Chapter

Development of Mathematical Models to Explore the Potential of Wind Fleets to Decarbonize Electricity Grid Systems

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Abstract

Real-time records of energy generation in the UK and Germany have been used to develop models for each country's electricity generation system, the objective being to provide a means of determining the likely economic limits of wind fleets and their consequent ability to decarbonise their grids. The results from the models, expressed in the form of marginal efficiencies, have then been codified in a pair of simple look-up tables, obviating the need for further reference to the models and providing a simple means of assessing the implications for the grids and their wind fleets of a range of future grid configurations, including increases in wind and solar fleet capacities, anticipated future loss in both countries of nuclear-generating capacity, possible replacement of petrol and diesel passenger vehicles with electric vehicles, and, for the UK only, the conversion of domestic boilers from gas to electricity. It is apparent that headroom, being the difference between annual average grid demand and base generation, is the single most important factor in determining how much wind capacity may be economically deployed in decarbonising grids.

Keywords: variable renewable energy, decarbonisation, upper economic limit, wind energy, carbon emissions

1. Introduction

Significant decarbonisation of electricity grids will, in many cases, necessitate considerable investment in wind fleets in order to displace generation from hydrocarbon sources. Wind fleets are ultimately limited in size by the highly variable nature of wind generation which causes wind shedding and loss of efficiency when generation exceeds what the grid is able to accept [1].

It is apparent that grids act towards their wind fleets as low-pass filters, and, as a result, when wind competes for limited access to their grids, it may only be properly analysed using real-time records. This chapter describes, with reference to the UK and Germany grid systems, the use of such records to build mathematical models for each system [2]. The models are then used to determine the upper economic level of deployment of wind fleets and the limits on their ability to decarbonise their grids. It is shown that the upper economic levels are determined by two factors headroom, a concept defined in the chapter, and the amount of wind shedding which is acceptable before further investment in capacity becomes uneconomic.

In this discussion, and indeed throughout the chapter, a distinction is made between generated wind power, which is referred to as GWe, and installed wind capacity, which is referred to as GWc. For small wind fleets (i.e. no wind shedding), the two important variables are related by the expression shown in Eq. (1):

$$\text{GWe} = \text{load factor} \times \text{GWc} \tag{1}$$

It is also noted that all references to carbon dioxide emissions are stated as carbon emissions, for the sake of simplicity.

2. Managing wind variability

Electricity grids cope with the variable output from small wind fleets by continually adjusting the output of dispatchable sources of generation under their control [1, 3]. These sources are mainly gas-fired generation in the UK and coal-fired generation in Germany. Ignoring problems such as failure of transmission systems, the grids should be able to accommodate all of the output from wind fleets which are small relative to the size of their grids. This will not, however, be the case for the large wind fleets envisaged in future.

The highly variable nature of wind generation creates two different but complementary problems for grids being served by very large wind fleets. When there are settled weather patterns, there are fairly frequent occasions when there will be sensibly no wind generation for several days, regardless of the size of the wind fleet. At the other extreme, for the large wind fleets envisaged in the future, there will be occasions when wind generation will be at least twice what the grids are able to accommodate, such as excesses of 40 GWe for the UK and 80 GWe for Germany. For each 24-hour period, a UK wind fleet would therefore be either unable to supply around 1000 GWh of energy or would be generating 1000 GWh in excess of demand on the grid. For Germany the daily deficits/excesses would be of the order of 2000 GWh.

It is sometimes suggested that energy storage is the solution to wind generation deficits and surpluses, but the problem with this approach is that while energy storage is technically feasible for small amounts of excess generation, it is unsuitable for large energy excesses. This assertion may be put into perspective by comparing the need to store and return to the grid multiples of 1000 GWh of energy with the capability of the world's largest storage array, Tesla's 0.13 GWh in South Australia [4]. It would require nearly 8000 Tesla-sized storage arrays to store 1000 GWh of excess produced in a day.

The cost of lithium-ion storage arrays is falling and may even reach $350 M per GWh by 2024 [5], but, even if this was the case, a 1000 GWh storage array would cost of the order of $350 Bn. Moreover, it is not just the extremely high capital cost which would prohibit such an investment; it is also the low utilisation of the facility itself. For long periods, the facility would be inactive through lack of wind, and during extended periods of high wind, the facility would become fully charged quickly and then inactive because the wind generation was still in excess of demand on the grid. Lithium-ion arrays will undoubtedly have a role to play in providing standby energy storage to cover for outages of a few hours (as in South Australia) or, perhaps, in storing excess solar generation to smooth grid demand over a 24-hour period, but they are unlikely ever to solve the problems created by the highly variable and largely unpredictable nature of wind generation [6, 7].

The UK has four pumped storage systems with a storage capacity of 30 GWh, capable of charging/discharging at around 2 GW. Because of their high capital cost and inherently low efficiencies, electricity from pumped storage systems is expensive. The high cost of pumped storage electricity is justified by the premium which may be charged; the storage reservoirs are charged at night, when electricity prices are low, and discharged each day during periods of peak demand and high prices. Pumped storage systems also play an important role in providing grid stability. MacKay [8] discussed the possibility of using pumped storage systems to address the problem of large energy surpluses/deficits which are an inevitable consequence of employing large wind fleets but concluded that flooding every potential storage site in Scotland would only provide a storage capacity of around 400 GWh.

An alternative to energy storage is to export surpluses to neighbouring countries which are in deficit. However, interconnectors are costly, particularly for a country like the UK which is surrounded by sea, and wind surpluses are inherently unreliable. Furthermore, as the Royal Academy of Engineering pointed out in 2014 [9], the UK weather is reasonably well correlated with that in neighbouring countries; it is likely that when the UK has wind surpluses, its continental neighbours will have wind surpluses of their own. The UK has around 4 GW of interconnectors, a 2 GW interconnector with France, a 1 GW interconnector with the Netherlands and, as of January 2019, a 1 GW interconnector with Belgium. All normally run at high capacity importing some 10% of the UK's electricity needs, mainly nuclear energy [10]. Germany is much more highly interconnected with its neighbours and mainly uses its interconnectors to export surplus solar generation. The models to be discussed in the next sections will assume that UK wind generation which is surplus to the requirements of the grid will be curtailed.

The models also assume that the grid distribution system is perfectly matched to the wind generation system and that whenever there is sufficient grid demand, all wind generation will be accommodated by the grid. This is clearly an oversimplification; data from the Renewable Energy Foundation suggests that even at UK wind penetration as low as 6%, there is wind curtailment every month, with wind curtailment payments in 2015 being £90 M increasing at £30 M per annum (p.a.) [11].

3. The modeling approach

Wind fleet load factors, which typically vary by ±10% depending on the windiness of the year, are available for the UK from government records [12] and for Germany on a Fraunhofer website [13]. In recent years the UK load factor has averaged around 0.3 and that of Germany around 0.2, the difference being accounted for by the UK being generally windier and having a higher portion of its wind fleet offshore. Histograms, load distribution curves and other statistical techniques are often useful when exploring the relationships between small wind fleets and the grids they serve [1], but once a wind fleet increases above the size at which wind generation has to be curtailed, wind generation is no longer linearly related to wind fleet capacity, and such techniques are not applicable.

The starting point for predicting GWe under circumstances of wind curtailment is the recognition that the grid acts towards the wind fleet as a low-pass filter; wind generation is accepted if it can be accommodated by the grid but must be curtailed if in excess. Because the total demand on the grid, which we shall call grid demand, is ever-changing, the low-pass filtering action the grid imposes on wind generation is also ever-changing. Logic dictates therefore that a model to simulate the interaction between a grid and a wind fleet large enough to incur wind curtailment must analyse real-time grid records, checking at each recording interval whether wind generation can be accepted or must be curtailed.

The authors have previously reported the empirical finding that four separate models produced using 2013, 2014, 2015 and 2016 records led to sensibly the same model, enabling them to conclude that only a single year's records are required to generate a model of general applicability [2]. 2017 was the first year for which UK solar generation records became available on the Gridwatch website and the year when solar generation started to compete with wind generation for access to the UK grid [14]. The UK model in the next section uses 2017 grid records.

The components of UK generation are recorded every 5 minutes, resulting in 104,832 data sets over the period of a year but are relatively easy to access since they may be downloaded directly from the web. German records on the other hand, available at hourly intervals, result in only 8760 data sets over the period of a year but are more time-consuming to access since they must be transcribed manually. To provide real-time graphical representations of results, it was decided to access the records a week at a time. The models, which are in spreadsheet form, first predict by extrapolation what wind generation would have been for a range of larger wind fleets, initially ignoring the need to curtail generation which the grid is unable to accommodate. The next step, for each time period and each wind fleet capacity of interest, is for the model to identify how much of the predicted generation the grid is able to accommodate. These predictions are averaged for each week, then for the year, to generate a prediction of annual average generation, GWe, for each GWc of interest. It will be shown that the GWe versus GWc relationships derived using the models provide a basis for quantifying the efficiency of the wind fleet and a means of exploring the extent to which the wind fleet will be able to decarbonise the grid for a range of different scenarios likely to be encountered in future years.

In order to undertake the modeling, the variable GWs, being the generated solar power in GW, must also be used. The sum (GWe + GWs) is then the combined wind and solar (generated) power.

4. Modeling the UK wind fleet

Table 1 summarises the main components of UK electricity generation (GW); the analogous solar and wind fleet capacities, for the years 2014–2017, a period during which wind capacity increased by 51% and solar capacity by 131%, are shown in **Table 2**. The data are obtained from the UK government records [15], with the exception of grid demand and wind generation records, which were calculated by averaging the real-time records downloaded from Gridwatch [12].

Year	2014	2015	2016	2017
Grid demand	34.3	33.1	32.4	33.0
Wind	2.44	2.65	2.44	3.70
Solar	0.462	0.860	1.188	1.316
Gas	11.52	11.40	16.36	15.61
Coal	11.44	8.66	3.50	2.57
Nuclear	7.28	8.03	8.18	8.03
Bio	2.58	3.34	3.43	3.63
Hydro	0.67	0.71	0.615	0.676

Table 1.
Sources of generated UK electricity: 2014–2017 (GW).

Year	2014	2015	2016	2017
Wind	13.07	14.31	16.2	19.84
Solar	5.53	9.54	11.90	12.78

Table 2.
Installed UK wind and solar capacities: 2014–2017 (GW).

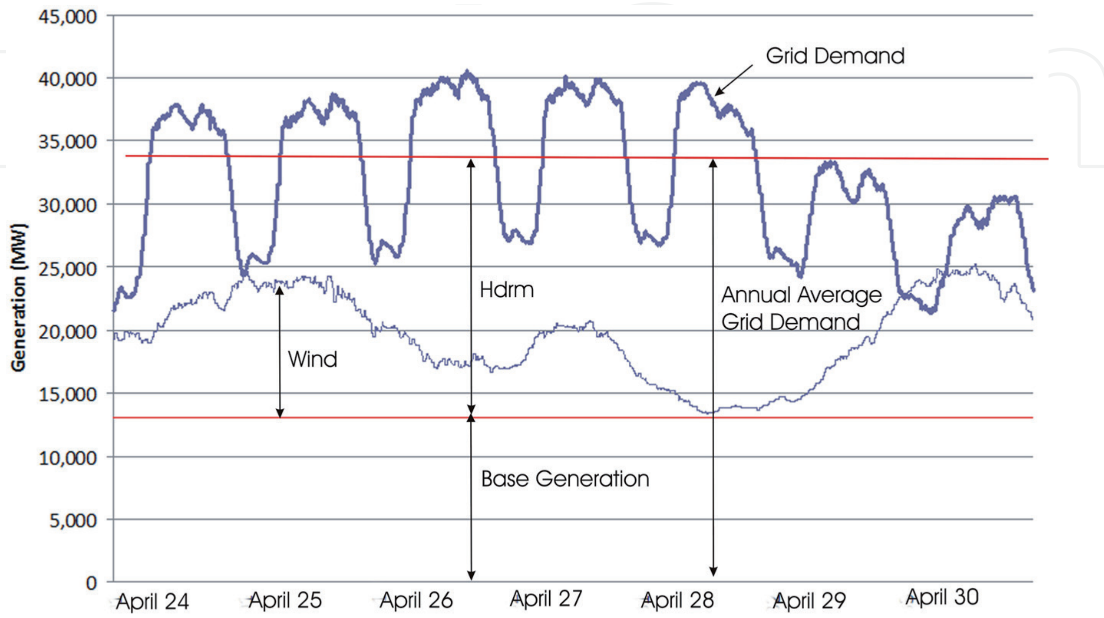

Figure 1.
Graphical representation of grid demand, wind generation and base generation, week 17 (April 24–30) of 2017.

In the simplified schematic of **Figure 1**, the calculated wind generation from a wind fleet of capacity 20 GWc (close to the actual capacity of 19.83 GWc in 2017) is shown sitting above the base generation, which is a composite of sources considered to be given preferential access to the grid over wind and solar generation. The elements of base generation are not fixed but will vary according to the operational strategy of the grid at the time. For some years, nuclear generation, which averaged 8.03 GW in 2017, was the largest component of base generation followed by imports. As mentioned earlier, by January 2019 the UK had 4 GW of interconnectors within the continent, which have run at close to full capacity importing mainly nuclear electricity from the continent, the latter being cheaper than UK electricity since it is not a subject to carbon tax [10]. These sources contributed 4 GW to base generation, but this may not always be the case in the future, particularly after the planned decommissioning of the German nuclear reactors in 2022 [16] and of the Belgian nuclear reactors in 2025 [17]. Because of the uncertainty about the future level of base generation, it is treated as a model input variable, allowing the consequences of a wide range of future base generation values to be investigated. In the illustration of **Figure 1**, base generation was set at 13 GW.

The difference between grid demand and base generation, which varied during week 17 of 2017 between a maximum of 27 GW during the day of April 26 and a minimum 8 GW on the night of April 30, was traditionally served by coal- and gas-fired generation. It is now the operational area to which wind and solar generations are given preferential access, dispatchable sources of generation only being used when there is insufficient wind and solar generation to satisfy grid demand. An important objective of the modeling study will be to provide a means of examining the efficiency with which the wind and solar fleets are able to satisfy grid demand, thereby displacing dispatchable generation and minimising the generation of carbon emissions.

Although **Table 1** shows the grid demand being relatively unchanged during the period 2014–2017, this will not always be the case for the future grid configurations we shall wish to investigate. As we shall discuss later, converting the UKs petrol and diesel cars to electric vehicles (EVs) would increase grid demand by around 10 GWe, and a much larger increase would result from a recent proposal by the UK Climate Change Committee that domestic gas heating should be replaced by electric heating by 2050 [18]. Although grid demand is not a model input, it is possible to simulate a change in grid demand by recognising that the operational area of the wind and solar fleets lies between base generation and grid demand and a 1 GW change in grid demand has the same impact on this operational area as a 1 GW change in base generation in the opposite direction. It is possible therefore to simulate a change in grid demand by an equal and opposite change in base generation.

The authors have previously reported their finding that replacing the real-time records of grid demand with a constant annual average grid demand in all 52 weekly models had only a minimal effect on the calculated annual average GWe [2]. An explanation for this finding is that curtailing wind generation at annual average grid demand rather than the actual ever-changing grid demand overestimates wind shedding for approximately 50% of the year and underestimates it for the other 50% of the year, the two effects cancelling each other out. This result leads to the conclusions that not only may we ignore the cyclic component of grid demand as a model variable but we can also visualise the operational area of the wind and solar fleets as lying between base generation and annual average grid demand, which is known as headroom [19] and in this chapter is referred to as Hdrm. The variable Hdrm provides a means of visualising the operational headroom available to the wind and solar fleets and is defined as

$$\text{Hdrm} = \text{Annual average grid demand} - \text{base generation} \tag{2}$$

Since annual average grid demand in 2017 was 33 GWe, Eq. (2) requires the choice of base generation values of 13, 3, −7, −17 and − 27 GWe as model inputs when using 2017 grid records to generate GWe vs. GWc curves for Hdrm values of 20, 30, 40, 50 and 60 GW.

It is possible to make a simple model which produces reasonably accurate GWe vs. GWc predictions using annual wind generation histograms in the absence of solar generation. However, statistical methods may not be used when wind and solar fleets are of such a size that not all their output can be accommodated by the grid. This observation may be understood by comparing the two wind generation predictions in **Figure 2** for a wind fleet of 20 GWc. The upper graphic, which does not include solar generation, shows that the high winds during the early hours of Sunday of April 30 would have caused a small amount of wind shedding at a time when grid demand fell to only 21 GWe but ceased when grid demand rose during the day. The lower graphic in **Figure 2** which includes solar generation shows wind shedding even at a time when grid demand had increased to 30 GWe because wind generation was being displaced by solar generation. Only models which analyse real-time data are able to assess such interactions which, when averaged over the year, allow calculations to be made of wind fleet efficiency.

Each of the 52 weekly models for 2017 was run with base generation values of 13, 3, −7, −17 and − 27 GW, and the weekly results averaged to yield the annual average GWe vs. GWc curves of **Figure 3** for Hdrm values of 20, 30, 40, 50 and 60 GW. In the weekly models, the solar generation was set at twice the levels recorded in 2017. The reason for this decision, and not any higher, is that the models show the

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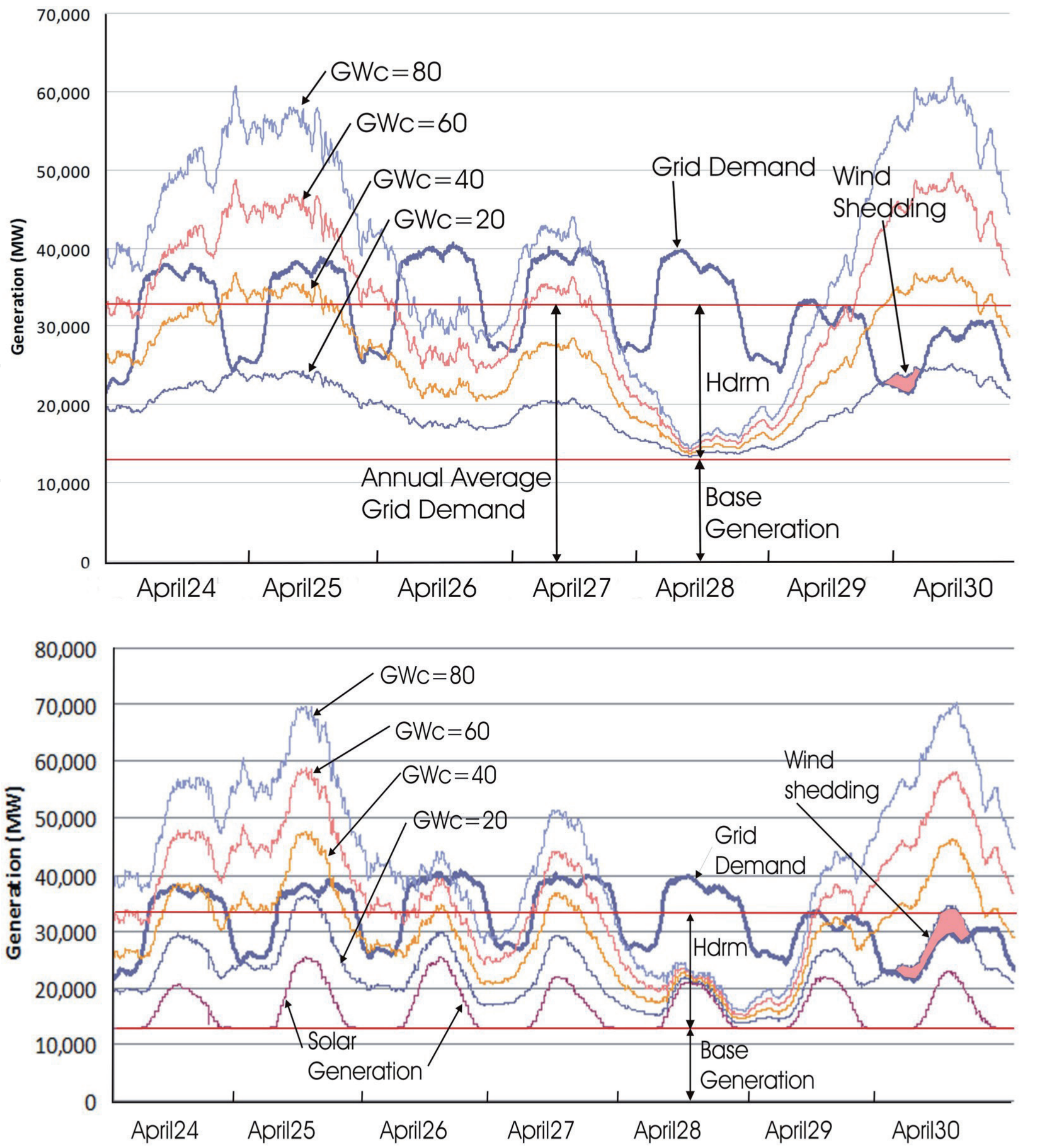

Figure 2.
Predictions of wind generation for week 17 of 2017 for wind fleet capacities of 20, 40, 60 and 80 GWc. the upper graphic shows the predictions for no solar generation, and the lower graphic shows twice the solar generation in 2017, with solar generation being given preferential access over wind generation.

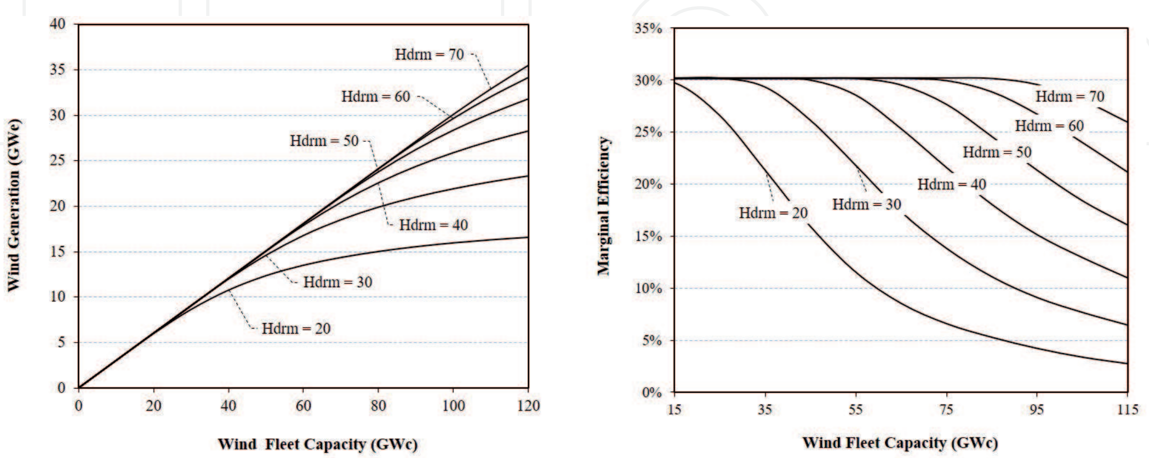

Figure 3.
GWe vs. GWc and marginal efficiency predictions for Hdrm values of 20, 30, 40, 50 and 60 GW.

combine wind and solar generation to be maximised when all solar generation is accepted by the grid, but, at twice the 2017 level, solar generation itself comes close to being shed when at its peak during the summer months.

Using the real-time data, it is possible to model the relationship between GWe and GWc for different Hdrm values, assuming twice the solar generation in 2017. The results are shown in the left-hand graphic of **Figure 3**. These curves were created by averaging the predictions of the 52 weekly models, requiring each of the 52 weekly models to be run five different Hdrm values and one level of solar generation (twice the 2017 value).

Since our interest is in providing tools which may be used to assess the upper economic limit of the wind fleet, it is necessary to develop a method of calculating the wind fleet efficiency from the GWe vs. GWc curves. A measure often used for general investment assessments is the incremental "benefit" of an investment divided by the incremental "cost" of that investment. An appropriate measure for a wind fleet is the incremental increase in wind generation, d(GWe), for an incremental increase in wind fleet capacity, d(GWc), which we shall call the wind fleet's marginal efficiency, where

$$\text{Marginal efficiency} = d(\text{GWe})/d(\text{GWc}) \tag{3}$$

Marginal efficiency is, by definition, the gradient of the GWe vs. GWc curves and hence may be calculated directly from the GWe vs. GWe curves, as has been done for the marginal efficiency curves, shown on the right-hand side of **Figure 3**. It is noted that the marginal efficiency is initially identical to the load factor, as defined in Eq. (1) but declines with increasing wind fleet capacity, that is, additional wind fleet capacity may increase the overall wind energy generated but at increasingly lower levels of efficiency. This parameter thereby provides an important analytical metric for establishing the critical point at which such increases in capacity are no longer economic.

It might be thought that the GWe vs. GWc and marginal efficiency curves of this figure will be of limited use, since they are restricted to five predetermined Hdrm values. A practical application might be interested in exploring the properties of a grid with a Hdrm value of, say, 27 GW which would suggest the need to laboriously rerun the 52 weekly models for a Hdrm of 27 GW and average the results. What obviates the need to rerun the models may be seen in Appendix A, which tabulates key grid parameters for a range of marginal efficiency and Hdrm values. This shows that (GWe + GWs)/Hdrm and residual generation/Hdrm, important derived parameters we shall use later, are almost insensitive to the value of Hdrm, so that (GWe + GWs) and residual generation may be easily calculated for any Hdrm value of interest.

Also included in the tabulations of Appendix A are the predictions of wind shedding (curtailment), which may be calculated from the ratio GWe/GWc using Eq. (4). Wind shedding predictions are important since unit costs are directly related to wind shedding and unit costs ultimately determine the economic upper limit of a wind fleet:

$$\%\text{wind shedding} = 100 \times (1 - (\text{GWe}/\text{GWc})/\text{Load Factor}) \tag{4}$$

Also tabulated in Appendix A is residual generation that the portion of Hdrm which cannot be met by wind and solar generation must be met by dispatchable generation, where

$$\text{Residual generation} = \text{Hdrm} - (\text{GWe} + \text{GWs}) \tag{5}$$

Since Appendix A reveals that a derived variable residual generation/Hdrm is practically insensitive to the value of Hdrm, this leads to the relationship between residual generation/Hdrm and % wind shedding which is graphed in **Figure 4**.

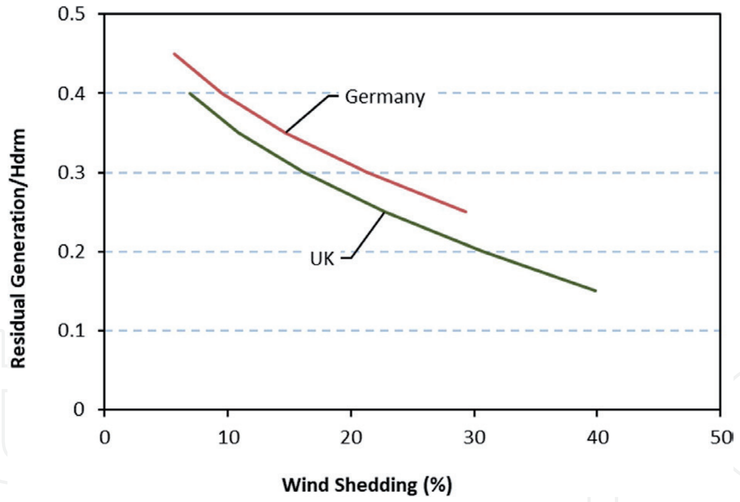

Figure 4.
Residual generation/Hdrm as a function of % wind shedding.

It is not the intention of this chapter to address the economics of wind and solar generation, since the economics will depend on unit costs and subsidy regimes which will change over time. However, the residual generation/Hdrm vs. wind shedding % relationship of **Figure 4** provides a useful guide to the future ability of the wind and solar fleets to decarbonise the grid, once the economics are known. Thus, if the UK wind fleet is only economic up to the point at which it sheds an average of 20% of wind generation, 25% of Hdrm must be generated from dispatchable sources. If on the other hand it is deemed economic to shed 38% of wind generation, the residual generation/Hdrm will be reduced to 16%. **Figure 4** therefore provides a useful illustration of the decreasing ability of a wind fleet to decarbonise a grid as the wind fleet increases in size, shown for both the UK and Germany.

4.1 Scenario 1: Increasing the UK wind fleet capacity to reduce carbon emissions

Table 3 summarises the UK's progress in reducing carbon emissions between 1990 and 2017. Carbon emissions from electricity generation was reduced from 203 million tonnes (MT) per annum to 113 MT per annum of which 76 MT carbon was from gas generation (15.61 GW at 4.87 MT carbon per GW) and 22 MT from coal generation (2.57 GW at 8.7 MT carbon per GW). The remaining 98.4 MT carbon emissions from gas and coal generation will in future years be further reduced by increasing wind and solar capacities.

It is now possible to calculate the impact of increasing wind fleet capacity on carbon emissions; the results are shown in **Table 4**. Columns 2 and 3 in the table are taken from Appendix A, and column 4 is the increase in (GWe + GWs) since

Year	1990	2017
Electricity generation	203	112.6
Business	119.9	66.1
Transport	125.3	124.6
Total	594.1	373.2
Source: UK government records [20]		

Table 3.
Main sources of UK carbon emissions (MT p.a., 1990 and 2017).

Marginal efficiency	GWc	(GWe + GWs)	Increase in (GWe + GWs)	Carbon emissions (MT/a)	d(carbon)/ d(GWc)
0.30	20.00	5.01		98.38	
0.20	35.64	11.75	6.74	55.71	2.73
0.15	44.05	13.4	8.39	47.67	0.96
0.10	56.22	14.92	9.91	40.27	0.61
0.05	82.52	16.78	11.77	31.21	0.34

Table 4.
Model predictions of carbon emissions as the wind fleet increases in size (assuming Hdrm = 20 and solar generation twice that in 2017).

2017. It is the UK government policy to eliminate coal-fired generation by 2025 [21], so it is assumed that the 2.57 GWe of coal-fired generation will be eliminated first, followed by a progressive reduction in gas-fired generation. Column 5 shows the residual carbon emissions for different marginal efficiency values.

The UK government's target is to achieve a wind fleet of around 40 GWc by 2030 [22]. If achieved, the emissions from gas and coal generation would be approximately half their 2017 level in 2030. Column 6 shows the decreasing efficiency of the wind fleet as it increases in size. Increasing wind fleet capacity from 20 to 35.64 GWc reduces carbon emissions by 2.73 MT per GWc, but this decreases to a mere 0.34 MT per GWc between 56.22 GWc and 82.52 GWc.

4.2 Scenario 2: reduction in nuclear capacity

The nuclear fleet contributed 8.03 GW in 2017, all from advanced gas-cooled reactors (AGRs) with the exception of the generation from the 1.2 GW Sizewell B pressurised water reactor (PWR). The life of the AGRs is limited by their graphite cores, and the expectation is that all the AGRs will have to be decommissioned by around the year 2030 [2]. Although it had been the UK government policy to maintain and even increase nuclear capacity by commissioning new PWR reactors, little progress has been made in meeting this objective. It is looking increasingly likely that Sizewell B will be the only nuclear reactor in service in 2030, with a consequent loss of around 7 GW of nuclear output.

The results of the simulation for the loss of nuclear generation are shown in **Figure 5**. Since the loss of 7 GW of nuclear generation leads to a similar increase

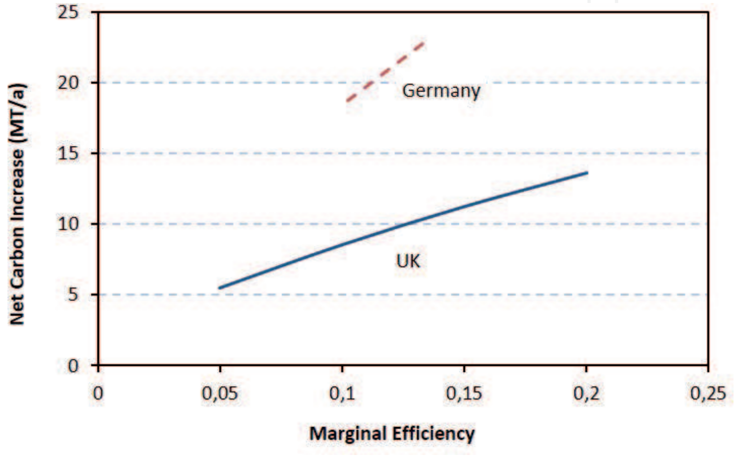

Figure 5.
Net carbon increase due to closure of the UK and German nuclear capacity.

in Hdrm, the additional capacity is partly supplied by wind and solar, expressed as (GWe + GWs) in Appendix A. The remainder, the extent of which will depend on the marginal efficiency of the wind fleet, will be required from dispatchable sources. Assuming that this required increase in generation will be from gas, carbon emissions will also increase as shown in **Figure 5** (also shown in this figure is the relationship between net carbon increase and marginal efficiency for Germany, which will be discussed in Section 5.2).

An interesting consequence of the loss of nuclear generation is that the headroom available to the wind and solar fleets is increased and hence their efficiencies. Thus, if 7 GW of nuclear generation were lost, for a given marginal efficiency, (GWe + GWs) would be increased, accompanied by an increase in dispatchable generation in order to meet the demand when wind is not available. Assuming a cut-off value for marginal efficiency of 0.1, the additional carbon emissions as a consequence of the closure of the nuclear capacity will be 8.5 MT p.a. in the UK and 18 MT p.a. in Germany.

4.3 Scenario 3: replacement of petrol and diesel vehicles by electric vehicles

As shown in **Table 3**, carbon emissions from electricity generation in 2017 were only 55% of the emissions in 1990, but transport emissions remained almost unchanged, becoming in 2017 the largest single source of carbon emissions. This would suggest that the UK's objective of significantly reducing overall carbon emissions further can only be met by reducing transport emissions.

According to MacKay [8], an electric vehicle (EV) driven under average UK conditions requires around 10 kWh of electrical energy a day, an average annual power requirement of 0.416 KW. In 2018 there were 34.9 million petrol and diesel passenger cars on UK roads [23] which are estimated to have produced carbon emissions of 66.3 MT [24]. An increase of electricity generation of 10.58 GWe would therefore provide enough power to replace the petrol and diesel cars with EVs, leading to a saving in transport emissions of 68.5 MT per annum carbon.

Results of the modeling for this scenario are shown in **Figure 6**. The increase in grid demand of 10.58 GWe would cause a similar increase in Hdrm, which could be supplied by wind and solar, supplemented by generation from dispatchable sources (probably gas) when these sources are not able to deliver the required power. There is a trade-off between the use of wind and gas; higher wind capacity will reduce the use of gas and hence increase the net carbon benefit but at the cost of increasing levels of wind shedding and hence lower marginal efficiencies, as shown in **Figure 6**

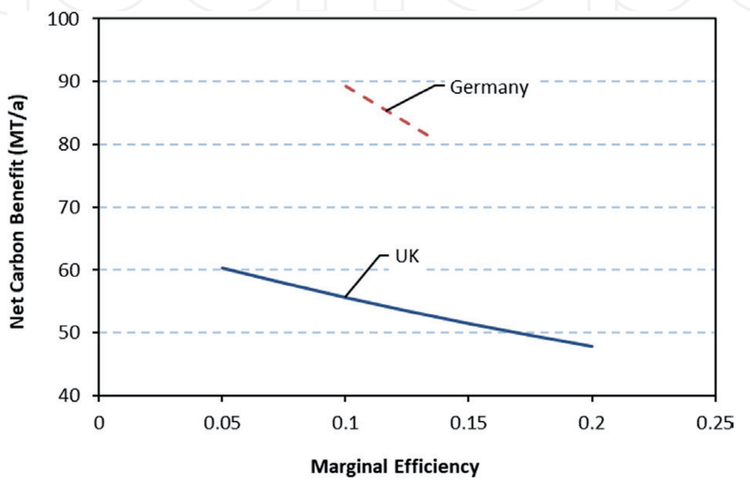

Figure 6.
Net carbon benefit to the UK and Germany following conversion to EVs.

Sector	Output (TWh)
Electricity generation	286
Energy industries	87.0
Services	105.9
Domestic	297
Industrial	92.5
Total	868.6
Source: Department of Business, Energy and Industrial Strategy [26]	

Table 5.
Consumption of natural gas by sector in 2017.

for both the UK and Germany (discussion of the latter is given in Section 5.3). Once again, the optimal level will depend on the relative costs of wind and gas, the carbon tax and national decarbonisation targets, as may have been specified in terms of the Nationally Determined Contributions [25].

4.4 Scenario 4: conversion of UK domestic heating to electricity

The UK government records show that in 2017 the domestic sector consumed 297 terawatt-hours (TWh) of natural gas, making the sector the largest consumer and slightly more than the 286 TWh consumed by electricity generation (see **Table 5**). About 85% of British houses are currently heated by natural gas, but the UK Climate Change Committee recommended in May 2019 that by 2050 all UK boilers should become low carbon [18]. Among other recommendations of the committee were a doubling of electricity generation to supply electric vehicles and heating, and an offshore wind fleet of 75 GWc, covering up to 2% of the UK seabed.

Although the committee was silent on the technologies likely to be used in converting domestic heating to electricity, the broad outline is consistent with the model predictions summarised in Appendix A. Thus, if we assume an additional grid demand of 40 GW and that it will be acceptable to run the wind fleet at a marginal efficiency of 0.1 (i.e. wind shedding of around 22%), the additional Hdrm of 40 GW would enable the wind fleet to generation 40* 0.75 = 30 GWe. This is consistent with a 75 GWc wind fleet operating with a load factor of 0.4 (which is not unreasonable for a future offshore wind fleet comprising large turbines). Since the additional grid demand is 40 GW and additional wind/solar generation only 30 GW, this would require 10 GW to be generated from dispatchable sources (about 87.6 TWh), which would be more than offset by the saving of 297 TWh in converting the domestic sector from gas to electricity.

5. Modeling the German wind fleet

Germany's Energiewende policy [27], aimed at producing a low carbon economy, includes a target reduction of greenhouse gas emissions to 55% of their 1990 levels by 2030 and, also by 2030, a target of producing 35% of electricity generation from renewables. These targets became more challenging after the decision in 2012 to phase out nuclear generation by 2022. Despite having the largest wind and solar fleets in Europe, Germany's reliance on electricity generation from burning lignite and hard coal results in high levels of carbon emissions. In February 2019, Germany took the controversial decision, opposed by the European Council and many of its

Generation sources	Generation (GWe)
Grid demand	62.81
Solar	3.97
Wind	8.94
Gas	3.43
Hard coal	12.12
Lignite	15.91
Nuclear	9.9
Bioenergy	5.36
Hydro	2.15

Table 6.
Main sources of Germany's electrical energy (2015).

neighbours, to import Russian gas via the Nord Stream 2 pipeline [28]. Replacing coal burning with the burning of imported gas should significantly reduce carbon emissions from electricity generation.

Table 6 summarises the annual average generation of the main sources of generation in 2015, taken from the Fraunhofer website (in this year, the values for wind and solar installed capacities were 44.6 GWc and 39.2 GW, respectively) [13]. Grid demand and solar and wind generation records were transcribed an hour at a time and averaged over the year, but the other records were the average values taken directly from the Fraunhofer website. The grid demand of 62.81 GW includes not only the electricity used in Germany but a net 5.29 GW exported (i.e. exports minus imports). The table reveals a wind fleet load factor of 0.2 in 2015, only two thirds of the average UK load factor, a consequence of lower average wind speeds and a smaller proportion of the German wind fleet being offshore. Germany's real-time grid records for 2015 (8760 data sets) were used to create a model of the German grid system.

The modeling approach adopted was as described earlier for the UK, with 52 weekly models incorporating the real-time records being scaled for a range of wind fleet capacities and then averaged over a year to create GWe vs. GWc and marginal efficiency curves. To enable future grid configurations with large Hdrm values to be evaluated, the models were used to predict the behaviour of wind fleets up to 260 GWc in capacity, although **Figure 7** illustrates predictions of wind fleets to 160 GWc only. The base generation of 9.9 GW in **Figure 7** represents the average nuclear generation of 2015.

Solar generation peaked at just under 25 GWs on several days during week 23 of 2015. **Figure 7** shows that twice the solar generation of 2015 would have caused a 160 GWc wind fleet to over-generate around 50 GWs during June 2, despite the fact that Germany's interconnectors were working at close to their maximum capacity, exporting up to 11.3 GW. This figure, therefore, provides a graphic illustration of why wind and solar fleets large enough to give rise to wind curtailment can only be modelled using real-time records.

The Hdrm value was approximately 52.9 GW in 2015 (grid demand of 62.8 GW less base generation of 9.9 GW). In order to explore a wide range of future grid configurations, the models were run for base generation values of 17.81, 7.81, −2.19 and 12.19 GW, equivalent to Hdrm values of 45, 55, 65 and 75GW, respectively. The GWe vs. GWc and marginal efficiency curves produced using the models are shown in **Figure 8**.

The data in the spreadsheet used to generate the curves of **Figure 8** was used to produce the look-up table of Appendix B for marginal efficiencies of 0.133, 0.1

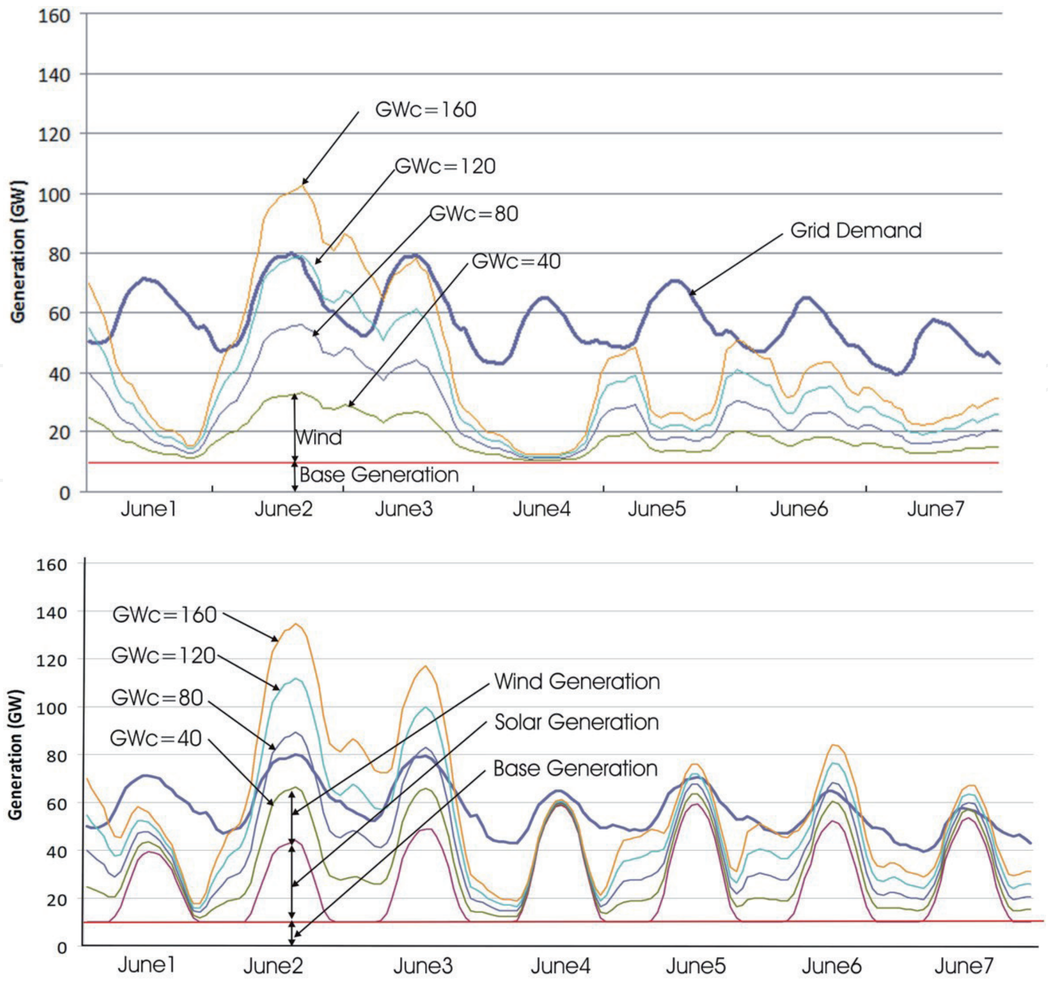

Figure 7.
Model predictions for week 23 of 2015. The upper graphic shows the model results for no solar generation and the lower graphic twice the solar generation in 2015.

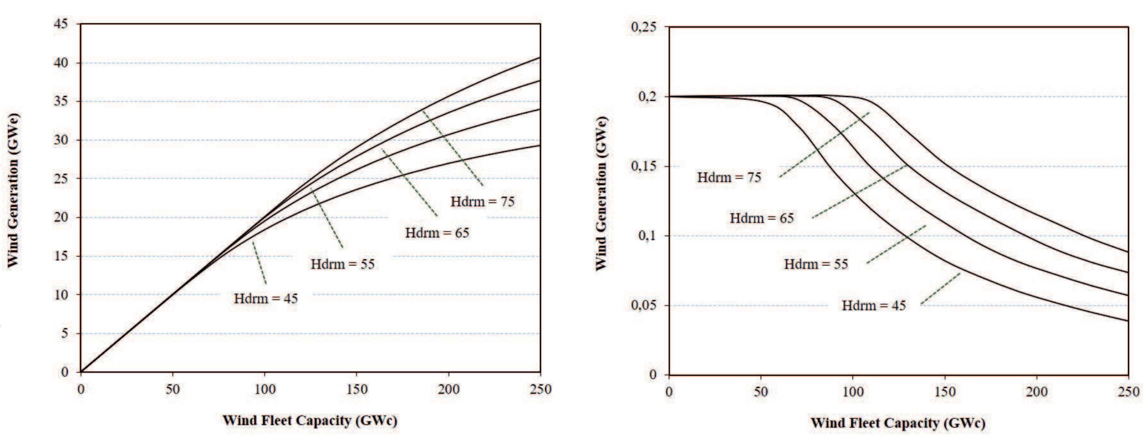

Figure 8.
GWe vs. GWc and marginal efficiency predictions for Hdrm values of 45, 55, 65 and 75 GW.

and 0.067. We shall now investigate, using the look-up table in Appendix B, three scenarios likely to be encountered by the German grid in future.

5.1 Scenario 1: Increasing Germany's wind fleet capacity in order to reduce carbon emissions

In 2015 German carbon emissions from electricity generation were 290.13 MT [13], consisting of 169.33 MT from brown coal (15.9 GW at 10.65 MT per GW), 106.16

Marginal efficiency	GWc	(GWe + GWs)	Increase in (GWe + GWs)	Carbon emissions (MT)	d(carbon)/d(GWc)
0.200	44.58	12.91	0	290.12	
0.133	119.56	29.98	17.08	110.50	2.40
0.100	154.62	34.12	21.21	74.28	1.03
0.067	213.54	38.78	25.87	33.46	0.69

Table 7.
Predicted reductions in carbon emissions with increased in wind fleet capacity.

from hard coal (12.12 GW at 8.76 MT per GW) and 14.62 from gas generation (from 3.44 GW at 4.25 MT per GW). The German grid Hdrm in 2015 was approximately 52.91 GW, and columns 2 and 3 in **Table 7** show the model predictions, by interpolation in Appendix B, of GWc and (GWe + GWs) values for a Hdrm value of 52.9 GW.

The increase in wind and solar generation since 2015, column 4, reduces the need for generation from dispatchable sources, and it is assumed that the reductions are in the order of the dirtiest sources first, that is, brown coal, followed by hard coal then gas. This assumption leads to the carbon emission predictions of column 5. Although it is not the objective of this study to take any view on the economics of wind generation, column 6 is a useful indicator of the decreasing effectiveness of the wind fleet in decarbonising the grid. Increasing the wind fleet from 44.58 to 119.25 GWc reduces carbon emissions by 2.40 MT per GWc, but increasing the wind fleet from 119.56 to 154.62 GWc reduces emissions by only 1.03 MT per GWc and from 154.62 to 213.54 GWc by only 0.69 MT per GWc.

5.2 Scenario 2: closure of Germany's nuclear generation capacity

In 2013, Germany decided to phase out its nuclear-generating capacity by 2022 [16]. A consequence of the loss of 9.9 GW of nuclear generation is that Hdrm will increase by 9.9–62.81 GW. It is possible to model the impact of this change on total carbon emissions as explained for the UK in Section 4.2. Assuming a marginal efficiency of 0.1, the additional carbon emissions are calculated to be 18.5 MT p.a., as shown in **Figure 5**. As for the other scenarios, there is a trade-off between wind fleet efficiency and carbon emissions: the lower the marginal efficiency, the higher the benefit. The optimum value will depend, as for the UK, on the relative costs of wind and gas energies, the carbon tax, and the German decarbonisation targets.

5.3 Scenario 3: replacement of petrol and diesel passenger vehicles with electric vehicles

In 2015, Germany had 47 million diesel and petrol passenger vehicles [29]. Assuming the same characteristics proposed by MacKay for the UK, these vehicles would have generated 126.2 MT carbon per annum, and the additional electrical power needed from the grid to replace these vehicles with EVs would be 19.5 GW. This increase in grid demand will increase the Hdrm available to the wind and solar fleets from 52.91 to 72.41 GW, and it is possible to model the impact of the additional capacity on carbon emissions as a function of the marginal efficiency.

The results of this modeling are shown in **Figure 6**; it is evident that there is considerable potential to reduce carbon emissions by replacing internal combustion engines with EVs.

6. Conclusions

This chapter explains why wind fleets, which compete for limited access to a grid, can only be modelled using real-time grid records, and why grids should be considered as acting towards wind fleets as time-varying low-pass filters.

Models of the UK and German grid systems are described using their real-time records which are available online. The models should have general applicability, although they would need to be updated should more efficient turbines with improved load factors be introduced. This would however be a simple matter of rerunning the models with revised scaling factors.

Since they incorporate large amounts of grid records across 52 weekly sub-models, the modeling process is somewhat cumbersome. However, the models may be used to create GWe vs. GWc and marginal efficiency curves from which look-up tables may be derived, which obviate the need for further model runs. The chapter describes the use of these look-up tables to investigate a number of important scenarios likely to be faced by the grids in the future. **Figure 4** provides a particularly useful quantitative insight into the ability/limitations of wind and solar fleets to decarbonise their grids. Residual generation, that portion of Hdrm which must be provided by dispatchable generation may be reduced by accepting higher levels of wind curtailment but wind curtailment comes at an economic cost. The level of wind curtailment, which will be deemed to be economic, will depend on the economic circumstances of the time and of the cost of reducing carbon emissions using alternative approaches.

Conflict of interest

The authors declare no conflict of interest.

Appendices

Appendix A. UK model predictions of grid configurations

The data in these tables has been derived from the GWe vs. GWc and marginal efficiency curves of **Figure 3**, that is, solar generation twice that in 2017 (cells marked N/A cannot be computed from the GWe vs. GWc and marginal efficiency curves of **Figure 3**).

Hdrm	**20**	**30**	**40**	**50**	**60**
Marginal efficiency = 0.20					
GWc	35.64	56.76	77.37	97.54	115.3
GWe	9.44	15.89	21.84	27.73	33.05
GWs	2.316	2.316	2.316	2.316	2.316
(GWe + GWs)	11.76	18.20	24.20	30.05	35.37
(GWe + GWs)/Hdrm	0.59	0.60	0.60	0.60	0.59
Residual Generation/Hdrm	0.41	0.40	0.40	0.4	0.41
GWe/GWc	0.27	0.28	0.28	0.28	0.28
% wind shed	10	6.7	6.7	6.7	6.7
Marginal efficiency = 0.15					
GWc	44.05	68.95	94.83	117.58	N/A
GWe	11.09	18.03	24.65	31.20	N/A

Hdrm	**20**	**30**	**40**	**50**	**60**
GWs	2.316	2.316	2.316	2.316	N/A
(GWe + GWs)	13.4	20.34	26.96	33.52	N/A
(GWe + GWs)/Hdrm	0.67	0.67	0.67	0.67	N/A
Residual/Hdrm	0.33	0.33	0.33	0.33	N/A
GWe/GWc	0.25	0.26	0.26	0.26	N/A
% wind shed	16.6	13.3	13.3	13.3	N/A
Marginal efficiency = 0.10					
GWc	56.22	86.86	117.17	N/A	N/A
GWe	12.6	20.02	27.59	N/A	N/A
GWs	2.316	2.316	2.316	N/A	N/A
(GWe + GWs)	14.92	22.51	29.91	N/A	N/A
(GWe + GWs)/Hdrm	0.75	0.75	0.75	N/A	N/A
Residual/Hdrm	0.25	0.25	0.25	N/A	N/A
GWe/GWc	0.224	0.233	0.235	N/A	N/A
% wind shed	25.3	22.3	21.6	N/A	N/A
Marginal efficiency = 0.05					
Hdrm	20	30	40	50	60
GWc	82.52	122.8	N/A	N/A	N/A
GWe	14.45	22.84	N/A	N/A	N/A
GWs	2.316	2.316	N/A	N/A	N/A
(GWe + GWs)	16.78	25.16	N/A	N/A	N/A
(GWe + GWs)/Hdrm	0.84	0.84	N/A	N/A	N/A
Residual/Hdrm	0.16	0.16	N/A	N/A	N/A
GWe/GWc	0.175	0.186	N/A	N/A	N/A
% wind shed	41.6	38.0	N/A	N/A	N/A

Appendix B. Germany model predictions of grid configurations

The data in these tables has been derived from the GWe vs. GWc and marginal efficiency curves of **Figure 8**, that is, solar generation twice that in 2017 (cells marked N/A cannot be computed from the GWe vs. GWc and marginal efficiency curves of **Figure 8**).

Hdrm	**45**	**55**	**65**	**75**
Marginal efficiency = 0.133				
GWc	99.08	124.97	148.16	172.59
GWe	18.2628	23.045	27.611	32.20
GWs	7.94	7.95	7.94	7.94
(GWe + GWs)	26.2028	30.985	35.55	40.147
(GWe + GWs)/Hdrm	0.582	0.563	0.5469	0.5353
Residual Generation/Hdrm	0.418	0.437	0.4531	0.4647
GWe/GWC	0.1843	0.1857	0.1864	0.1865

Hdrm	**45**	**55**	**65**	**75**
% wind shed	7.83	7.12	6.83	6.71
Marginal efficiency = 0.1				
GWc	128.41	161.55	194.18	226.03
GWe	21.60	27.39	32.95	38.40
GWs	7.94	7.94	7.94	7.94
(GWe + GWs)	29.54	35.33	40.89	46.34
(GWe + GWs)/Hdrm	0.656	0.642	0.629	0.618
Residual Generation/Hdrm	0.34	0.36	0.37	0.38
GWe/GWC	0.168	0.169	0.169	0.170
% wind shed	15.9	15.2	15.2	15.0
Marginal efficiency = 0.0666				
GWc	176.59	223.31	N/A	N/A
GWe	25.54	32.203	N/A	N/A
GWs	7.94	7.94	N/A	N/A
(GWe + GWs)	33.48	40.13	N/A	N/A
(GWe + GWs)/Hdrm	0.744	0.7288	N/A	N/A
Residual Generation/Hdrm	0.256	0.2712	N/A	N/A
GWe/GWC	0.1446	0.1446	N/A	N/A
% wind shed	27.6	27.6	N/A	N/A

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