# Keeping UK lights on during the transition to net zero

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## SUMMARY

- The UK is legally committed to achieving 'net zero' carbon emissions by 2050. After that date, the energy supply will be almost exclusively via electricity.
- Electricity demand will double by 2050, in particular, to meet the requirements of electric vehicles and heat pumps. This increase will have to be delivered from carbon-free sources, and the nation will be dependent on reliable grid supplies.
- Although many largely unproven technologies have been proposed, the basis for net zero in 2050 will have to be wind and nuclear power, with lesser amounts of other sources such as solar PV, carbon capture and storage, biomass, imports, and hydro.
- The output from the UK offshore and onshore wind farm fleet frequently drops below 20% of installed capacity. Solar PV is largely ineffective in UK winters. A significant nuclear new build programme (tens of MW) will be required to ensure carbon-free grid supplies even during calm midwinter periods.


## 1. INTRODUCTION

**The UK, along with the rest of the world, faces huge challenges in reducing carbon dioxide discharges to 'net zero' in time to prevent unacceptably high increases in global average temperature. This article reviews the scale of these challenges for the UK and looks at the role of nuclear generation within the future generation mix.**

In June 2019, the UK became the first major economy to pass legislation that commits the country to net zero emissions by 2050 (The Climate Change Act 2008 (2050 Target Amendment) Order 2019). 'Net zero carbon emissions' has become a popular phrase, although its precise meaning can be unclear. The definition used by both the Institute for Government [1] and National Grid is "Net zero refers to achieving a balance between the amount of greenhouse gas emissions produced and the amount removed from the atmosphere."

An explanation of net zero by The Energy Savings Trust (a NGO) is as follows [2]: "To reach net zero, emissions from homes, transport, agriculture, and industry will need to be cut. In other words, these sectors will have to reduce the amount of carbon they put into the atmosphere. But in some areas, like aviation, it will be too complex or expensive to cut emissions altogether. These 'residual' emissions will need to be removed from the atmosphere: either by changing how we use our land so it can absorb more carbon dioxide or by being extracted directly through technologies known as carbon capture, usage, and storage (CCUS)." (It is noted that CCUS reduces emissions but does not eliminate them.)

As a minimum, therefore, 'net zero' will mean very large-scale adoption of electric vehicles (EVs) and non-fossil fuel heating (such as heat pumps), enhanced energy conservation measures, and phasing out fossil-fuelled generation (including natural gas/CCGT). This article looks at some of the challenges of maintaining reliable electricity supplies in a net zero UK.

### Notes for context:

1. Throughout the following, both 'GB' and 'UK' are used appropriately in context.
2. Speculative, expensive, or unproven means of large-scale low-carbon electricity generation such as fusion, tidal and wave power, carbon capture and storage have not been addressed. Large-scale hydrogen production, storage, and transmission is also unproven, although small-scale trials have been carried out.
3. Biomass (wood pellets) is currently used at the 2.6 GW Drax power station in Yorkshire. It is assumed for present purposes that Drax will stop operation before 2050 and that biomass will no longer be a significant fuel for power generation.

## 2. CURRENT HYDROCARBON USAGE AND FUTURE ELECTRICITY DEMAND

UK hydrocarbon usage has changed significantly since the 1980s (Figure 1). The 'dash for gas' in the 1990s led to a dramatic reduction in coal consumption, and the large-scale introduction of wind turbines since 2000 has now led to the virtual elimination of coal use altogether in the UK. There has been significant de-industrialisation as much of UK manufacture has moved to Asia, leading to reduced energy demand. There was also a significant transition from petrol to derv from 1990 to 2015, although this has now stalled because of concerns about diesel engine emissions.

| Type of fuel | Coal | Natural gas | Petrol | Derv | Fuel oil | Gas oil | Aviation fuel |
|---|---|---|---|---|---|---|---|
| MTOE (2019) | 5.28 | 74.36 | 13.19 | 26.14 | 2.50 | 7.54 | 15.18 |

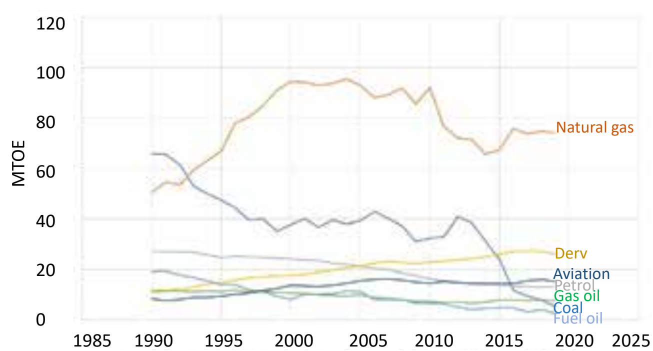


**FIGURE 1: UK hydrocarbon fuel use 1990-2019. (MTOE= Million Tonnes of Oil Equivalent).**

Source : ONS Energy use: Fossil fuels by fuel type, https://www.ons.gov.uk/economy/environmentalaccounts/datasets/ukenvironmentalaccountsfuelusebytype

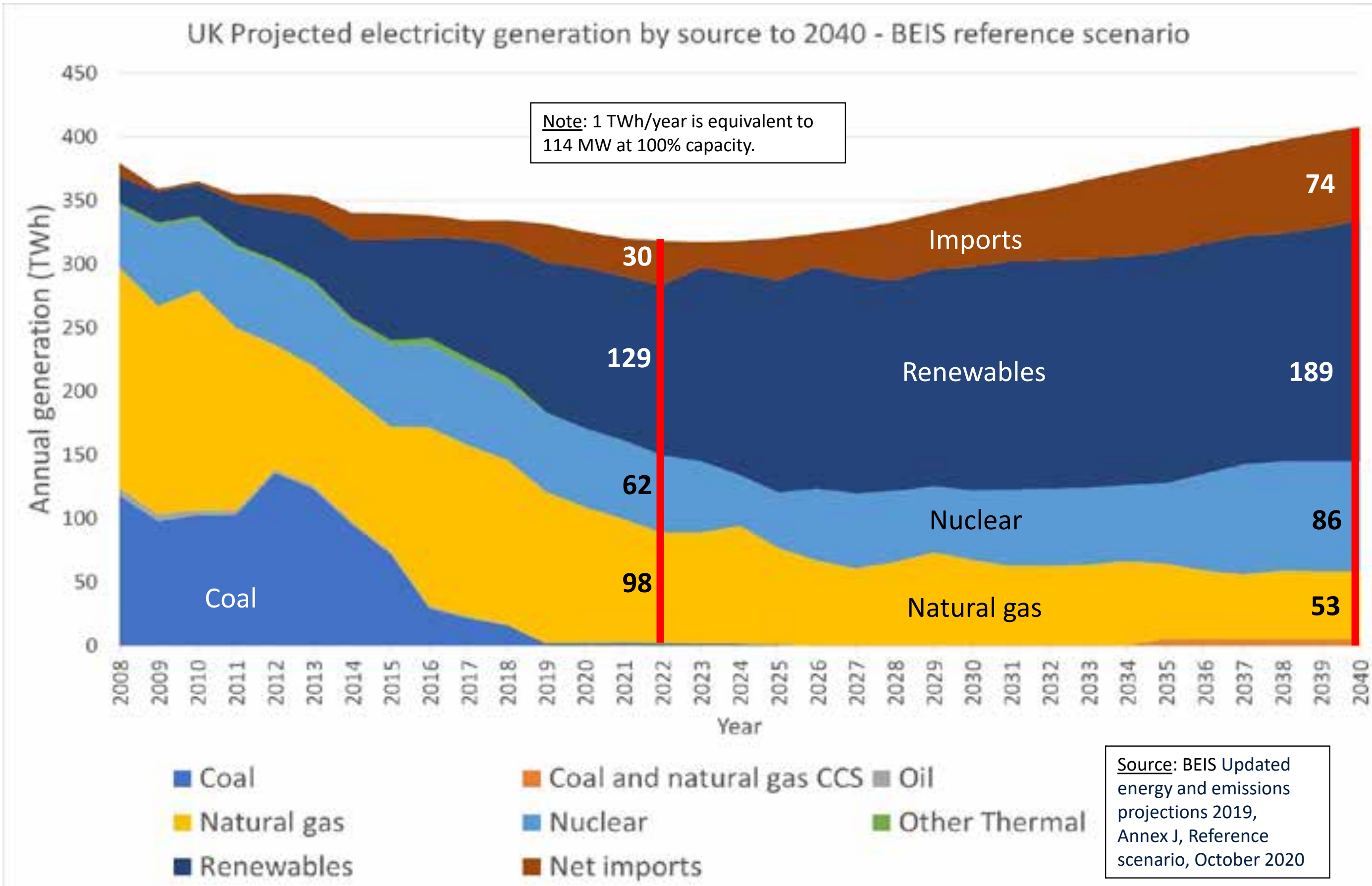


**FIGURE 2: Annual electricity generation (TWh) to 2040 – BEIS 2020 reference scenario.**

We can *estimate* increased generation requirements arising from a complete transition to electric vehicles (EVs) and heat pumps using data from the table in Figure 1[1] by means of simple sums, using a variety of assumptions, as follows:

(i) Petrol use in 2019 was 13.19 MTOE/yr = 552 x $10^{15}$ J. This is equivalent to (0.3 engine efficiency/0.9 electric motor efficiency) x 552 x $10^{15}$ J of energy for equivalent EVs, which is equal to 184 x $10^{15}$ J, or 51 TWh of generated electricity. This figure neglects the benefits of regenerative braking in EVs.

(ii) Derv use in 2019 was 26.14 MTOE/yr = 1094 x $10^{15}$ J. This is equivalent to (0.45 engine efficiency/0.9 electric motor efficiency) x 1094 x $10^{15}$ J of energy for equivalent EVs, which is equal to 547 x $10^{15}$ J, or 152 TWh of generated electricity. This figure neglects the benefits of regenerative braking in EVs.

(iii) Similarly, estimates can be made of the changes to electricity demand that will arise from a transition from natural gas domestic heating systems to heat pumps. DUKES 2020 [3] (the last set of UK energy data prior to the COVID-19 pandemic which temporarily affected electricity demand) gives 2019 usage of natural gas for domestic heating as 310 TWh. If there were 100% replacement of domestic central heating with heat pumps with (say) a coefficient of performance of 2.0, then 155 TWh of additional electricity demand would arise (again neglecting transmission losses).

Other developments such as hydrogen are neglected here. Hence, a ‘business-as-usual’ scenario, with 100% replacement of internal combustion engines with electric vehicles and 100% replacement of gas boilers with heat pumps, may lead to an increase in annual UK electricity demand of up to (51+152+155) or 358 TWh/yr. This amount neglects transmission losses, industrial use of natural gas, reductions in demand that might arise from improved insulation and changes to surface travel, and population changes – but a conclusion that the annual UK demand of ~700TWh (compared to the current value of ~320 TWh, see Figure 2) by 2050 seems reasonable.

This is a massive increase in electricity supply for the UK to achieve net zero by 2050 – more than doubling the current annual electricity generation. However, there seems to be some confusion in government about this large change, with apparently inconsistent projections being published almost simultaneously. The Department of Business Energy and Industrial Strategy (BEIS) in its ‘reference scenario’[2] published in 2020 [4] only projects an electricity demand of some 400 TWh by 2040, as shown in Figure 2. However, other work by BEIS [5] says annual electrical power demand by 2050 may reach 672 TWh, a value that tallies with the Climate Change Committee’s Sixth Carbon Budget [6]. Another analysis by the National Grid [7] indicates a 2050 power demand

[1] Conversion factors and other data are given in Appendix 1.

[2] The BEIS 2020 reference scenario is based on “central estimates of economic growth and fossil fuel prices”. This scenario “contains all agreed policies where decisions on policy design are sufficiently advanced to allow robust estimates of impact”.

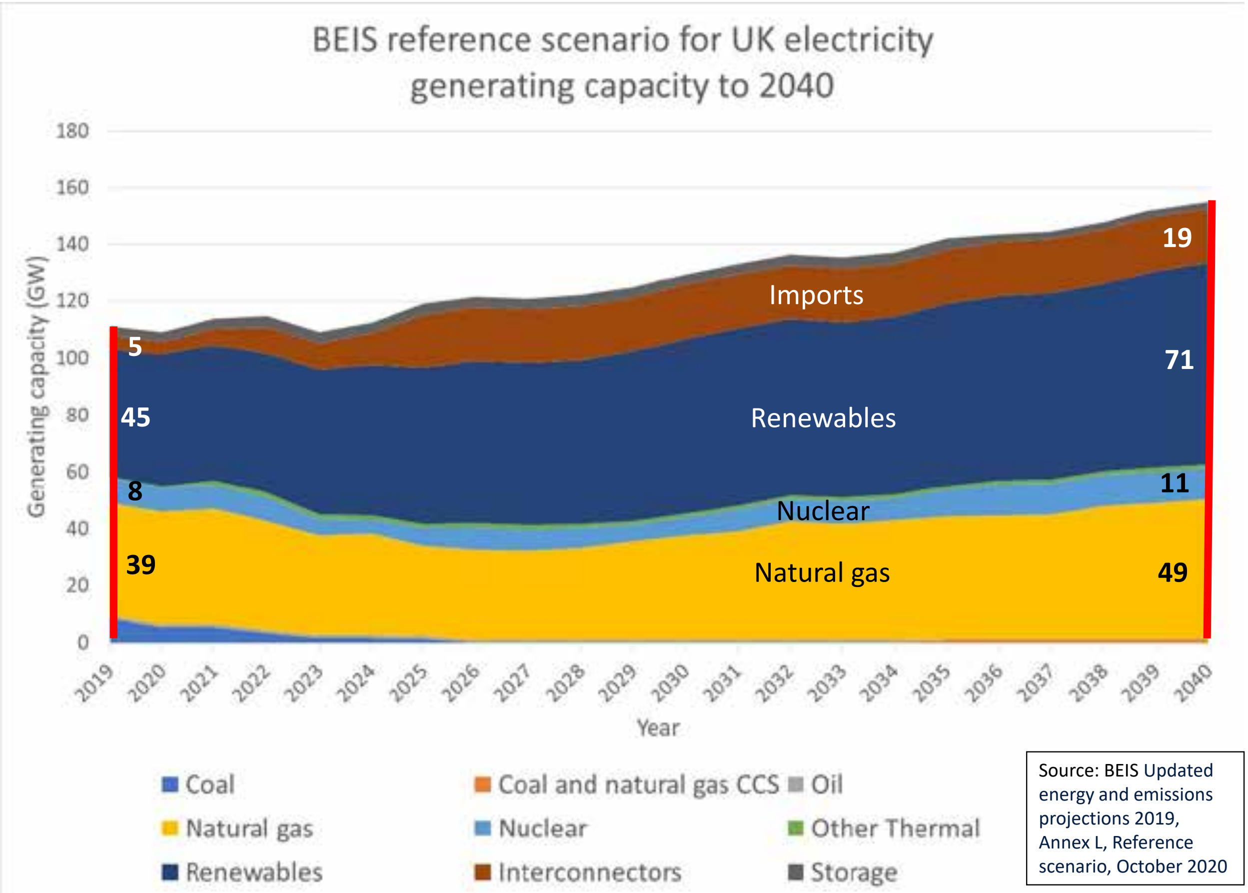


**FIGURE 3: Installed generating capacity (GW) to 2040 – BEIS 2020 reference scenario.**

of 742 TWh. (BEIS has since amended its 2050 position quite significantly in the October 2021 "Net Zero Strategy: Build Back Greener" [8], which identifies a potential 460-510 TWh demand by 2035, and a potential 690 TWh demand by 2050, with a further 240-500 TWh demand for hydrogen production.)

There is therefore a large gap between BEIS's 2020 reference scenario for 2040 electricity supply and BEIS's anticipated electricity demand for net zero in 2050. If BEIS's 2020 reference scenario is all that is achieved by 2040, then there will have to be a dramatic expansion of generation during the 2040s to achieve net zero by 2050. This potential doubling of UK electricity supply by 2050 will have to occur within the dual constraints of (a) meeting carbon emissions constraints and (b) avoiding blackouts.

The BEIS 2020 reference scenario for 2040 includes projections for the installed generating capacity mix (Figure 3). The strategy presented in this diagram appears clear, namely that by 2040 renewables (primarily wind) will supply the bulk of UK electricity, supplemented by imports and nuclear energy, but a large amount of gas turbine plant will remain available as a standby in the event of low wind and solar power during periods of high demand such as occur during winter anticyclones. The 2040 scenario in Figure 3 shows a small increase in nuclear to 11GW, which would be consistent with Sizewell B (with life extension), Hinkley Point C, Sizewell C, and 3.4 GW of as-yet-unidentified nuclear plants (perhaps Rolls-Royce SMRs).

The 2040 reference scenario in Figure 3 also shows a significant increase in gas turbine capacity (albeit running at a lower capacity factor), to cope with the high variability of wind turbine output, as discussed below. And yet, a corollary of 'net zero by 2050' must be that most gas turbine power generation will be phased out during the 2040s.

The UK Government has recently (October 2021) published its "Net Zero Strategy: Build Back Greener" [8], which further develops some of the ideas in the BEIS 2020 reference scenario. Notably, this new strategy now commits to powering the UK "entirely by clean electricity, subject to security of supply" by 2035. It also commits to other measures: A "Future Nuclear Enabling Fund" for nuclear technologies including Small Modular Reactors; 40 GW of offshore wind capacity by 2040; 1GW of floating offshore wind by 2030; ambitious targets for low carbon hydrogen production; deployment of new "flexibility measures" including storage to help smooth out future price spikes.

## 3. VARIABILITY OF DEMAND AND VARIABILITY OF RENEWABLE GENERATION

Matching daily and seasonal variation in electricity supply and demand is the problem facing grid controllers. GB electrical energy storage is limited at present to pumped storage at Dinorwig (in Gwynedd) and Cruachan (in Argyll), which can each supply hundreds of MW for a few hours. New, additional pumped storage opportunities are severely constrained by geographical and environmental considerations.

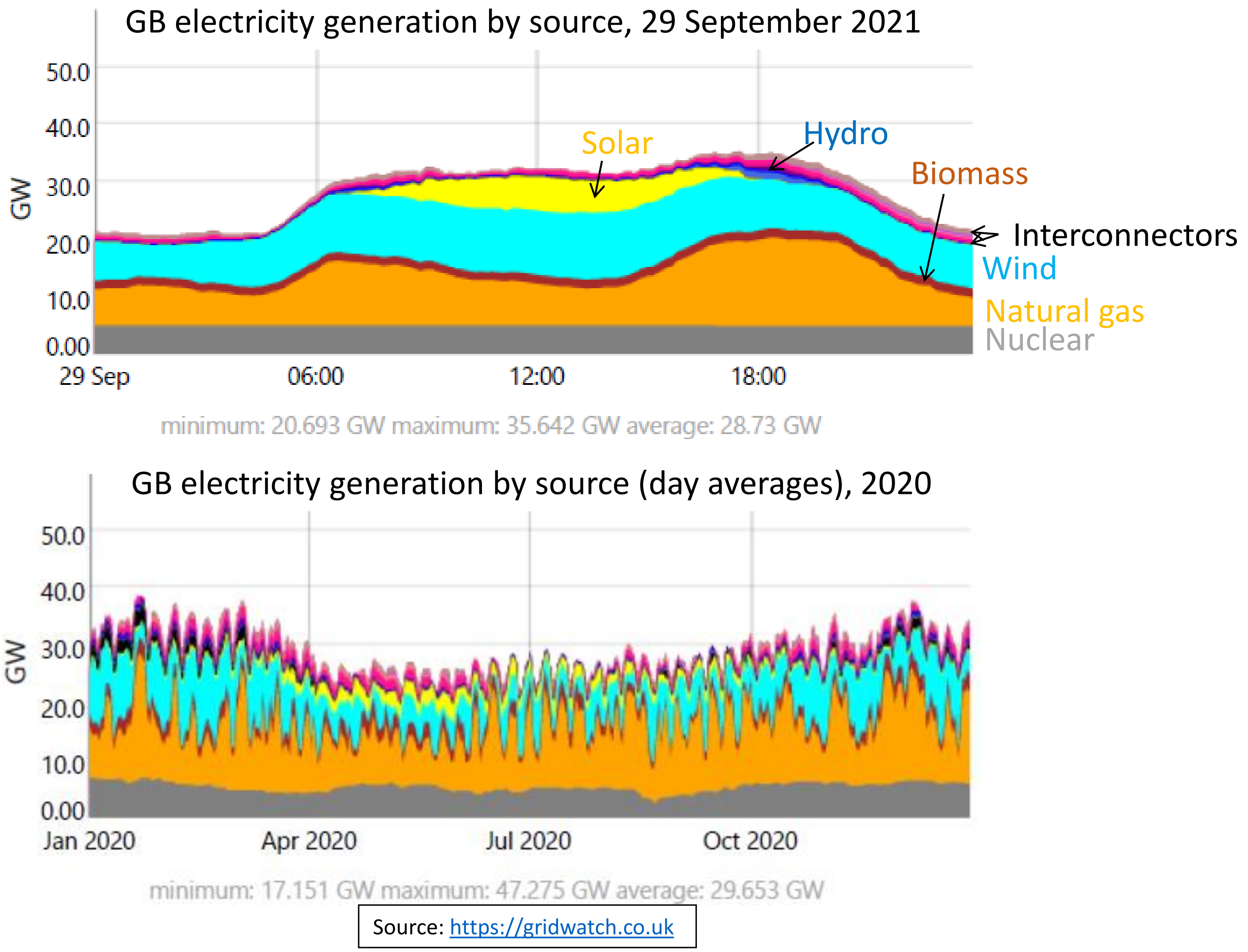


**FIGURE 4: Variability of renewable generation output in GB.**

Future large-scale use of battery storage is an unknown factor at present, but its adoption seems limited by cost considerations. The 100 MW Tesla-built battery storage plant in South Australia works well, but it was built for a bet by a billionaire, so its economics are unproven [9]. Other storage technologies have been proposed, but their large-scale adoption is uncertain – although hydrogen production, storage, and subsequent use for either transport or power generation may be a contender. Other possible means of storage have been reviewed recently by Jacobs [10].

Typical GB winter evening peak demand may currently reach 50 GW, while summer night minimum demand falls below 20 GW. A detailed breakdown of typical values is presented in Figure 4, which shows electricity supply for a typical autumn day in 2021, and daily averages throughout 2020.

Upper diagram: Changing electricity demand and supply during a representative autumn day in 2021. This shows how solar power (in yellow) is of course limited to daytime, with gas turbines, pumped storage and imports being used to meet the evening peak demand.

Lower diagram: Day averages throughout 2020 show several interesting features including

(i) the high variability of wind power (in light blue) through the year, with gas turbines smoothing out the troughs,
(ii) weekly cycles in daily demand with minima appearing each weekend,
(iii) solar power contribution (in yellow) being insignificant outside the period March to September,
(iv) the reduction in demand following covid-19 lockdown in late March 2020.

Both diagrams show nuclear operating as baseload. (*Note that evening peak demands are significantly greater than day average values.*)

There has been impressive growth in wind generation in the years since 2010 (Figure 5), to a current installed capacity of about 24 GW. Wind generation is examined more closely in Figure 6, which shows GB wind turbine output for two years (October 2019 to September 2020, and October 2020 to September 2021). These diagrams include the covid-19 pandemic period with consequent lower demand, but wind power is a preferred source

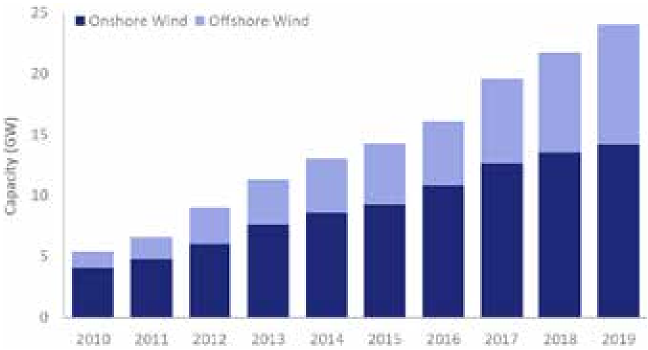


**FIGURE 5: Growth of UK wind generation installed capacity since 2010 [11].**

Installed wind capacity. Source: BEIS Energy Trends, March 2020

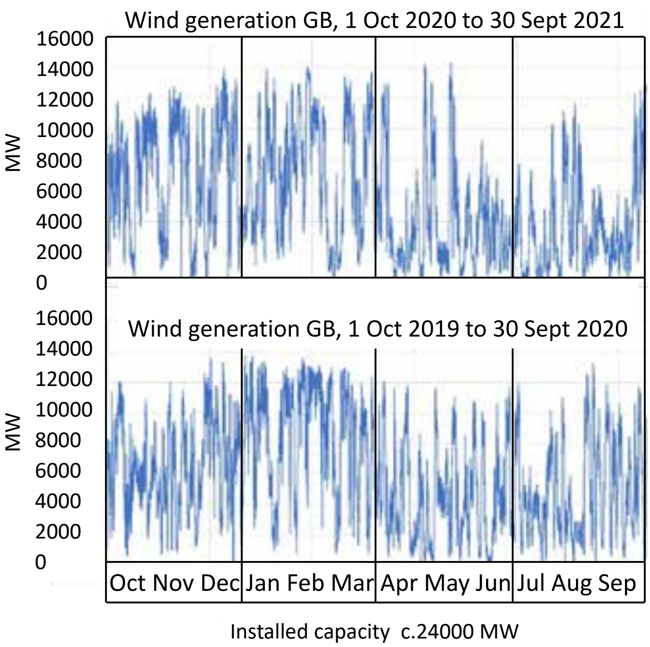


**FIGURE 6: Wind generation in GB (top) for Oct 2020 to Sept 2021 and (bottom) for Oct 2019 to Sept 2020.**

of supply since its marginal cost is zero, so 'turndowns' for wind power have been rare. Figure 6 also shows that seasonal variation in the GB wind turbine fleet output is not consistent from year to year; British weather does not follow the patterns.

Figure 7 presents a cumulative distribution of the GB wind turbine fleet output, using 5-minute values of output, during the period October 2020 to September 2021. For an installed fleet capacity of c.24 GW, output seldom exceeds 12GW (only about 5% of the time) and is below 2 GW about 20% of the time. Fleet power output is between 2 GW and 9 GW about 60% of the time.

A recent example of low wind generation was in February-March 2021 when Britain experienced its longest spell of low wind output in more than a decade. For eleven days between 26th February and 8th March calm weather covered the country, and the capacity factor of the UK wind fleet did not go above 11%. Wind farm output fell to as low as 0.6 GW on 3rd March [12][3].

[3] The same report notes that the Germans have coined a word for simultaneous low wind and low solar power – a 'Dunkelflaute', meaning 'dark wind lull'.

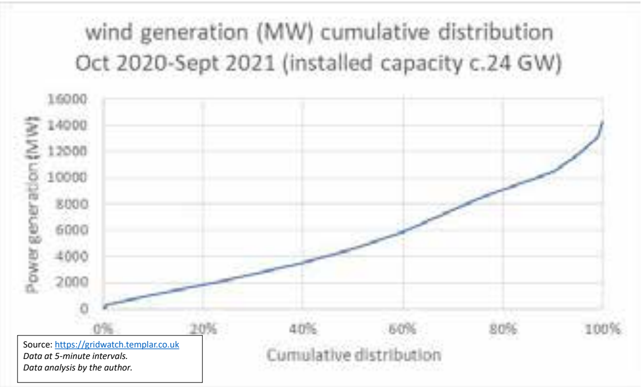


**FIGURE 7: Cumulative distribution of the output from the GB wind turbine fleet, 5-minute time intervals, October 2020 to September 2021. (Author's analysis based on data from Gridwatch)**

Another recent example of tightness of supply can be found (Table 1) on 28th December 2020 at 1300 GMT, where the contribution from wind power was only 1.5 GW.

| Generation source | GW |
|---|---|
| Nuclear | 6.1 |
| Natural gas CCGT | 21.0 |
| Biomass | 1.6 |
| Coal | 0.3 |
| Wind | 1.5 |
| Solar | 1.2 |
| Hydro | 1.3 |
| Other | 0.4 |
| Interconnectors (total) | 3.8 |
| **Demand** | **37.2** |

**Table 1: GB electricity supply on 28th December 2020 at 1300 GMT.**

For grid controllers and generating plant designers and operators, it is perhaps equally significant to consider the rate of change of wind turbine fleet electrical output as it is to consider the electrical output itself. (Forecasting wind turbine outputs using weather forecasts is now a critical part of grid control activities). The rate of change of output from the collective GB fleet of wind turbines during the period October 2020 to September 2021 is presented in Figure 8, which presents cumulative distributions for 5-minute and one-hour wind output variabilities. These analyses were done by subtracting wind electrical outputs at every 5-minute time interval from the corresponding outputs either 5 minutes or one hour previously, then assessing the percentiles for each magnitude of change.

The results in Figure 8 show that, although 80% of the time the GB wind turbine fleet output remains reasonably constant at both 5-minute and one-hour intervals, there are nonetheless times when output from the entire fleet, despite being geographically spread across Great Britain and its continental shelf, can vary by +/-150 MW in 5 minutes or +/- 1000 MW in one hour. Matching this rate of change represents both a challenge and an opportunity for nuclear plant designers and operators.

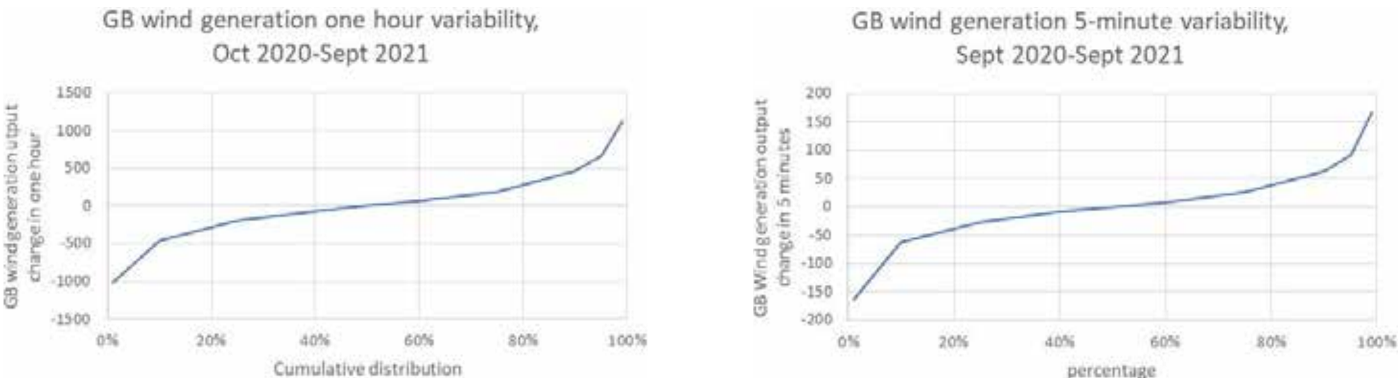


**FIGURE 8: Variability of GB wind turbine fleet output at one-hour (left) and 5-minute (right) intervals, October 2020 to September 2021. The diagrams present the probabilities of variations of wind turbine fleet output within the defined timescales. (Author's analysis based on data from Gridwatch.)**

The International Energy Agency has pointed out that net zero means electricity must "become the core of the energy system" [13]. In net zero, society will become almost entirely dependent upon electricity, even more than already. The electricity grid supply will have to be robust because blackouts will be life-threatening (e.g., hospitals, old people) or expensive (e.g., freezers full of food may have to be discarded). In addition to a risk of blackouts from loss of supply during periods of low wind and solar power, the reduced numbers of large generators – such as nuclear, coal, or CCGT plants, which act to anchor voltage and frequency – may create risks of grid instabilities and blackouts. After the closure of the last Advanced Gas-cooled Reactor power stations in about 2030, Peterhead CCGT plant in Aberdeenshire may be the only large generator in GB north of Drax in Yorkshire, so the potential for grid instability is real. The solution to this problem lies in improved grid control systems – 'so-called 'smart grids' [14] - for wind turbines, at least in north GB, where (on current plans) there may be no large generators.

If the grid supply is not robust, people may resort to buying hydrocarbon-fuelled domestic generators (which would defeat the purpose of trying to become 'net zero') or else buying costly storage batteries and inverters. (Recent advertisements show the domestic storage Tesla Powerwall 2 provides 13.5 kWh storage for about £10000.) Any apparent iniquity in the reliability of electricity supplies – where the rich can afford back-up supplies while the poor cannot - may prompt political debate about 'energy justice'.

Continuity of electricity supply will therefore become a political imperative during the transition to net zero. Any significant blackouts – especially in mid-winter - will be a vote-loser, no matter what rhetoric about climate change may be forthcoming.

Texas state average temperature departures from normal for the 7-day periods centred on the coldest day for December 1989, February 2011, and February 2021 'Arctic outbreaks', showing that the February 2021 outbreak had the most significant extended period of below normal temperatures (-15C) compared to earlier outbreaks.

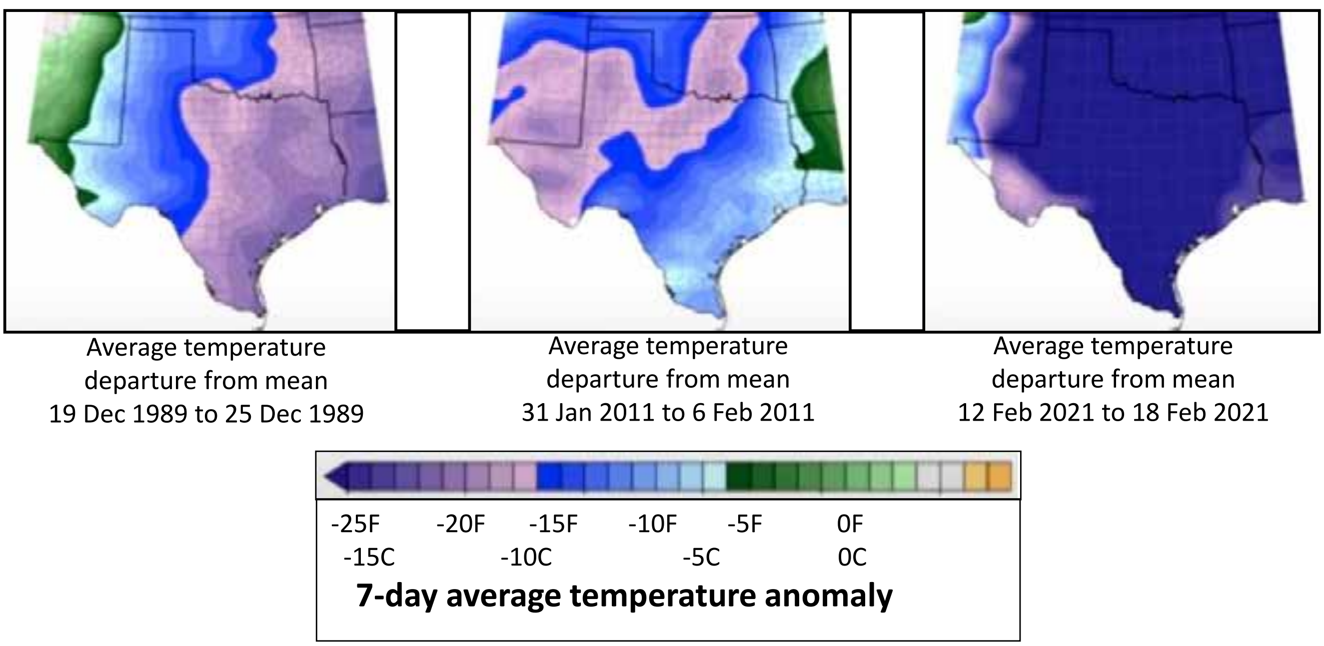


**FIGURE 9: A video still showing the extent of the temperature anomaly in Texas during the February 2021 blackout [16].**

Excessive dependence on wind generation as gas turbines are phased out during the 2040s will not be acceptable. Increasing imports to perhaps much more than 100TWh per year seems an unlikely solution. Phasing out gas turbines must surely necessitate a corresponding increase in flexible nuclear generation.

## 4. LESSONS FROM ELSEWHERE: THE TEXAS BLACKOUT, FEBRUARY 2021

High dependency on wind generation leads to risk of grid instability and blackouts especially (for the UK) during winter anticyclones. A reminder of the consequences of large-scale winter blackouts has occurred recently in Texas.

The Texas electricity grid only has weak links with the rest of the US. Texas had an extremely unusual cold spell in February 2021 which began with the 'Groundhog Day blizzard', which lasted from 1st to 5th February. Wikipedia [15] reports that "The storms caused a massive electricity generation failure in the state of Texas, leading to shortages of water, food, and heat. More than 4.5 million homes and businesses were left without power, some for several days. At least 210 people were killed directly or indirectly, with some estimates as high as 702 killed as a result of the crisis."

The storm was truly exceptional – but unusual storms may become more common with climate change, including in the UK. An excellent video [16] on the 'Practical Engineering' channel on YouTube gives a good summary of events in Texas. Figure 9 presents a still from the video showing the extent of the cold snap – there was a -25°F (-15°C) temperature anomaly across the whole state from 12th to 18th February.

## 5. CONCLUSIONS OR CONCLUDING REMARKS

Energy supply in 'net zero' is likely to be almost exclusively via electricity. Wind and nuclear generators have very low carbon footprints. Solar PV has a moderate footprint, and carbon capture and storage have a higher footprint.

Output from the entire GB wind turbine fleet can fall to a small fraction of its capacity during calm periods and changes can happen rapidly. A big challenge in the net zero world will be keeping the lights on, especially in winter anticyclones when power from both solar and wind can be very low (so-called 'Dunkelflaute'), and when demand is high.

Any prolonged blackouts in an all-electric economy, as well as having serious consequences, especially for hospitals and the elderly, will have serious political ramifications.

There will be a large expansion of electrical generation to meet the UK's target of net zero by 2050. This will include further large increases (many tens of GW) in onshore and offshore wind farms. There will also have to be closure of many (or most) natural gas/ CCGT plants in the 2040s, so significant amounts of other reliable supplies will be needed. Very large-scale expansion of imports to meet this gap seems unlikely. It seems inevitable that new nuclear – perhaps tens of GW additional capacity - will be required for carbon-free electricity supplies to be assured.

Flexible generation is necessary to manage the variability of wind generation. New nuclear is capable of flexible response to meet this requirement.


## Acknowledgement

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## Appendix 1

**Notes and conversion factors:**

MTOE = million tonnes of oil equivalent

Calorific value of 'oil equivalent' = 41868 kJ/kg (Source: Wikipedia 'Tonne of oil equivalent')

Thermal efficiency of petrol engine ~ 30% (Source: Wikipedia 'Engine efficiency')

Thermal efficiency of diesel engine ~ 45% (Source: Wikipedia 'Engine efficiency')

Efficiency of Li-ion storage batteries ~ 99%

Efficiency of electric motors ~ 90%

1 TWh = 3.6 x $10^{15}$ J

1 TWh/yr = 114 MW at 100% capacity factor

Capacity factor = (actual annual output in MWh)/(rated maximum output in MW * 8760 hours/year)

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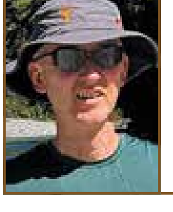


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