant Capacity (GW)	94.89	117.19	146.89	125.49

Table 1 – Generation mixes for the four different scenarios[7].

[7] The difference between the National Grid annual electricity demand of 328TWh and DUKES demand (minus Ireland) of (368TWh) has been taken into consideration. Thus when using National Grid future energy scenario demands, 40TWh has been added to the value. The difference is due to the considerations of station load, pumping load, interconnector flows and embedded generation.

2.4. Energy Storage and Interconnection Scenarios

The technical analysis in EnergyPLAN uses an optimisation strategy that seeks to minimize fuel consumption as described in [25]. After performing a technical optimisation of each of the original systems the energy storage and interconnection levels within the scenarios are varied to assess the technical benefits. This section provides the rationale for the levels of energy storage and interconnection that could be technically achievable within the 2020 and 2030 electricity system scenarios.

2.4.1. Interconnection

The operational and proposed GB interconnectors were listed in section 2.2 and there are a total of 7.35GW that are currently considered, see **Error! Reference source not found.**. The price and volume of electricity flows through interconnectors are determined by the price imbalance between the two connected regions [11]. As Wilson et al. [11] mention, the ability of interconnectors to increase resilience is dependent on the difference in the plant mix across the two connected regions. The price across Europe may be high at low wind periods and it is for this reason that there is a concern over the feasibility of using Norway, a country with almost half of Europe's hydropower reservoir capacity [38], as an energy battery for Europe. If many European countries move towards high wind systems, the demand and value of dispatchable capacity may increase significantly. Detailed modelling of the interconnected regions is required to fully understand the profitability of interconnectors.

Name	Capacity (MW)	Status
GB – France	2000	Operational
GB – Northern Ireland (Moyle)	500	Operational
GB - Netherlands	1000	Operational
GB – France	800	Under Development (2020)
GB – Ireland	350	Under Development
GB – Ireland	500	Under Development
GB - Norway	1200	Proposed (2020)
GB - Belgium	1000	Proposed (2018)
Total	7350	

Table 2 – Capacity and status of GB electricity interconnectors [11].

This study considers the technical optimisation and initially assumes that 75% of the capacity is available for export during high wind scenarios. This value was assumed as much of the existing and planned interconnection capacity is to countries with low wind penetration. Specifically 4GW of the planned and operational capacity is to France and Norway, neither of which have high wind systems. A sensitivity study of this parameter is included, see section 4.2. Further work is required to understand the ability of interconnectors to contribute to supply security and this will likely require a pan European electricity market model., which is out with the scope if this study.

The potential change to the maximum technically feasible wind capacity is assessed under differing interconnection scenarios and total interconnection capacities of 0GW, 3GW, 6GW, 9GW and 12GW are assessed. While 12GW is considered to be highly ambitious, it has been included to highlight the benefit of a well-connected GB electricity system.

2.4.2. Energy Storage

As discussed in the introduction, a large increase in renewable generation will create new challenges for the operation of the electricity system and storage has been outlined as a technology to manage some of these challenges [11]. A number of storage technologies exist and are at varying stages of development.

Pumped hydroelectric storage has existed in the GB system for a number of decades and the largest station, Dinorwig, was developed under the Central Electricity Generating Board (CEGB). While, at present, no large scale sites have been developed since the liberalisation of the electricity market, SSE has proposed two schemes [33]. Coire Glas and Balmacaan are considered to be technically feasible and each could have a capacity of 600MW with 30GWh of storage [39].

A second potential bulk energy storage technology is liquid air. At present the technology is not fully commercialised, however, the potential for liquid air in the UK was outlined in a report by the liquid air network [40].

As with interconnection, a number of energy storage scenarios are considered. Installed capacities of 0 – 8GW and a range of volumes are modelled. It should be noted that the storage volumes are site dependent. For example, Dinorwig (1700MW) has a storage volume of 9GWh, yet the storage volume at Coire Glas (300MW+) has a potential for 30GWh. A single LNG storage tank could have the ability to store enough liquid air to generate 16.6GWh of electricity [40]. These statistics show that when discussing storage, it is not only important to discuss the capacity of the storage device but also the quantity of stored energy. Historically, storage units may have been used for rapid response and to stabilise the grid. However, with the increase in variable renewables, optimising the level of stored energy becomes increasingly important, so that energy can be either generated or absorbed for a longer period of time.

2.5. Calculating the Maximum Technically Feasible Wind Penetration

This section describes the method for calculating the maximum technically feasible penetration of wind.

As the level of wind in the system increases, excess production of electricity becomes a greater issue. Due to a grid stabilisation share of 30% (as used in [41]) and an inflexible nuclear capacity, at periods of low electricity demand and high wind speeds (with high installed wind capacity), excess wind generation is likely. The EnergyPLAN tool calculates the critical excess electricity production (CEEP); this is a summation of the excess electricity at each hour. Also, the EnergyPLAN tool calculates the primary energy supply (PES).

In this study, the maximum technically feasible penetration for wind has been calculated using the same approach as described in [21]. This approach calculates a compromise coefficient (COMP), namely from the changes in CEEP and PES between increasing levels of wind generation.

As described in [21], the maximum technically feasible level of wind occurs when the increase in electricity that has to be exported is greater than the reduction in energy required to power the electricity system. The COMP coefficient is used to define this value. The COMP coefficient is the ratio between the reduction in PES (ΔPES) and the increase in CEEP (ΔCEEP) in each simulation.

$$COMP = \Delta PES/\Delta CEEP$$

Equation 1 – Compromise coefficient used for calculating the maximum technically feasible penetration of wind.

Table 3 provides an example of the calculation of the COMP coefficient for the reference system, showing that between 45 and 46GW, CEEP increases by 1.09TWh/year and PES reduced by 1.14TWh/year. Between 46 and 47GW, CEEP increases by 1.14TWh/year and PES reduced by 0.99TWh/year. Thus moving from 46 – 47 GW shows an increase in CEEP that is greater than the reduction in PES. This is past the technically optimum point defined by the COMP coefficient. When COMP is greater than 1, the PES reduction is greater than the increase in CEEP. When COMP is less than 1, the PES reduction is less than the increase in CEEP and hence is past the maximum technically feasible wind penetration. For a further example of this see [21].

Wind Capacity (GW)	Wind Generation (TWh)	CEEP (TWh/year)	PES (TWh/year)	COMP ΔPES/ΔCEEP (-)

42	119.93	11.59	664.5	
43	122.78	12.55	663.05	1.51
44	125.64	13.55	661.71	1.34
45	128.49	14.59	660.46	1.20
46	***131.35***	***15.68***	***659.32***	***1.05***
47	134.2	16.82	658.33	0.87
48	137.06	18.02	657.49	0.70

Table 3 - CEEP, PES and COMP for Increasing Wind Penetrations for the Reference System

The increase in CEEP and reduction in PES is further highlighted in Figures 2 and 3. In Figure 2, until approximately 15% wind penetration there is virtually no CEEP in the system; however this increases very quickly at around 25%. Figure 3 illustrates the change in PES for an increasing wind penetration and at around 35% the PES begins to increase.

Using this COMP coefficient, the maximum technically optimised level of wind in the reference system occurs at a wind penetration of 31% (46GW). At this level, renewables account for 42% of the electricity supply and the PES is 659.32TWh. The emissions at this wind penetration level are 290.4gCO_2/kWh. While such a system would be a significant improvement on the 2012 system, in order to meet the carbon targets, emissions will require to be significantly reduced beyond this value.

The sensitivity of the CEEP curves for the four scenarios will be tested against different levels of energy storage and interconnection, in order to better understand the technical benefits to the electricity systems.

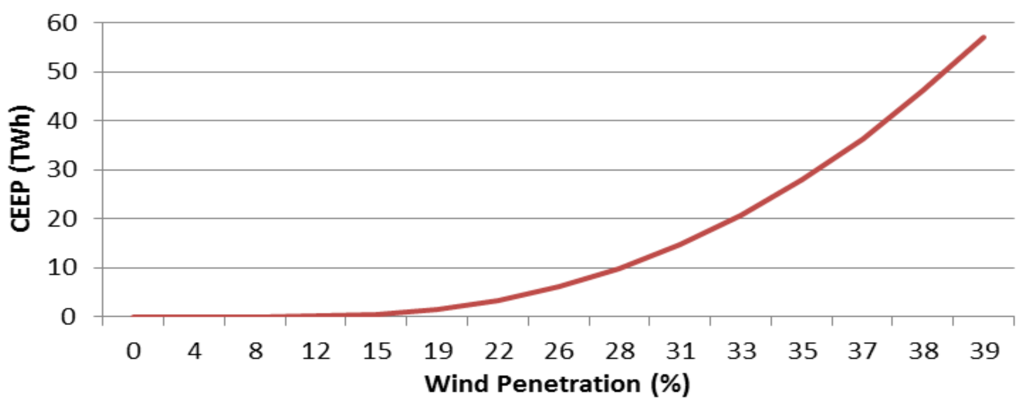

Figure 2 - Curtailment in the GB electricity system under increasing wind penetration.

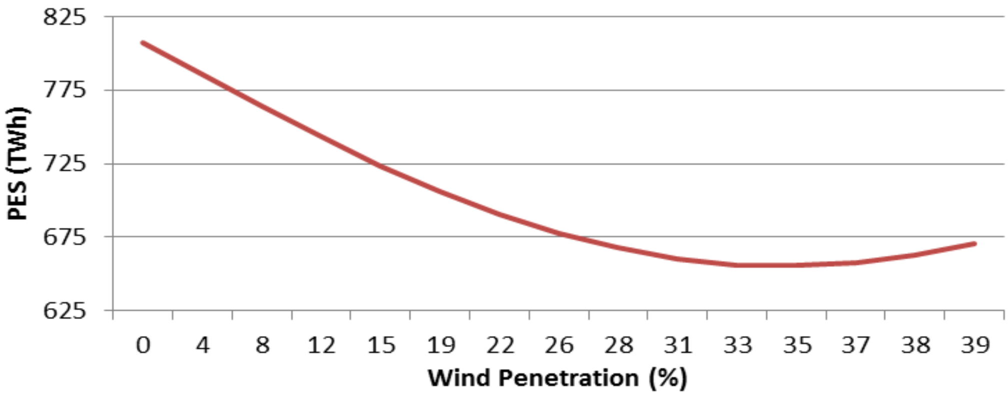

Figure 3 – Change in PES with increasing wind penetration.

3. Results and Discussion

3.1. Reference Model Accuracy

As mentioned in section 2.2, the validation procedure for the reference model can be found in [26] and therefore is not described in detail here. The calculated annual and monthly electricity demand was compared against the National Grid values [42] and found to be simulated correctly, as shown in Table 4[8].

Month	Average Monthly Electricity Demand (MW)		Difference (MW)	Percentage Difference
	Modelled GB (2012)	Actual GB (2012)		
January	39820	39280	540	1.37
February	40616	40682	-66	-0.16
March	36374	36596	-222	-0.61
April	34996	34868	128	0.37
May	33494	33578	-84	-0.25
June	31442	31626	-184	-0.58
July	31325	31196	129	0.41
August	31111	31102	9	0.03
September	31988	32093	-105	-0.33
October	35123	34834	289	0.83
November	38037	37864	173	0.46
December	38733	39037	-304	-0.78

Table 4 – Comparison of the modelled monthly electricity demand to the actual electricity demand.

After validating the demand side of the model, the electricity from the various generators was compared against the actual annual production [36]. Table 5 shows that the modelled production from wind, hydro, solar, power plants and nuclear was within reasonable tolerance of the actual production.

Production Type	Modelled Production (TWh)	Actual Production (TWh)	Difference TWh	Percentage Difference
Wind	19.65	19.58	0.07	0.36
Hydro	5.25	5.28	-0.03	-0.57
Solar	1.17	1.18	-0.01	-0.85
Power-Plants	263.37	264.40	-1.03	-0.39
Nuclear	71.54	70.05	1.49	2.13

Table 5 – Comparison of the modelled and the actual electricity production.

[8]For the reference model a demand of 368TWh has been used. This figure has been derived (as discussed in footnote 6) as there was no available real data to validate. To ensure that the demand was being simulated correctly, National Grid INDO data was used for the validation. However, the INDO data does not take into consideration station load, pumping loads and interconnector exports.

Due to the aggregation of power plant units in the EnergyPLAN model, the production for coal, oil and gas plants could not be validated independently. However, the annual fuel consumption for each fuel could be compared against [7]. Table 6 shows that the model is within reasonable tolerance. Therefore, having compared the model data to actual 2012 figures the reference model was considered to be accurate and a suitable platform for the four scenarios.

Fuel	Modelled Fuel Consumption (TWh)	Actual Fuel Consumption (TWh)	Difference TWh	Percentage Difference
Natural Gas	206.53	214.15	-7.62	-3.56
Coal	398.32	399.25	-0.93	-0.23
Oil	8.85	9.08	-0.23	-2.53

Table 6 – Comparison of the modelled fuel consumption to the actual fuel consumption[9].

3.2. Scenarios Results

Table 7 shows the results of the technical optimisation for the four scenarios. As with the reference system results, the coal, oil and gas consumption are included. As expected, the gas consumption increases in each of the systems, as more coal and oil power stations are limited in the operation.

Parameter	Slow Progression 2020	Slow Progression 2030	Gone Green 2030	High Nuclear 2030
Natural Gas (TWh/yr)	349.65	332.34	256.77	309.42
Coal (TWh/yr)	132.44	0	0	29.12
Oil (TWh/yr)	0	0	0	0
Wind (TWh/yr)	50.05	93.18	124.41	68.33
Hydro (TWh/yr)	5.25	5.25	5.25	5.25
Nuclear (TWh/yr)	64.74	64.74	91.95	143.86
Solar (TWh/yr)	3.73	6.51	16.85	8.53
CEEP (TWh/yr)	0.03	5.04	38.35	3.05

Table 7 – Fuel consumption and power production for the four scenarios.

The wind and solar generation levels vary significantly across the scenarios and as expected the systems with a higher renewable penetration experience the greatest levels of CEEP.

Table 7 shows the results of a static analysis. The wind in each of the scenarios was then varied from 0 – 60GW, in increments of 5GW, and the wind curtailment calculated. The maximum technically feasible wind penetration was calculated using the COMP coefficient, described in

[9] As sub national fuel consumption statistics are not available from DECC, the whole UK system (i.e. demand equal to 376TWh/yr) was modelled to validate fuel consumption data. It should be noted that Northern Ireland's contribution to UK capacity is less than 3% and of this 83% is conventional thermal generation. As thermal units are measured as a single unit in EnergyPLAN, the total consumption is not affected significantly.

section 2.5. Figure 4 shows that under each of the scenarios, the patterns for wind curtailment are very similar.[10] Further, until 20GW of wind capacity, there are few periods with CEEP. However, after 20GW this increases very quickly. To be technically beneficial, increasing the storage and interconnection capacity should reduce both wind curtailment and primary energy supply.

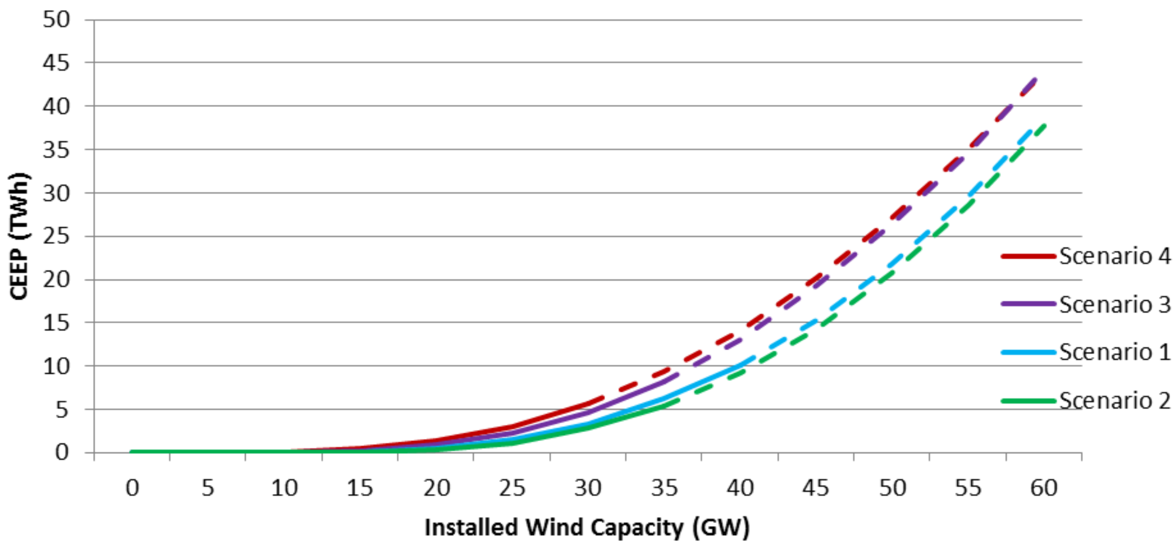

Figure 4 – Increase in the curtailment with wind capacity.

Table 8 shows the specific values for the maximum technically feasible wind penetration, both in terms of percentage of electricity supply and wind capacity. The system emissions at the maximum penetration are also shown.

	Slow Progression 2020	Slow Progression 2030	Gone Green 2030	High Nuclear 2030
Maximum Technically Feasible Wind Penetration (% of supply)	31	30	26	21
Maximum Technically Feasible Wind Capacity (GW)	42	37	35	30
Emissions at Maximum Wind Penetration (gCO_2/kWh)	260	202	174	185

Table 8 – Maximum technically feasible wind penetration and system emissions for each scenario.

As shown in Table 8, the gone green scenario has a maximum technically feasible wind penetration of 26% (35GW), the equivalent to 91.73TWh, well below the 57GW listed in Table 1. In this case there is a difference of 24GW between the technically optimised penetration and the scenario value. The CEEP within this scenario (at 57GW wind capacity) is the equivalent to over

[10] The point in which the solid line becomes dashed illustrates the maximum technically feasible wind penetration in each of the scenarios.

10% of the total electricity demand. Thus the system is not operating in a technically efficient manner. While installing the maximum technically feasible capacity of wind would significantly reduce emissions, the potential for further emission reductions is limited and thus remains well above that required to decarbonise the electricity supply.

It is acknowledged that the market may provide the opportunity for a greater level of wind to be installed, i.e. in a situation where the cost of coal and gas is so high that even with a high rate of wind curtailment; new wind capacity could remain a profitable investment. Le and Bhattacharyya [16] calculate the optimum level of wind to be integrated into the UK system to be 80TWh, using the 2012 wind data; this would be the equivalent to 28GW. This suggests that the gone green scenario will neither be technically or economically optimised. For example, building 57GW of wind into a system that has a total supply cost optimised wind capacity of 28GW, and a technically optimised wind capacity of 32GW, would lead to a very expensive and inefficient system. Further, the emissions remain well above the level required to decarbonise the system.

The maximum feasible wind penetration in the high nuclear scenario is just 21% (or 27GW). While the wind level shown in Table 1 is technically feasible, the system does not have much scope to further increase the wind capacity. Should the GB system develop to have a high level of inflexible nuclear capacity and wind generation, a high level of CEEP would be expected, unless significant measures were taken. These measures may include, but are not limited to, interconnection, energy storage, greater integration with the transport sector (for example electric vehicles) or demand side response.

Both slow progression scenarios are technically feasible; however if the wind capacity was increased to the maximum wind penetration, the emissions in both systems remain in excess of 200gCO_2/kWh. While compared to 2012, this is a significant emissions reduction; the requirement for 2050 is the near decarbonisation of the electricity system. It is clear that the system has to operate in a more technically optimised manner to meet the emissions targets and a high capacity of wind and solar alone will not provide sufficient carbon reductions.

From a systems perspective, CEEP and PES can be reduced by demand side response, energy storage, interconnection and by increasing plant flexibility. In this study we now investigate the impact of the changes in energy storage and interconnection.

3.3. Changes to Energy Storage and Interconnection

The initial results can give some insight into the operation of the system. It is clear that the systems are not technically optimised and at high wind penetrations will be subject to high levels of curtailment. The scope of this study is to understand the potential benefits of increasing energy storage and interconnection to the maximum technically feasible level of wind and we show that this can be done by increasing interconnection and energy storage.

For clarity, only the gone green scenario has been included within the results. (It should be noted that the results of all the scenarios follow the same general trends). It is perhaps unlikely that a high level of interconnection, energy storage and wind will be installed by 2020 and for this reason the results obtained from the gone green was chosen to be included within this paper.

3.3.1. *Energy Storage*

Many studies have considered the benefits on energy storage in future highly renewable national and regional energy systems [43] [44] and [45]. This study considers the technical benefits of a range of potential storage scenarios in future GB power systems. In section 2.4.2, the energy storage options were briefly reviewed. The scenario capacities and storage volumes shown in Table 9 are thought to be technically plausible by the year 2030, although the higher levels have been included to show the advantage of greater storage volumes and these are seen to be highly ambitious.

Storage Capacity (GW)	Storage Volume (GWh)	Maximum Wind Capacity (GW)	Maximum Wind Penetration (%)	CEEP at Maximum Penetration
2	100/200	36/37	0.27/0.28	5.91/6.48
4	200/400	37/38	0.29/0.29	4.82/5.16
6	300/600	38/40	0.30/0.31	4.02/4.70
8	400/800	40/42	0.31/0.33	4.07/4.35

Table 9 – Effect of storage capacity and volume on the gone green scenario.

Table 9 shows the change in the maximum wind penetration as both the storage capacity and storage volume are increased within the gone green system. It is observed that increasing the energy storage from the current level to 8GW, with a storage content of 800GWh, would increase the maximum wind penetration from 26% - 33%.

As illustrated in Figure 5, under the 6GW and 300GWh storage scenario, the maximum wind penetration is increased from 26% - 30% and, significantly, the CEEP is reduced from 8.21 to 4.02TWh. In the initial gone green system, the maximum wind penetration is achieved at 35GW capacity. However, in this energy storage scenario, the maximum penetration level is achieved at 38GW. Thus for only a 9% increase in wind capacity the wind penetration can be increased by 15%. It should also be noted that without energy storage, 38GW would only provide 28% of the electricity demand and the CEEP level would be 11TWh.

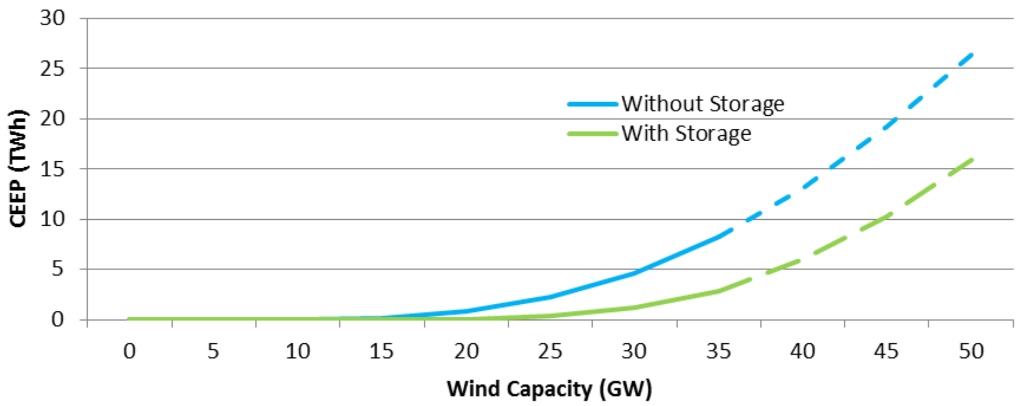

Figure 5 – The change in CEEP when energy storage is added to the system.[11]

As would be expected, under all storage scenarios, the CEEP is significantly reduced. The storage provides an opportunity for excess energy generation, during periods of high wind and low electricity demand, to be absorbed. Indeed by adding just 4GW of storage, with a volume of 200GWh, CEEP can be reduced by approximately 50% and the maximum wind capacity increased from 35 – 37GW. While this is a significant improvement, it remains below the 57GW outlined within the gone green scenario.

3.3.2. Interconnection

As outlined in section 2.2, the level of interconnection could increase significantly in GB over the coming decades. However, the ability to rely on interconnections for electricity will depend on the market arrangements and plant mix within the two connecting regions.

Interconnection Capacity (GW)	Maximum Wind Capacity (GW)	Maximum Wind Penetration (%)	CEEP at Max Penetration (TWh)
0	31	0.21	13.79
3	33	0.24	10.02
6	35	0.26	7.26
9	36	0.28	4.66

Table 10 – Effect of interconnection capacity on CEEP and maximum wind penetration.

Table 10 shows that interconnection can significantly increase the maximum wind penetration. Also, as with energy storage, interconnection significantly reduces the CEEP.

[11] The maximum technically feasible wind penetration is illustrated as in Figure 4.

Further, it should be noted that in the gone green scenario, 7.1GW of interconnection is already installed. Thus, as expected, the 0GW and 3GW interconnection scenarios show a reduction in the maximum wind penetration, compared to Table 8. While in section 2.4.1 it was acknowledged that the ability of interconnections to either have the capacity to import or export as and when required is a function of the market, it is unlikely that investors would support a scheme that didn't compliment both systems.

By increasing interconnection, the maximum wind penetration can be significantly increased. Similarly, moving towards a gone green scenario without the 7.1GW of interconnection would result in a large amount of CEEP and low maximum wind penetration. Again, as with the energy storage scenarios, the CEEP is significantly reduced.

3.3.3. Combined Interconnection and Energy Storage

The final analysis is to assess a combination of increased interconnection, increased energy storage and decreased minimum plant capacities (to be discussed within section 4). A number of combination strategies have been developed and these strategies are as follows;

- Strategy 1: Storage capacity increased by 2GW, with a storage volume of 100GWh. Interconnection of 6GW and minimum plant capacity of 10GW.
- Strategy 2: Storage capacity increased by 4GW, with a storage volume of 200GWh. Interconnection of 9GW and minimum plant capacity of 7.5GW.
- Strategy 3: Storage capacity increased by 6GW, with a storage volume of 200GWh. Interconnection of 12GW and minimum plant capacity of 5GW.

As shown in Figure 6, the curtailment is significantly reduced as the energy storage and interconnection are increased and the minimum power plant capacity decreased. Table 11 shows the maximum wind capacity and penetration for each of the scenarios, along with the CEEP at the maximum wind penetration.

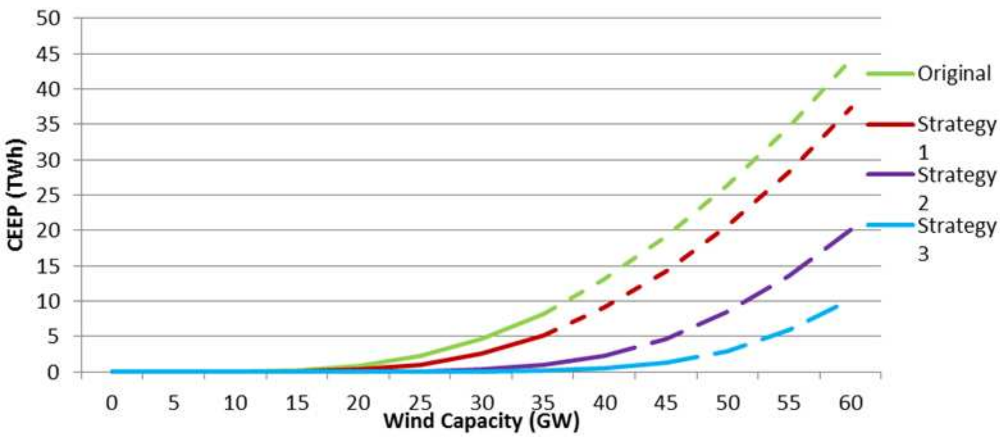

Figure 6 – Change in CEEP for each combined interconnection, energy storage and minimum plant capacities.[12]

Strategy	Maximum Wind Capacity (GW)	Maximum Wind Penetration (%)	CEEP at Maximum Penetration (TWh)
Original	35	26	8.21
1	36	27	5.12
2	44	34	4.10
3	48	39	2.09

Table 11 – Effect of storage, interconnection and minimum plant capacity on CEEP and maximum wind penetration.

It should be noted that strategy 1 is similar to the original gone green scenario, with an increased level of storage. Within this scenario, the maximum wind capacity is increased to 36GW and wind supplies 27% of electricity demand.

Strategy 2 sees a significant increase in the maximum wind penetration through the enabling of a more flexible system and increase in storage and interconnection. The ability to build a further 6GW of interconnection and 4GW of storage is considered to be technically plausible, with the two potential SSE pumped hydro sites alone providing 1.2GW of storage capacity. The storage volume of 200GWh is large; however it was outlined earlier that a single LNG tank alone could provide 16.6GWh of storage.

The final strategy would require a high level of interconnection, beyond what is being considered today. This strategy has been included to highlight the levels of interconnection and storage that would be required to have a system in which about 40% of electricity is supplied by wind power. Within this scenario the electricity system emissions are reduced to

[12] The maximum technically feasible wind penetration is illustrated as in Figure 4.

113gCO_2/kWh a significant improvement on the original gone green scenario that had an emissions intensity of 174gCO_2/kWh.

It is clear, in all of the scenarios that storage and interconnection do indeed increase the maximum technically feasible level of wind in the system. While the 57GW is not realised in any of the systems, because the system is operating in a more technically efficient manner the utilised wind production, about 135TWh[13] (for 48GW), is much greater than the 124TWh used within the original gone green scenario (for 57GW). These figures provide a very strong case for building a more technically efficient system, for less wind capacity the penetration level is greater, and confirms the case for the need of a whole systems approach. A combination strategy significantly increases the maximum capacity of wind that can be integrated into the electricity system. The CEEP is significantly reduced and for this reason the maximum wind penetration is increased. Comparing the third strategy to the gone green system, shows that the wind capacity can be increased from 35GW to 48GW and the penetration increases from 26% to 39%.

4. Sensitivity of Minimum Power Plant Capacity and Interconnection Capability

4.1. Minimum Power Plant Capacity

It was mentioned in section 2.5, there is a requirement for grid stabilisation and this was assumed to be 30%, in line with [41]. In the UK, this share could be the equivalent to 6.6GW, at the lowest demand level, and 17.7GW at the highest demand level [42][14]. EnergyPLAN also requires an input for the minimum power plant level. The minimum plant capacity refers to the conventional plant that must be operational at any given hour. As the level of wind increases, it is expected that plants will operate at this level for increasing lengths of times. The minimum power plant within the reference model has been assumed to be 10GW.

The reason for varying the minimum power plant parameter was to understand how increasing flexibility, by reducing the minimum power plant capacity, could increase the maximum technical feasible level of wind in the power system. Operational gas and coal plants have a minimum stable generation level. During a storm, in a system with high wind penetration, the output from wind power would be very volatile. Ramping gas and coal plants according to the volatile wind output to ensure that demand is met would be challenging. Determining the

[13] Utilised wind production is equal to total wind production minus curtailed wind production. For combination strategy 3 this is equal to 137.06TWh – 2.09TWh = 134.97TWh. For the original gone green scenario, at 57GW wind capacity, the utilised wind production is 162.76TWh – 38.35TWh = 124.41TWh.

[14] This is based on the total gross system demand and includes station load, pump storage pumping and interconnector exports.

minimum power plant capacity within a high wind system requires further research and this will likely require a more detailed model. However, based on the information reviewed in this paper it is unlikely that the GB system in 2030 could operate without conventional power plant capacity, and even if it could on a temporary basis, it is unlikely it would be possible to do so for an extended period of time.

Minimum Power Plant (GW)	Maximum Wind Capacity (GW)	Maximum Wind Penetration (%)	CEEP at Maximum Penetration (TWh)
10	35	0.26	7.39
7.5	40	0.30	8.13
5	43	0.33	7.61

Table 12 – Effect of minimum power plant capacity on CEEP and maximum wind penetration.

The sensitivity of the minimum power plant capacity to the gone green system was tested and the results shown in Table 12. While decreasing the minimum plant capacity significantly increases the maximum wind penetration, the CEEP values remain high. This is because there remains no technology that can absorb excess energy from wind power. Thus, even if plants were flexible enough to meet the demand requirements within a system that is constantly under strain, due to a high wind capacity, energy storage and/or interconnection will be required to absorb excess generation.

4.2. Interconnection Capability

It was acknowledged in section 2.4.1 that the ability interconnectors to deliver resilience will depend on the plant mix across the interconnected regions and that detailed modelling of the interconnected regions would be required to fully understand the profitability of interconnectors. If many countries move towards high wind systems, the demand and value of dispatchable capacity will likely significantly increase. While detailed pan European electricity market analysis to determine the profitability and flows across interconnectors is not within the scope of this project, it is important to test the sensitivity of available interconnector capacities.

Originally a value of 75% was assumed for export capability during high wind scenarios, this value was assumed as much of the existing and planned interconnection capacity is to countries with low wind penetration. Specifically 4GW of the planned and operational capacity is to France and Norway, neither of which have high wind systems. Beyond 2020 in a European system with a high variable renewable penetration, the ability to export excess wind generation will significantly reduce as countries become more interconnected. As suggested, understanding interconnector flows in future high variable renewable energy systems will require a pan European electricity market analysis and this is not within the scope of this study.

Table 13 shows the sensitivity of interconnector capabilities for the gone green scenario. Export capabilities of 40, 60, 80 and 100% have been assessed. Becker et al. [46] suggest in a highly interconnected high variable energy system that 40% of excess generation may be exportable. It should be noted that the interconnector capacities suggested within the scenarios are not excessive, with a maximum capacity of 12GW capacity by 2030, see table 10, considered to be a highly ambitious scenario. The wind penetration in the most ambitious 2012 scenario is 40%.

Interconnector Export Capability (%)	Maximum Wind Capacity (GW)	Maximum Wind Penetration (%)	CEEP at Maximum Wind Penetration (TWh)
100	35	26	5.93
80	34	25	6.90
60	33	24	8.02
40	33	23	10.30
75 (Original)	34	25	7.39

Table 13 - Sensitivity of Max Wind Capacity, Penetration and CEEP to Interconnector Capability.

As shown in Table 13, the impact of interconnector export capability is as expected. CEEP increases as export capability decreases, thus in a highly interconnected European system with high variable renewable penetration, CEEP would be expected to increase. Though, this is highly dependent on how the plant mix across Europe and interconnector capacity changes over the next two decades. The maximum wind penetration decreases, due to a reduction in the maximum wind capacity and increase in CEEP.

While the results are indeed sensitive to the assumed interconnector export capability, it should be noted that even with 40% export capability the maximum wind penetration increases and CEEP reduces from a system with no export capability. Thus there remain technical benefits to increasing interconnection capacity.

5. Conclusion

Under legally binding legislation, the UK is required to reduce emissions by 80% on 1990 levels by 2050. To meet these targets, the Committee on Climate Change has stated that 30-40GW's of low carbon generation will have to be built through the 2020's. This study has shown that increasing interconnection and energy storage within the GB power system is fundamental to the development of a low carbon electricity system. Interconnections and energy storage enable a greater penetration of wind energy and in turn reduce system emission intensity.

After developing and validating a model of the GB power system using the EnergyPLAN tool, four future energy scenarios were analysed and the maximum technically feasible wind penetration calculated. The results have shown that without an increase in the storage and interconnection capacity, even the most ambitious gone green scenario emissions remain in excess of 170gCO_2/kWh. While this is a significant improvement compared to the 483gCO2_2/kWh intensity of 2012, it is clearly above the 50gCO_2/kWh recommended by the Committee on Climate Change [47] [6] [48].

In addition to the 3.3GW of existing interconnection capacity, a further 4GW of interconnections are being considered. The technical benefits of these projects have been clearly demonstrated in this study, showing that under the gone green scenario the maximum penetration of wind can be increased from 21 – 28%. Not only is the maximum wind penetration increased, but the critical excess electricity production reduced from 13.79 to 4.66TWh. Energy storage was also found to be significantly beneficial to the system with 6GW increasing the maximum wind penetration from 26 – 30% and reducing critical excess electricity production to 4.02TWh.

Combining electricity storage with strengthened interconnections appears to provide the most effective means of increasing wind penetration. Indeed, with 9GW of interconnection and 4GW of storage, the maximum technically feasible wind capacity is increased from 35 – 44GW. In this scenario wind energy supplies 34% of electricity generation. The critical excess electricity production is also reduced to 4.1TWh.

The best case scenario shows an emission intensity of 113gCO_2/kWh for the GB electricity system, within this scenario 48GW of wind capacity provides a higher level of usable energy to the system than the 57GW within the original gone green scenario. Thus as a result of energy storage and interconnection, a system with less wind capacity has a lower carbon intensity. Understanding this requirement for a whole systems approach is essential for the development of a low carbon electricity system.

If the UK is to meet the carbon reduction targets the electricity system will have to be decarbonised. However, the GB electricity system has a limited capacity to absorb variable renewables at the levels of penetration likely to be required by the ambitious policy targets. Additional interconnection and energy storage can enable a greater maximum wind penetration and as a result, a reduced carbon intensity. The work presented in this paper indicates that the lowest emissions likely to be achievable though large scale wind deployment combined with significant storage and interconnector development will be around 113 gCO_2/kWh. While a considerable improvement over current levels, this remains above the 50gCO_2/kWh recommended by the Committee on Climate Change. To achieve further reductions the UK electricity system will need better integration with other energy sectors, such as the electrification of the heat and transport sectors.

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