SOLAR POWER IN BRITAIN

The impossible dream

Dr. Capell Aris

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CONTENTS

Executive summary

- Supporters of renewable energy argue that wind- and solar-generated electricity can form the basis of a secure, affordable, low-carbon energy supply for the UK and EU, despite the inherently variable and intermittent nature of these sources.

- This paper first contributes to the debate by estimating the output of a model UK fleet of solar farms rated at 8.4GW, by using ten years of half-hourly aviation weather reports as a data source.

- The key findings for such a solar fleet are that:
    - It has a capacity factor of just 9% when the panels are new, and so generates less than a tenth of its nominal output over the course of a year.
    - It produces hardly any power in winter when demand is highest.
    - Power output is severely intermittent, lying below 10% of installed capacity for 5,790 hours a year and exceeding 60% for only 7.

- The claim that a mixture of solar and wind generation can smooth out this intermittency is found untrue. Under this compounded system, power output falls below 10% of installed capacity 97 times a year for periods of between 6 and 141 hours.

- This study evaluates three other proposed solutions to the intermittency problem, and comes to the following conclusions:
    - Pumped storage is currently the best and most cost-effective solution for large-scale energy storage, but would be enormously expensive on such a huge scale and have a severe environmental impact, even in the unlikely event that enough UK sites could be identified.
    - Battery storage on this scale is likely to be even more expensive and batteries would require frequent replacement.
    - Interconnectors to a northern European renewable-energy grid would be ineffective, because both solar and wind resources vary with time across the region in much the same way as for the UK.

- With the energy storage technology available for the foreseeable future, no combination of wind and solar energy with backup storage would be suitable to supply a significant proportion of grid electricity without full conventional backup being available.

- However, intermittent renewable energy could have a useful role to play if it was used primarily for domestic space and water heating. An option which has been successfully implemented in New Zealand in the past.

1. Introduction

During the period 2005 to 2015 the UK's installed solar generating capacity rose from zero to approximately 7GW, almost all of which is connected to the UK's local distribution grids rather than the UK transmission system. The commonest solar generation technology used in Europe is photovoltaic, flat panels mounted with fixed azimuth and pitch. A wide choice of photovoltaic materials is available, varying in efficiency and cost. In Europe the commonest material selected is cheap, and inneficient amorphous silicon.

In the UK these solar panels are either fixed to domestic roofs and receive Feed in Tariff (FIT) subsidies, or ground-mounted in the form of large solar farms receiving Renewable Obligation Certificates (ROCs). The historic split between the installed capacities of these types is shown in Table 1.

TABLE 1: GROWTH OF UK SOLAR CAPACITY (MW) BY SUBSIDY TYPE[17]

	2008	2009	2010	2011	2012	2013	2014	2015
ROCs	1	2	3	7	10	600	2415	4665
FITs	2	6	65	936	1623	2093	2749	3104
TOTAL	3	8	68	943	1633	2693	5164	7769

The fleet receives renewable energy payments which have varied from year-to-year as shown in Table 2.

TABLE 2: SOLAR SUBSIDY LEVELS

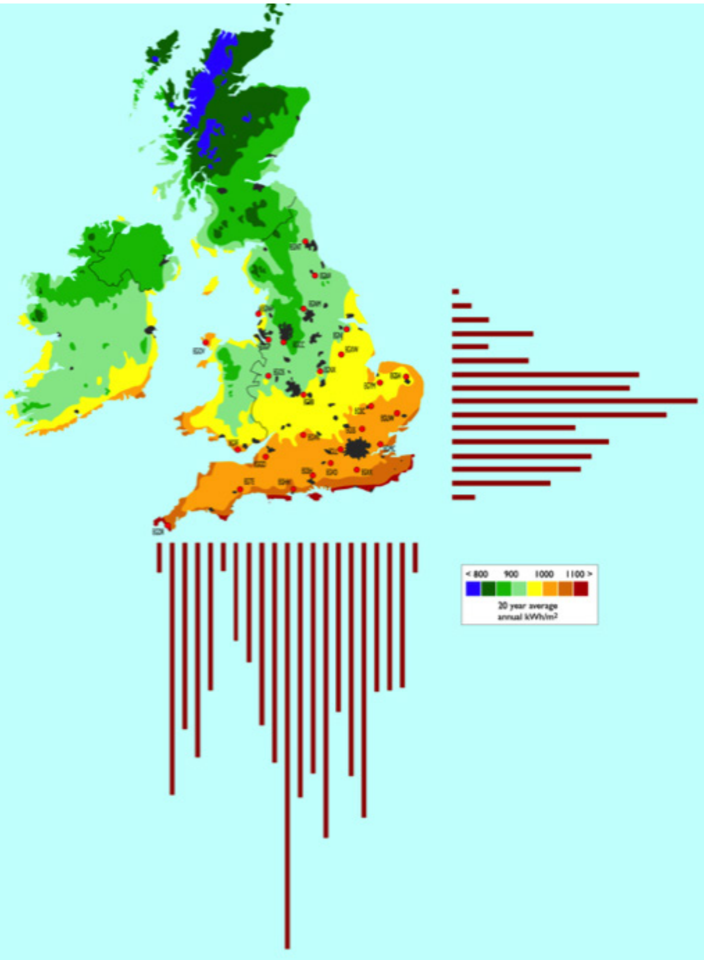
	2009	2010	2011	2012	2013	2014	2015
FITs p/kWh			43.30	45.40	21.65	14.38	12.05
ROCs multiplier	2	2	2	2	1.6	1.4	1.3
ROCs price	37.19	36.99	38.69	40.71	42.02	43.30	42.44
ROCs payment £/MWh	74.38	73.98	77.38	81.42	67.23	60.62	55.17

FITs are a payment per kWh produced whether or not that energy is consumed locally or exported. ROCs have been awarded at the rate of 2 per MWh of solar generation, dropping to 1.3 in 2015. The redemption rate of each ROC has risen over the same period. Both subsidy rates are set to decrease dramatically in the next months, but the total renewable energy subsidy is likely to pass the Levy Control Framework target of £7.6 bn by 2020.

Some large, ground solar arrays are mounted on factory roofs or brownfield sites but, contrary to government guidance, the vast majority cover 100 square kilometres of what was previously agricultural land, much of it of prime quality see (Figure 1). The shift from agricultural production to ground mounted solar panels results in a loss of agricultural income of between £2m (grade 3 land) to £6m (grade 1) per annum.

Only 170MW of this solar fleet is located in Scotland, and there are few solar plants in Iceland, Norway, Sweden and Finland. This suggests that solar power of this type is uneconomic further north than the England-Scotland border.

FIGURE 1 LOCATION OF THE UK SOLAR FLEET



Brown bars represent relative installed capacities for each latitude and longitude (Solar Power Portal).

There are contrasting views on the performance of solar power in the UK. It is claimed that ground mounted solar power is approaching grid-parity with CCGT, which is usually taken to mean equal costs when only build and fuel costs are considered. In their reportby KPMG *UK Solar beyond the Subsidy,* the case is argued that when compared to a load following CCGTs (load factor 61%), but acknowledge that CCGT requires no mechanism to cope with solar power intermittency and is also dispatchable.[1]

For roof-mounted solar generation, ex-Energy Minister Greg Barker claimed that "Installing solar panels on household roofs is a better investment than a pension . . . and if your panel is well-sited, it could yield 8 per cent or more". However, this claim usually ignores all maintenance and decommissioning costs and makes no analysis of normal project finance discounting.

There are also notes of caution from National Grid who have recently stated that in the summer months, large volumes of solar generation coupled with minimum demand could require increased storage on the system in order to avoid load cycling nuclear plants.[2] They also raise concerns about the system inertia of the grid system (which could jeopardize frequency regulation).

Given these contrasting views of solar generation benefits and problems, and the additional solar subsidy costs experienced on energy bills, it is regrettable that there has been little analysis of the performance of this generation fleet other than perhaps statements of annual solar production. However, it is apparent that no detailed solar generation data is available. Current power output and summary, half-hourly energy production data is available for all other generation types but not for solar generation. All solar generation is connected to the local distribution grids (not the transmission system) of the UK and only reports summary data over extended periods.

The first aim of this work was to build and test a model for half-hourly solar energy production sensitive to the location, date and time, azimuth and tilt of the solar panels, and the prevailing weather conditions such as pollution, fog, mist and cloud cover.

The UK Meteorological Office will hold comprehensive data for UK weather conditions but although this is publicly funded, the data is not made freely available to private individuals. Therefore, historic aviation weather reports provided the weather information for this study, just as they did in my earlier paper *Wind Power Reassessed*.[3, 4] This data was then used to study solar power production levels, variability, intermittency, and capacity credit. Similar aviation data exists for Europe, and this was used to extend the study to cover solar generation in northern Europe and thus investigate the possibility of the use of interconnectors to mitigate the intermittency of the UK renewable fleets.

Throughout this paper reference will be made to results of my earlier wind power study so that the performance of the total UK renewable generation fleet can be assessed.[3, 4]

2. Data source and solar power modelling

To calculate solar power production at a stated location we need two sources of data:

1. A prediction of the sun's altitude (elevation) and azimuth in relation to any date, time and position on the earth's surface.
2. Contemporary information about prevailing visibility and cloud conditions.

The sun's position can be determined using one of the many computer algorithms that are published by organisations such as the Greenwich Observatory and NASA. Aviation reports taken from airports half-hourly can be used as a source of visibility, weather and cloud cover.

2.1 AVIATION WEATHER REPORTS

Large airports and RAF stations are obliged to routinely gather and report good quality meteorological data. Conditions are reported in a coded form compliant with an international standard.

Observations are usually taken at least hourly and within most countries at fixed times. As an example (the fields in red describe the visibility, weather conditions, and cloud cover and level):

07/01/2005 08:50 METAR EGOV 070850Z 22031KT 4000 -RADZ OVC008 11/10 Q1010 NOSIG=

(7th January 2005 METAR report for Valley (EGOV), time 08:50 UTC, wind 31 knots from 220°, visibility 4,000 metres, light rain and drizzle, cloud: overcast at 800 feet, temperature 11°C, dew point 10°C, pressure 1,010mB, no significant change during next two hours, METAR ends).

Records for 28 sites over a period of ten years have been downloaded from www.ogimet.com and placed into Excel spreadsheets. The visibility and cloud data were then extracted by means of macro analysis. Details of these sites are given in Figure 2 and Table 3.

FIGURE 2: UK INSOLATION AND AIRFIELD DATA SITES

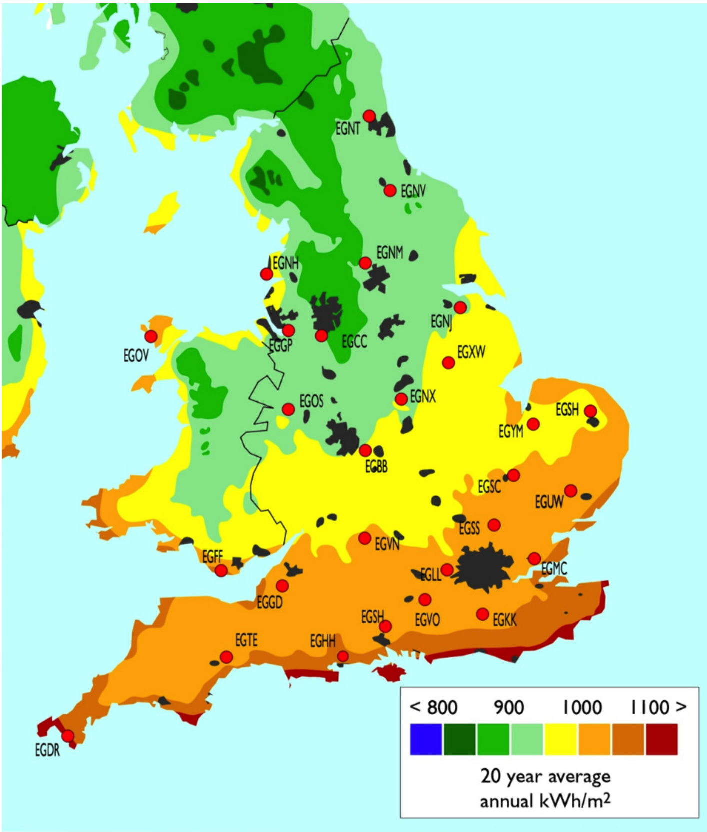


TABLE 3: UK AIRFIELDS ISSUING METARS USED IN THIS STUDY.

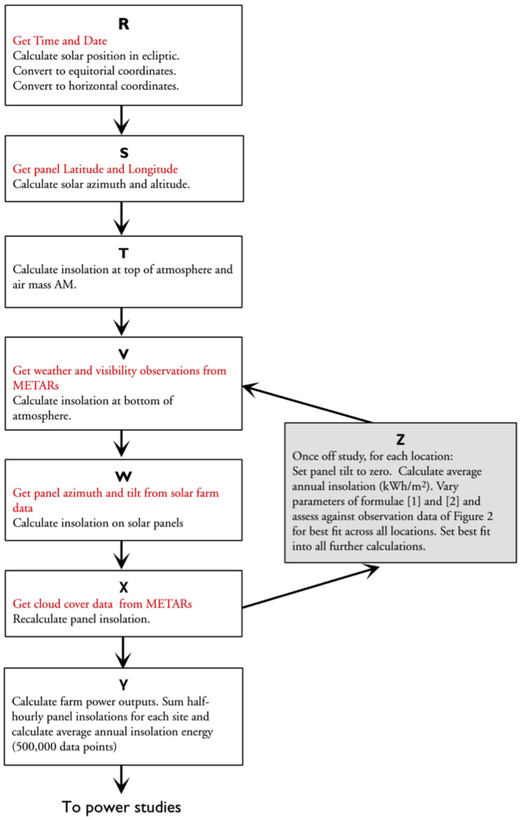
NAME	ICAO‡	LATITUDE	LONGITUDE	HORIZONTAL INSOLATION kWh/m2 p.a FROM FIG. 3	SIZE OF SOLAR FARM (MW)
Culdrose*	EGDR	N50º05’08”	W05º15’17”	1,100	300
Exeter†	EGTE	N50º44’03”	W03º25’17”	1,025	300
Bournemouth†	EGHH	N50º46’49”	W01º50’16”	1,075	300
Southampton†	EGHI	N50º56’58”	W01º21’20”	1,025	300
Gatwick	EGKK	N51º09’10”	W00º11’24”	1,025	300
Odiham*	EGVO	N51º14’03”	W00º56’34”	1,025	300
Bristol†	EGGD	N51º22’02”	W02º42’46”	1,025	300
Cardiff	EGFF	N51º23’51”	W03º20’47”	1,175	300
Heathrow	EGLL	N51º28’11”	W00º27’08”	1,000	300
Southend†	EGMC	N51º34’15”	E00º42’00”	1,050	300
Brize*	EGVN	N51º45’00”	W01º35’01”	1,025	300
Stansted	EGSS	N51º52’58”	E00º14’02”	1,025	300
Wattisham*	EGUW	N52º07’32”	E00º57’15”	1,025	300
Waddington*	EGXW	N52º07’32”	E00º57’15”	975	300
Cambridge†	EGSC	N52º12’13”	E00º10’30”	1,000	300
Birmingham	EGBB	N52º27’12”	W01º44’47”	950	300
Marham*	EGYM	N52º38’54”	E00º33’02”	1,000	300
Norwich†	EGSH	N52º40’33”	E01º17’09”	1,000	300
Shawbury*	EGOS	N52º47’52”	W02º40’00”	925	300
East Midlands	EGNX	N52º49’51”	W01º19’28”	950	300
Valley*	EGOV	N53º14’45”	W04º36’45”	1,025	300
Liverpool†	EGGP	N53º20’00”	W02º50’55”	925	300
Manchester	EGCC	N53º28’15”	W02º23’20”	900	300
Humberside†	EGNJ	N53º34’38”	W00º20’50”	975	300
Blackpool†	EGNH	N53º46’18”	W03º02’10”	950	300
Leeds†	EGNM	N53º52’00”	W01º39’10”	925	300
Teesside†	EGNV	N54º30’28”	W01º25’29”	925	300
Newcastle	EGNT	N55º02’14”	W01º41’24”	925	300

* These airports report hourly rather than half-hourly.
† These airports do not report 24/7.
‡ ICAO stands for International Civil Aviation Organisation.

2.2 MODEL STRUCTURE

Figure 3 shows the flow diagram for the method of calculating solar panel production.

FIGURE 3: STUDY AND CALCULATION FLOW DIAGRAM



For any date and time calculate the azimuth and altitude of the sun, given the position of the solar panels (*Boxes R and S*). There are several websites showing computer program expressions and examples for the necessary calculations.[5, 6]

The insolation at the top of the atmosphere is derived from use of the Stephan Boltzman equation. This can be taken as a constant (1.353kW/m2), modified to allow for the changes in solar distance throughout the year (*box T*).

The attenuation of this insolation as it passes through the atmosphere is affected by the slant depth of atmosphere to the solar panels. The relative air mass AM expresses the atmospheric slant thickness as ratio to the vertical depth and is given by the formula:[6]

$$AM = 1/\cos(90 - altitude)$$

Solar radiation is attenuated as it passes through the atmosphere by ozone, air molecules, water vapour and dust particles. The formula, found by observation, to calculate the solar insolation density arriving at the solar panels is usually taken as:

$$I = 1.1 * 1.353 * A^{(AM)^B} \quad [1]$$

The multiplication by 1.1 accounts for indirect insolation reaching the panels. A and B are constants which have values 0.76 and 0.618 in clear air, and 0.56 and 0.713 in polluted air (*box V*).[7] Use of trigonometry calculates the panel insolation accounting for the panel tilt and azimuth (*box W*).

Several papers deal with the effect of clouds on panel insolation and usually arrive, again by observation, at a formula of the type:[8, 9]

$$I_C = I * (1 - D * F^E) \qquad \textbf{[2]}$$

Where D (0.7 - 0.75) and E (2.8 – 3.4) are constants and F is the observed cloud cover ratio lying between 0 and 1—box X; I_C is the insolation density below the clouds. For each location the sum of all the half-hourly insolation powers divided by 20 gives the annual insolation energy.

To establish best-fit values for the constants contained in equations [1] and [2], the processes described in *boxes V*, *W* and *X* are repeated, setting the panel tilt to zero, using trial values of the constants (*box Z*). For each location the sum of the calculated insolation powers divided by 20 gives the average location insolation energy per annum. This is compared with the values taken from Figure 2; 500 sets of these constants were trialled. All of the trials sets produced summed errors between 2 and 4 percent. At the end of the trial, equations [1] and [2] were set as:

$$I = 1.1 * 1.353 * (0.49 + (0.19 * \frac{visibility}{10,000}))^{(AM)^B} \qquad \textbf{[1]'}$$

with B of equation [1]’ set as

$$B = 0.714 + (0.0397 * \frac{visibility}{10,000})$$

and

$$I_C = I * (1 - 0.78 * F^{3.1}) \qquad \textbf{[2]'}$$

The visibility value is the METAR observation, halved if the METAR reports observations of rain, drizzle, thunderstorms, fog, haze, hail, snow, or smoke.

2.3 THE MODELLED UK SOLAR FLEET

The insolation energy calculations produced in the preceding calculations are then used to work out the electrical energy production for each half hour by the modelled fleet panels at each location, with a panel azimuth and tilt set to 180º and 35º respectively, scaled to match predictions from a utility produced by JRC (*box Y, Figure 3*).[10] This process is then further scaled for various losses such as panel reflections, dirt on the panels, Ohmic resistance of the low-voltage, DC cabling, inverting the power to AC and the distribution grid transformer to determine the energy delivered at the output terminals of the distribution transformer adjacent to the solar farm.[11] This path is taken as 79% efficient.[11]

Figure 1 shows ground mounted solar farms throughout most of England and Wales, where house roof installations are also widely spread. Installations of both types are reported to have reached close to 7GW and, given the recent speed of growth, it is possible that the total is nearer to 8GW. The model solar fleet is therefore taken to comprise 28 sites (Table 3) each with a 300MW solar farm.

The UK solar fleet is divided between 58% of ground mounted panels, where the panel azimuth and tilt are usually 180º and 35º, and 42% of roof mounted where they follow the house position and design. Roof mounted installations rarely follow ideal practice. The efficiency of solar collection as a function of roof azimuth is shown in Figure 4. If we assume that only houses with an azimuth between 90º and 270º are mounted with solar panels then their average efficiency is reduced to 87.7%. This result has been calculated allowing for the effect of visibility and cloud reductions (*boxes V*, *W* and *X*) and shows no bias away from the ideal azimuth of 180º.

FIGURE 4: ROOF MOUNTED SOLAR EFFICIENCY AS A FUNCTION OF HOUSE AZIMUTH

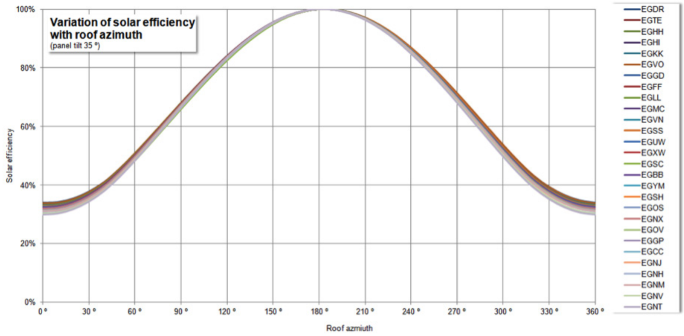
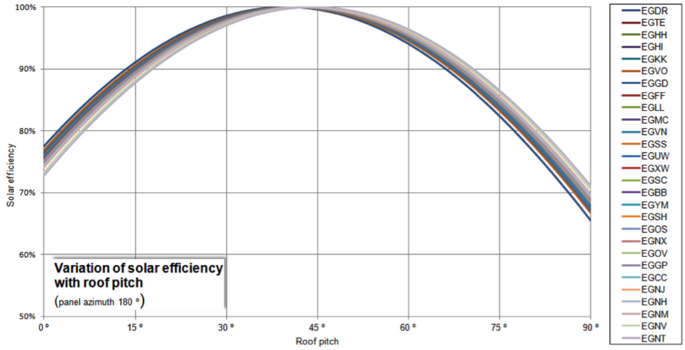


Figure 5 shows solar efficiency as a function of roof pitch. The average value between 27º and 57º is 98.8%. There is a slight shift in ideal pitch with increasing latitude which is to be expected from the insolation calculations.

FIGURE 5: ROOF-MOUNTED SOLAR EFFICIENCY AS A FUNCTION OF ROOF PITCH



Roof mounted installations are usually no bigger than 4kW capacity and I assume that their export production is consumed locally even though peak production is at noon when domestic consumption is low; this slice of solar energy thus avoids passing through any of the many distribution transformers.

Ground mounted solar farms have much higher capacities and are intended to export through the distribution grid to the transmission grid. I assume 3% losses for this passage. Each location then has a delivery efficiency given by

$$\begin{aligned}&\textit{Overall efficiency}\\&\qquad = (\textit{Proportion ground mounted} * \textit{Distribution losses}) + (\textit{Proportion roof mounted} * \textit{Azimuth average} * \textit{Pitch average})\end{aligned}$$

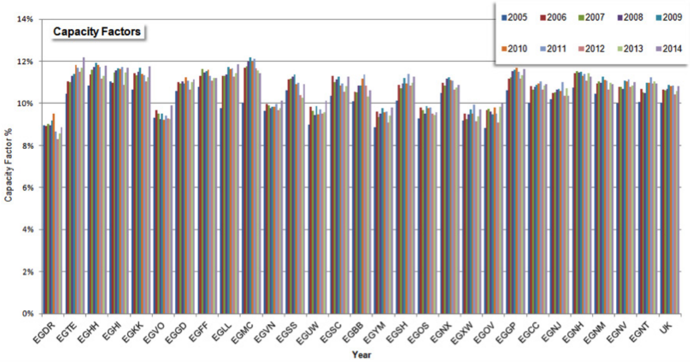
thus

$$\begin{aligned}&\textit{Overall efficiency}\\&\qquad = (0.58 * 0.97) + (0.42 * 0.877 * 0.988)\end{aligned}$$

which gives 92.7% efficiency. From panel output terminals to transmission system delivery we have an overall efficiency of approximately 73%.

3. Model Capacity Factors

FIGURE 6: CAPACITY FACTORS FOR THE MODELLED UK SOLAR FLEET



The capacity factor for the solar fleet is taken to be the ratio between actual energy production and the energy produced if production at installed output were continuous.

The results for Culdrose are below that expected from inspection of the UK insolation map (Figure 2); this is probably because Culdrose is very close to the sea and may be experiencing inshore cloud-baring winds and haar effects.

Figure 6 allows one final check on the accuracy of the model since we can compare the solar capacity factors generated by the model with those presented in DUKES 2015, see Table 4.

TABLE 4: COMPARISON OF DUKES 2015 SOLAR CAPACITY FACTORS WITH MODEL RESULTS

	DUKES 2015 CAPACITY	MODEL CAPACITY	PERCENTAGE DIFFERENCE
2012	11.2%	10.4%	7.7%
2013	9.9%	10.5%	-5.7%
2014	11.2%	10.8%	3.7%

The DUKES results take

i. the installed solar capacity as the average of the installed capacities at the beginning and end of each year, and
ii. the production at the output terminals of the first distribution transformer,

whereas the model has used a fixed fleet size and measured production at entry to the transmission system as described in the final paragraph of Section 2.3. It is not known whether the DUKES figures allow for cloud cover. These differences may account for the small discrepancies between the model and the built solar fleet.

The production calculations reported above are all for new solar panels. It is known that solar panel capacity factors decline with age. (For a comprehensive literature review of this effect see Jordan and Kurtz.[13]) The observed ageing rates have an average value of 1% for amorphous silicon technology installed after 2000. There is variation on this value within manufacturer, batch and location making performance somewhat unpredictable. Figure 7 shows the year by year decline of production and Table 5 summarises the impact of ageing on production over a 30 year period.

In the remainder of this study the entire solar installation is assumed to be new, with no ageing effects considered.

FIGURE 7: SOLAR PANEL POWER OUTPUT DECLINES WITH AGE AT A RATE BETWEEN 0.5 AND 2% PER ANNUM

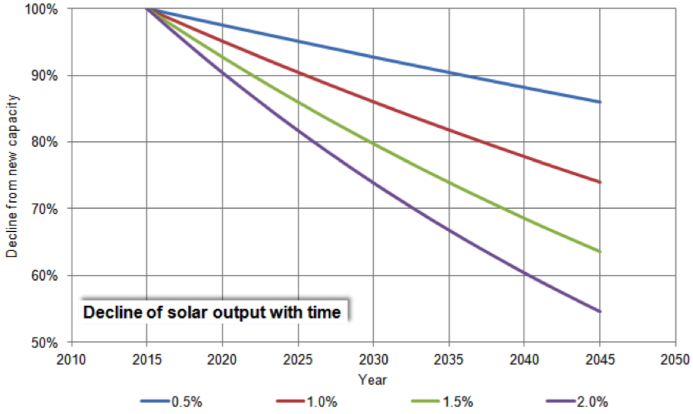


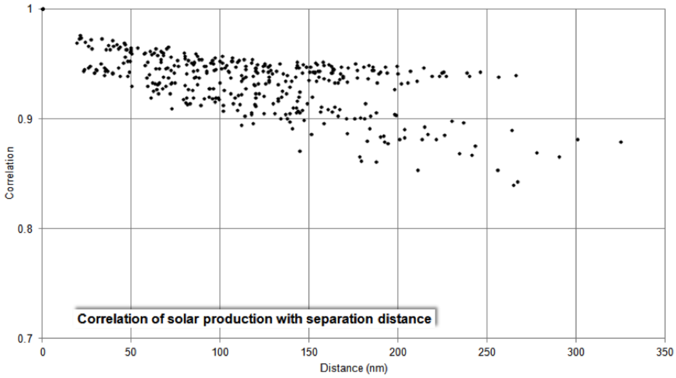
TABLE 5: IMPACT OF AGEING ON AVERAGE PRODUCTION OVER A 30 YEAR PERIOD

AGEING FACTOR	IMPACT OF AGEING
0.5%	92.6%
1.0%	85.9%
1.5%	79.8%
2.0%	74.2%

4. Spatial Correlation of Solar production

Because the UK is spread across a small range of longitude, solar peak insolation passes across the UK in approximately 24 minutes. The solar fleet is also spread over a small range of latitude so, apart from variations in visibility and cloud-cover, we can expect a considerable correlation of solar generation across the UK solar fleet. For each modelled site the solar production time series has been tested for correlation with all other sites and the results plotted as a function of separation distance, see Figure 8 (overleaf).

FIGURE 8: CORRELATION OF SOLAR PRODUCTION AT EACH SITE WITH ADJACENT SITES



5. Time dependency of solar power production

The model output was analysed by year, season, month and half-hour period. The following results are all for the solar farms when new.

There is a little variation from year to year in annual production—Figure 9.

Both the seasonal (Figure 10) and monthly (Figure 11) output averages show the highest production occurs in the summer months. I have added tables of all seasonal and monthly capacity factors - see Tables 7 and 8.

Figure 12 is the average half-hourly solar production. Since we will be interested to explore what contribution solar power can make towards meeting the winter peak this has been explored for winter month data extractions as shown in Figure 13. It is obvious from this that solar power can make little or no contribution to meeting UK peak demand, which takes place during the period between 4pm and 8pm in winter.

FIGURE 9: YEARLY SOLAR FLEET AVERAGE PRODUCTION

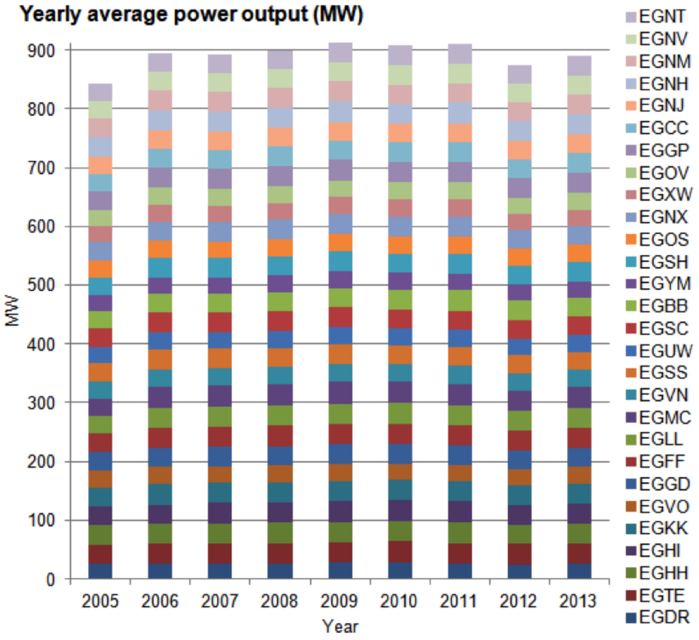


FIGURE 10: SEASONAL SOLAR FLEET AVERAGE OUTPUT

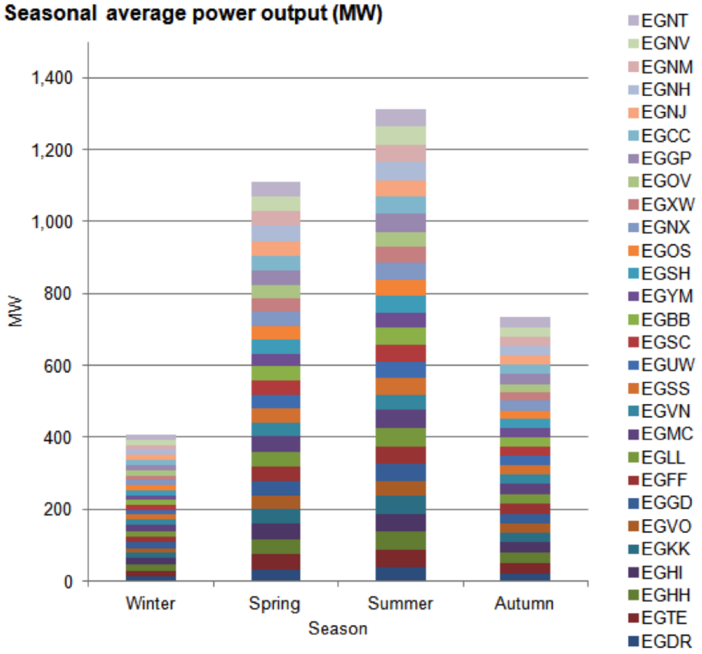


TABLE 7: SEASONAL CAPACITY FACTORS

Winter	Spring	Summer	Autumn
4.8%	13.2%	15.6%	8.7%

FIGURE 11: MONTHLY SOLAR FLEET OUTPUT - IN DECEMBER THE 8,400GW FLEET CAN ONLY DELIVER 300MW - WHEN NEW

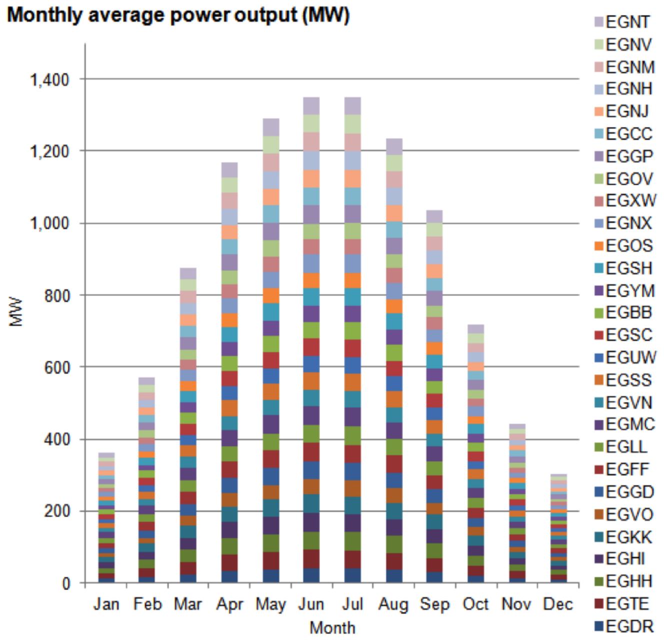


TABLE 8: MONTHLY CAPACITY FACTORS

Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
4.3%	6.8%	10.4%	13.9%	15.4%	16.1%	16.1%	14.7%	12.3%	8.5%	5.3%	3.6%

FIGURE 12: HALF-HOURLY SOLAR FLEET OUTPUT. NOTHING AT NIGHT!

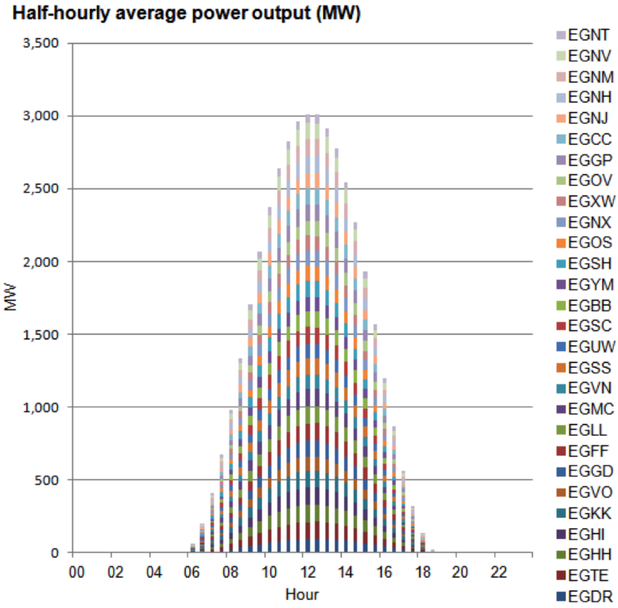


FIGURE 13: WINTER MONTHS' DAILY, AVERAGE SOLAR PRODUCTION AND UK WINTER LOAD

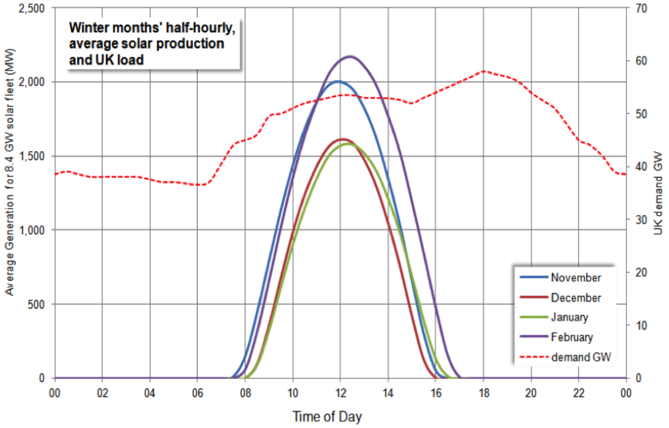
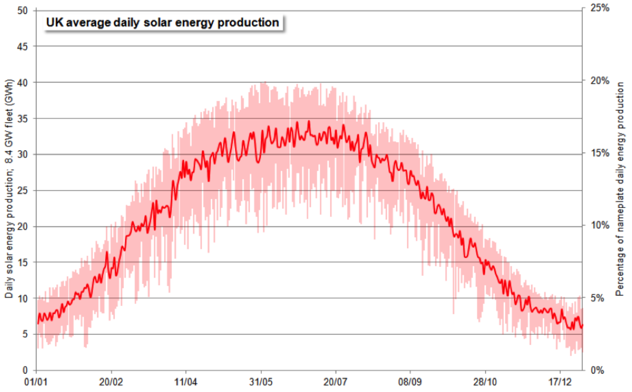


Figure 14 shows the average daily solar energy production throughout a year, calculated by averaging model data over the ten year sampling period, and gives another view of the observations shown in Figures 10, 11 and 13. These four graphs together illustrate that the solar fleet is of little importance during winter.

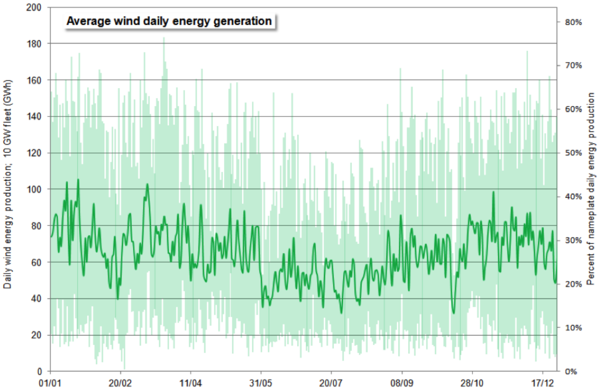
FIGURE 14: DAILY SOLAR ENERGY PRODUCTION THROUGHOUT THE YEAR*



*The pale red bars show the extremes of production throughout the sample.

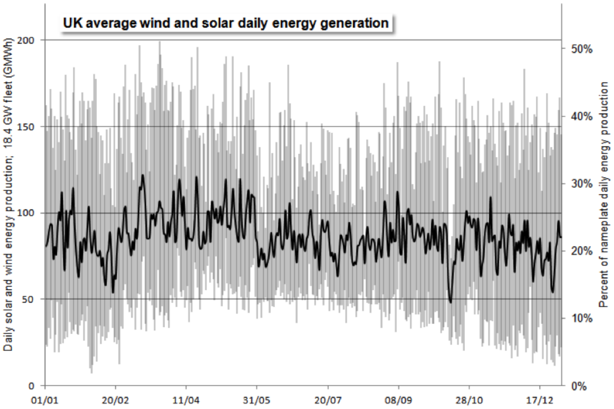
Similar to Figure 14, Figure 15 shows daily wind energy production throughout the year, calculated by averaging model data over the nine year sampling period of the *Wind Power Reassessed* study carried out last year.[3, 4] Figure 16 shows the same graph for the two fleets added together. The two fleets could be claimed to compliment each other in that the summer surge in daily solar energy production somewhat levels the daily energy production to around 80GWh each day. This would be the production expected from a 3.3GW fossil fuel power plant, i.e. 18% of the installed capacity of the combined wind and solar fleets. This may mislead some to conclude that with backup plant of 82% of the renewables' installed capacity that all of the intermittency problems will be solved. This is not the case. A closer look at the performance of the combined fleet in the winter months shows that daily energy production can fall below 25GWh per day, which is only 5.6% of installed capacity, implying a much greater capacity requirement for back up plant. Sections 8 and 9 will show that even this figure is optimistic.

FIGURE 15: DAILY WIND ENERGY PRODUCTION THROUGHOUT THE YEAR*



*The pale green bars show the extremes of production throughout the sample.

FIGURE 16: AS FIGURES 14 AND 15 FOR THE COMBINED, MODELLED, WIND AND SOLARFLEETS



6. Solar generation probability distribution and production duration curves

Figures 17 and 18 (overleaf) show the probability distribution and production duration curves for the modelled solar fleet. Both of these plots include the curves for the modelled wind fleet, the combined solar and wind fleets and, for comparison, a typical fossil fuel plant. The probability that the solar fleet will produce full output is vanishingly small.

FIGURE 17: GENERATION PROBABILITY DISTRIBUTION FUNCTIONS FOR UK RENEWABLES

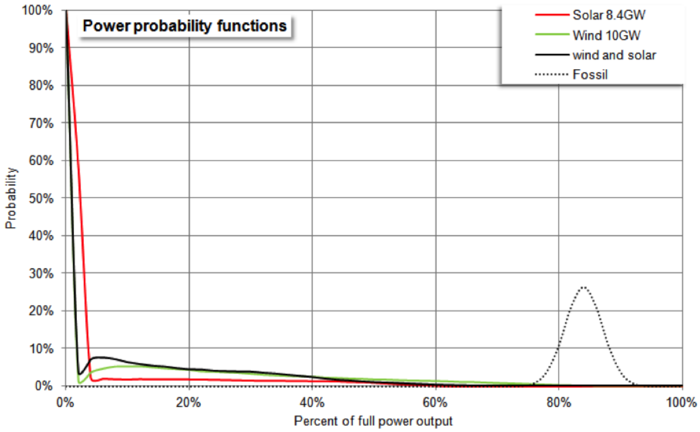


Figure 18 supports the following statements for the solar fleet:

i. Power never exceeds 70% of installed capacity (8.4GW).
ii. Power exceeds 60% of installed capacity for 7 hours per annum.
iii. Power exceeds 50% of installed capacity for 210 hours per annum.
iv. Power is below 20% of installed capacity for 6,629 hours (39 weeks) per annum.
v. Power is below 10% of installed capacity for 5,790 hours (35 weeks) per annum.
vi. Power is totally absent for 5,074 hours (30 weeks) per annum.

By any reasonable assessment, this performance standard is pitiful.

Figure 18 supports the following statements for the combined wind and solar fleet:

i. Power never exceeds 70% of installed capacity (18.4GW).
ii. Power exceeds 60% of installed capacity for 30 hours per annum.
iii. Power exceeds 50% of installed capacity for 257 hours per annum.

iv. Power is below 20% of installed capacity for 4,940 hours (29 weeks) per annum.

v. Power is below 10% of installed capacity for 2,743 hours (16 weeks) per annum.

FIGURE 18: PRODUCTION DURATION CURVES FOR UK RENEWABLES

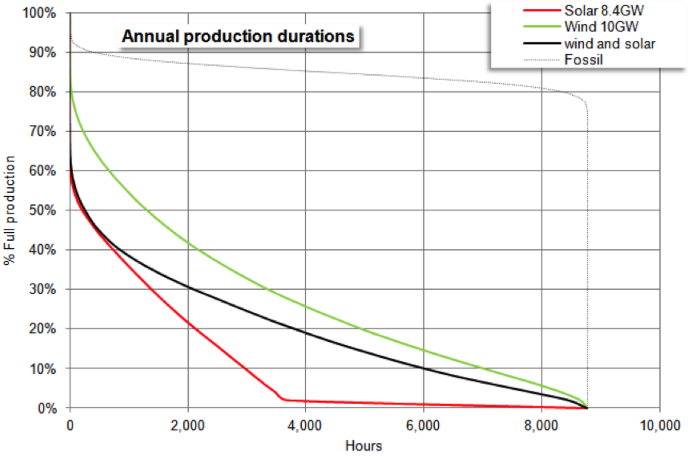
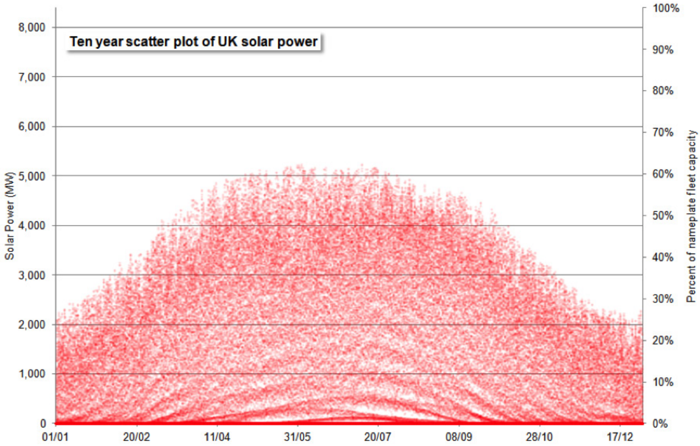


Figure 19 shows a scatter plot for the annual solar fleet production. The x-axis appears emphasised, but this is caused by the incidence of zero power outputs during the ten year study. Power output never exceeds 70% of installed capacity (right-hand axis) due to both the low panel production and the losses associated with cabling, transformers, non-ideal roof alignment and other factors (Section 2). The fringing in the plot is thought to be due the stepped nature of the METAR data used to calculate insolation.

FIGURE 19: SCATTER PLOT OF TEN YEARS POWER OUTPUT FOR THE SOLAR FLEET



The scatter plot of the previously modelled wind fleet is shown in Figure 20, and the combined wind and solar fleets in Figure 21.

FIGURE 20: SCATTER PLOT OF NINE YEARS POWER OUTPUT FOR THE WIND FLEET

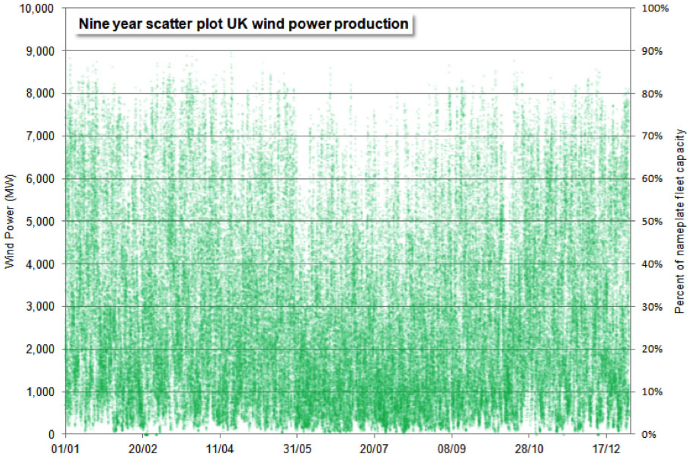
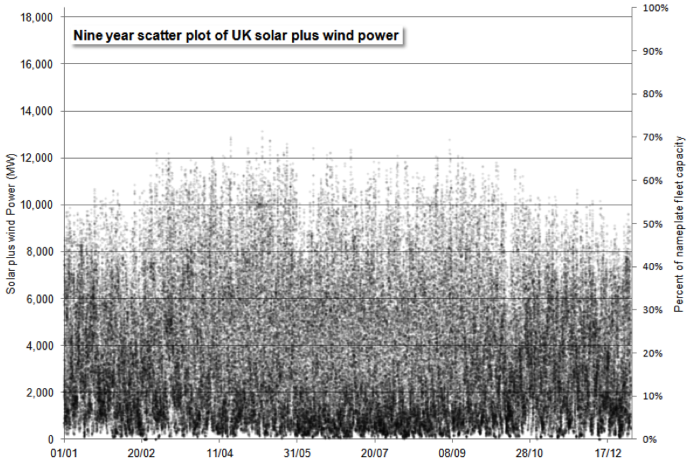


FIGURE 21: SCATTER PLOT OF NINE YEARS POWER OUTPUT FOR THE COMBINED SOLAR AND WIND FLEETS

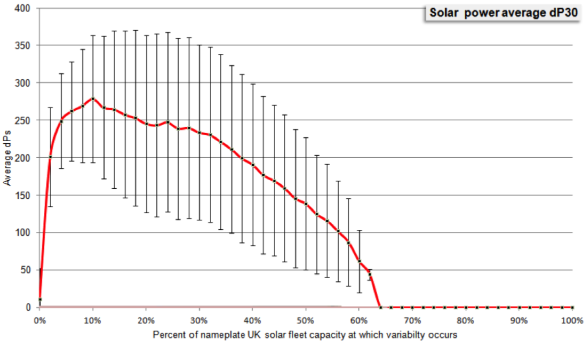


Now the two fleets do not compliment each other. In Figures 19, 20 and 21 the heavy clustering of observations close to the horizontal axis shows the high incidence of low power output. The level of dependable power output seems negligible—perhaps a few hundred megawatts at best.

7. Solar power variability

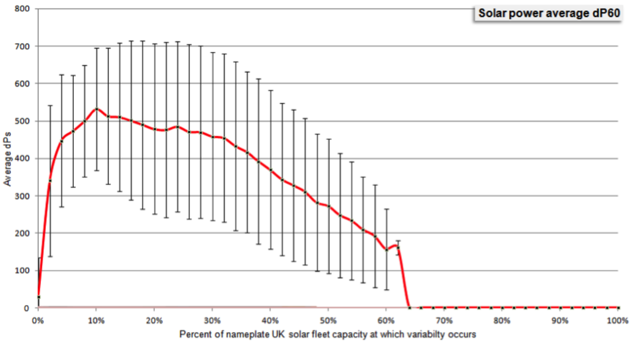
The variation of the UK solar power production across timespans of 30 minutes (ΔP30), 60 minutes (ΔP60) and ninety minutes (ΔP90) has been calculated and plotted in Figures 22a–c. Each of the plots shows the average MW variation as a function of the percentage of UK solar installed output, together with error bars equal in length to the standard deviation of variation at each point.

FIGURE 22A: POWER VARIATION ACROSS A TIME INTERVAL OF 30 MINUTES



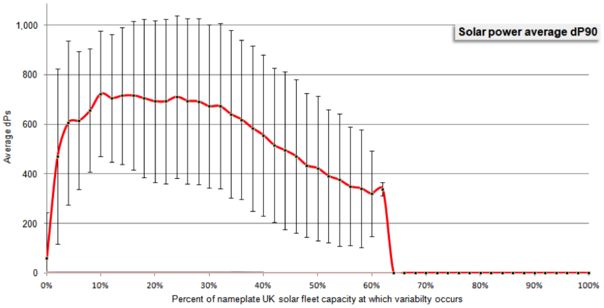
Note: Standard deviation shown as error bars.

FIGURE 22B: POWER VARIATION ACROSS A TIME INTERVAL OF 60 MINUTES



Note: Standard deviation shown as error bars.

FIGURE 22C: POWER VARIATION ACROSS A TIME INTERVAL OF 90 MINUTES

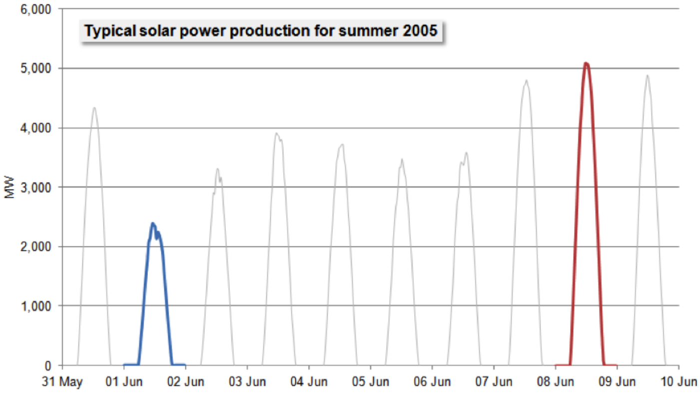


Note: Standard deviation shown as error bars

In the previous paper, I also plotted the results for each of the UK locations when modelling the production of a wind fleet.[3, 4] Since solar production is nearly uniform across the UK, and because there are now 28 stations, more than the 22 of the wind study, this is not done here to avoid cluttering of these graphs.

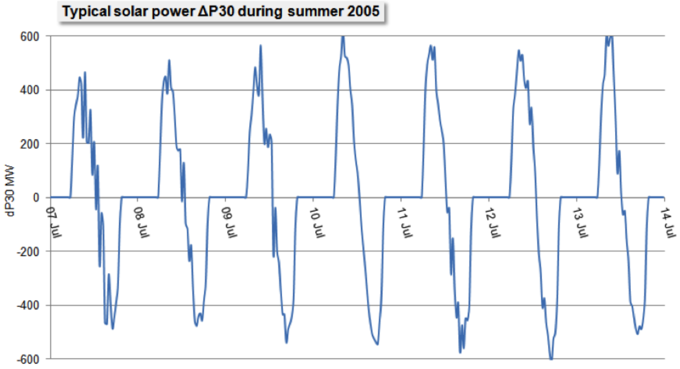
All of the power rates of change shown here are higher than those for wind. The reason is obvious when we look at Figure 12 or view samples of daily production such as those of Figures 23a–b.

FIGURE 23A: EXAMPLE OF SUMMER PRODUCTION



Note: the red and blue peaks show the variation between peak and minimum summer production in 2005

FIGURE 23B: TYPICAL SOLAR POWER RATE OF CHANGE OBSERVED DURING THE SUMMER MONTHS



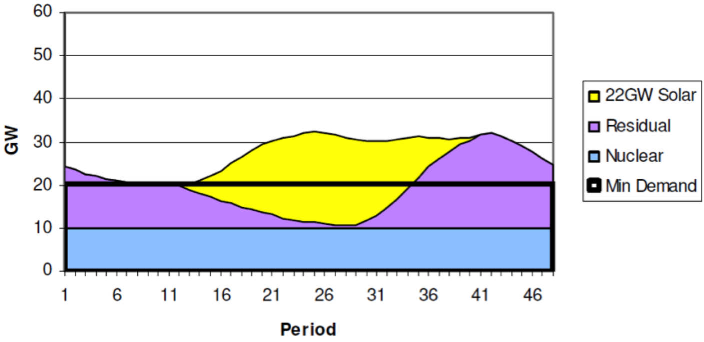
The UK grid load varies daily from a low, overnight base to higher industrial demand during the day, and there is usally a peak towards the evening rush hour. An example of this peak demand is shown for a winter's day in Figure 13. Grid load is generally lower in summer. The lowest times of grid load occurs on sunny Sundays when there is a reduced indiustrial demand. With no solar and wind generation connected to the grid, the grid operator would have to cope with rising energy demand during the morning, and then declining demand in the evening.

As well as meeting demand, the grid must be maintained at or very close to the standard grid frequency of 50Hz. A sudden loss of generation capability (caused, perhaps, by a loss of a transmission connection to a large 600MW generation set) causes the grid frequency to drop. When this happens on the continental electrical grid there is very little effect on grid frequency because the generator and load have such a large rotational inertia, loss of generation can be resolved by adding extra generation over a period of several minutes. But the UK is an island grid (as is Ireland, which has the further disadvantage of being much smaller than the UK) and contingency plans have to be made for a spare, fast response generation plant to be available to meet such generation losses. Typically this plant is drawn from either Dinowig or Ffestiniog pumped storage plants or from large steam sets (usually coal-fired) running at part load. Counter intuitively, more response plant is required in summer than in winter because the grid inertia is lower in summer.

The solar power ramping shown in Figure 23 requires additional grid management. In the morning, the rise of daytime solar production may coincide with the morning demand surge, but otherwise may be too early (requiring deloading of other plant, followed by loading to meet demand) or too late (requiring unloading during the remainder of the morning). Then, after noon, the fall in solar production must be met by loading conventional generators; if the fall in solar production coincides with the evening demand surge, the loading rate will be raised above normal. Any variability of wind will exacerbate this situation. All of these management actions raise costs and increase carbon dioxide emissions.

National Grid have considered the impact of solar ramping in their Solar Briefing PV Note; Figure 24 is copied from this briefing note.[15]

FIGURE 24: THE IMPACT OF SOLAR DAYTIME RAMPING ON GRID LOAD ON A SUNDAY IN SUMMER[15]



In their discussion of solar power ramping at the start and end of the day, the NGC comment

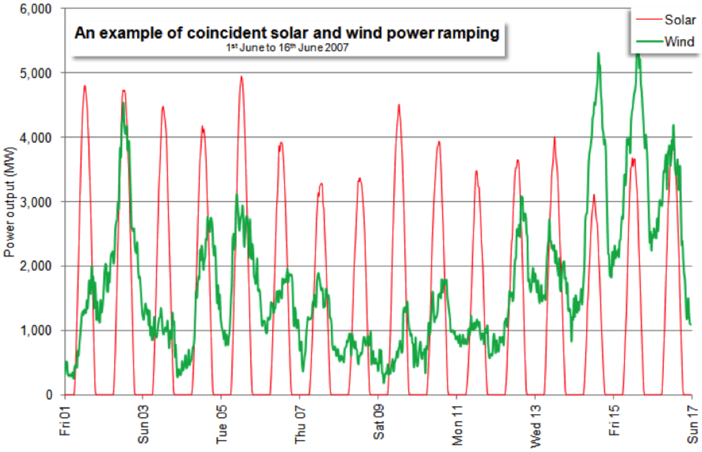
> . . . at the start of the ramp up [in the morning], there could be no fossil generation synchronised apart from that providing frequency response. This will make the management of the ramp very difficult using plant that has just synchronised, wind, pumped storage and interconnectors.

Their concern is driven by the possibility that solar ramping will occur at a time when the grid has very low inertia or stiffness. With a 22GW solar generation fleet, early summer mornings could see very little inductive inertia in the generation and load mix; the only generation inertia may be that of the nuclear plants. Wind turbines with generators connected directly to the grid can provide grid inertia, but may create an added difficulty by changing output quickly at the same time as the solar fleet, and perhaps increasing the ramp rate.

The UK has a solar fleet of just below 8GW, much lower than the fleet hypothesised by NGC in Figure 24, but there may be evidence that we are on the way to inertia problems already - Figure 25 shows typical solar summer generation through several days. Figure 26 shows the solar and wind ramps adding during 14th June 2007.

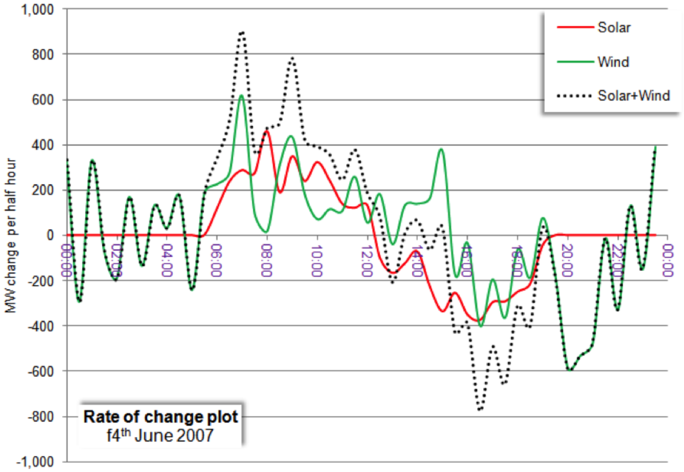
The solar and wind early morning ramps are seemingly synchronised for 12 of the 16 days shown. There is also some overlap of the downward ramps at the end of daylight hours. Caution is needed here since the observation is not unexpected. Each of the METAR stations will have the insolation and temperature gauges, and anemometers close together and we must expect that as the ground temperature around the weather station rises, the anemometers will be driven by resulting convection currents. However, the same phenomenon will occur at wind farms.

FIGURE 25: WIND AND SOLAR POWER PLOTS FOR JUNE 2007



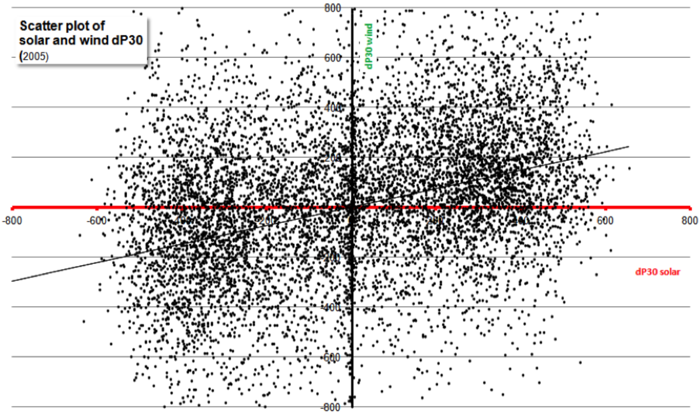
Note: the coincidence of solar and wind power ramping

FIGURE 26: SOLAR AND WIND RAMPS ADDING



In Figure 27 I show the scatter plot of solar (x-axis) and wind dP30 observations for 2013 (the year with the most complete set of METAR observations). There is clearly a weak, positive correlation between the two sets of observations: we could presume that this was due to convection currents caused by solar heating the land. This same correlation is seen in each of the nine years of the study period (not shown).

FIGURE 27: SCATTER PLOT OF DP30 OBSERVATIONS OF SOLAR AND WIND FOR THE YEAR 2013



The peaks for Figure 23 indicate renewable generation could remove as much as one third of the fossil fleet capacity requirement during the summer midday peak. As well as the difficulties with inertia, we now see a requirement for considerable load cycling in the fossil fuel generation fleet. Load cycling will reduce the efficiency (and raise CO2 emissions) of operating the fossil fuel plants as they thermally cycle to meet a more volatile load profile, and raise both production and maintenance costs of the fossil fuel plants.

Figures 28 and 29 show the dP30 variability found for the wind fleet model and for the wind and solar model fleets added together. Higher variability is seen in the wind and solar combined fleet, this is repeated in the dP60 and dP90 plots (not shown).

FIGURE 28: DP30 FOR THE MODEL WIND FLEET[3, 4]

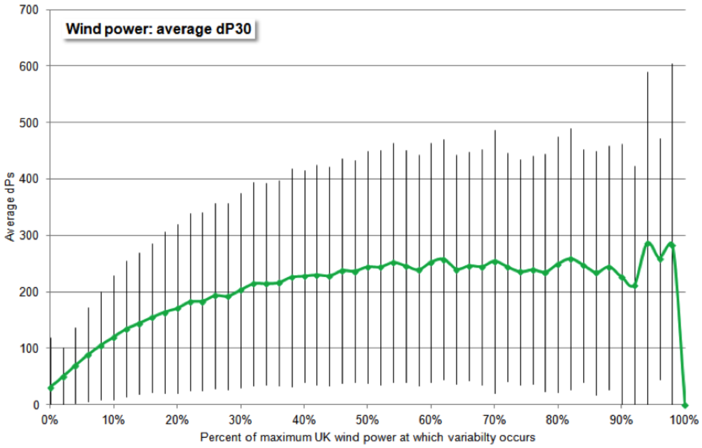
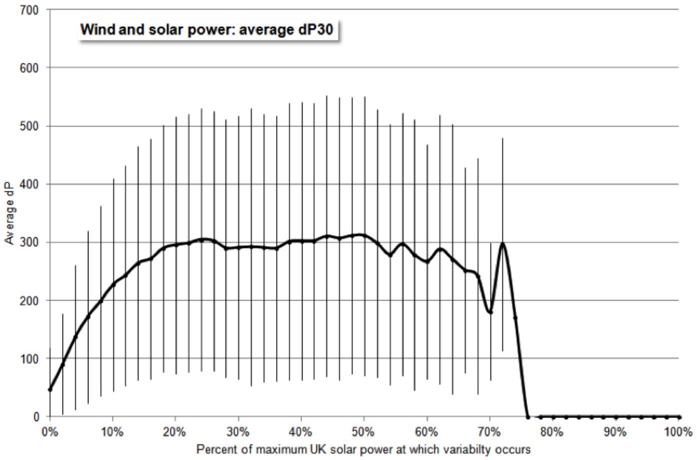


FIGURE 29: DP30 PLOT FOR THE WIND AND SOLAR FLEETS ADDED TOGETHER



8. Capacity Credit

The grid system manager must attempt to balance the varying energy taken from the electricity grid by ensuring sufficient generation capacity is available. UK grid supply system reliability was historically taken as a risk of no more than four winters of grid supply failures every 100 years, thus implying a 4% risk of failure. The capacity credit of an individual power source is the amount of power output from that source that may be statistically relied upon by the grid system manager to meet the demand load.

FIGURE 30: ILLUSTRATING THE CAPACITY CREDIT CALCULATION METHOD

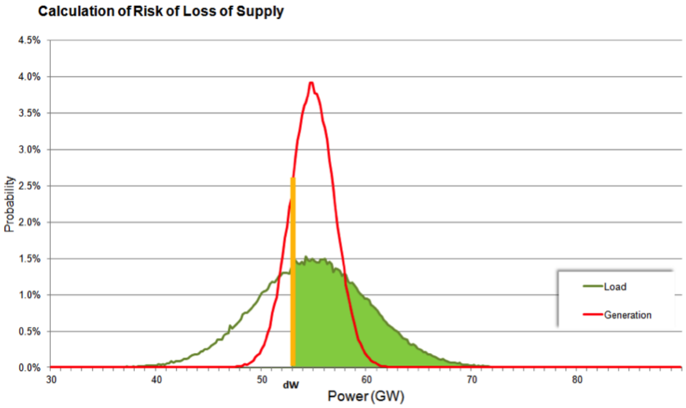


Figure 30 illustrates the method of calculating the risk of loss of supply (or Loss of Load Probability - LOLP) for a given demand load forecast and generation capacity. Derivation of LOLP requires analysis of the intersection of the grid demand and generation probability distribution functions.[18, 19] The probability of not being able to meet the demand for each segment of the generation power distribution function (pdf) is the product of generation probability (the orange shaded area) and the probability that the demand load will exceed the generation level (the green shaded area). Summing across all segments of the generation pdf then gives a total risk of loss of supply for the modelled generation capacity.

To determine the capacity credit for the solar fleet proportion of a mixed wind and fossil fuelled fleet, it is necessary to:

i. Define the demand load size and distribution. Here the mean load is taken to be 60.5GW, following a normal distribution with a standard deviation of 9.77% (comprising 9% forecast uncertainty and 3.8% weather uncertainty).
ii. Take the fossil fuel generation to have a normal distribution with a standard deviation of 3.75%.
iii. Vary the fossil fuel size to determine the amount needed to supply the test demand with a risk of loss of supply of 4%, using the techniques described above and illustrated in Figure 30.
iv. Repeat this exercise, but now with a combination of the modelled solar fleet and varying fossil fuel fleet sizes. The pdf for the combined solar and fossil fleet was generated by adding at each timestamp of the model the outputs of solar fleet and the fossil fleet. The solar fleet output was determined as described in Section 2; the fossil fuel fleet was calculated using random figures from Excel NORMINV function scaled to the trial fossil fleet size and the standard deviation fixed at 3.75%.

v. The reduction in fossil fuel capacity requirement seen between steps iii and iv gives the solar capacity credit in GW.

The results are shown in Figure 31a and reveal that the output from the 8.4GW of solar plant has displaced the need for approximately 653MW of fossil plant. Figure 31a demonstrates that in November, December and January solar power is zero through most of the period of peak demand. Figure 31b shows the capacity credit calculation for the solar fleet's production in winter months and then for production between 4 p.m. and 8 p.m. in winter months. In winter months the capacity credit is 300MW, and between 4 p.m. and 8 p.m. it is zero.

FIGURE 31A: RISK ASSESSMENT USED TO DETERMINE THE CAPACITY CREDIT FOR THE FLEET

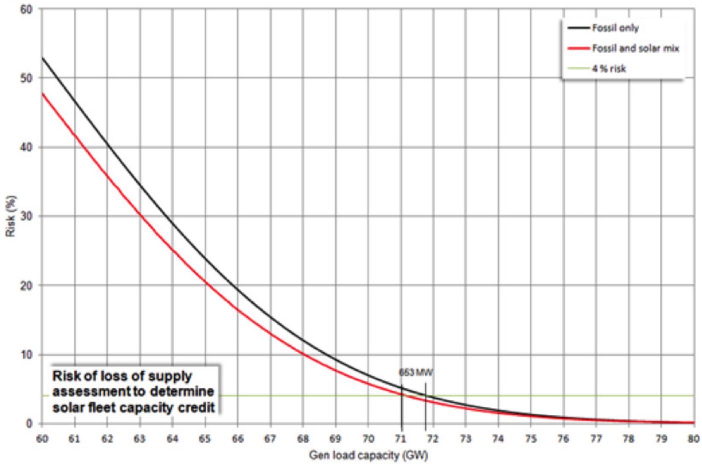
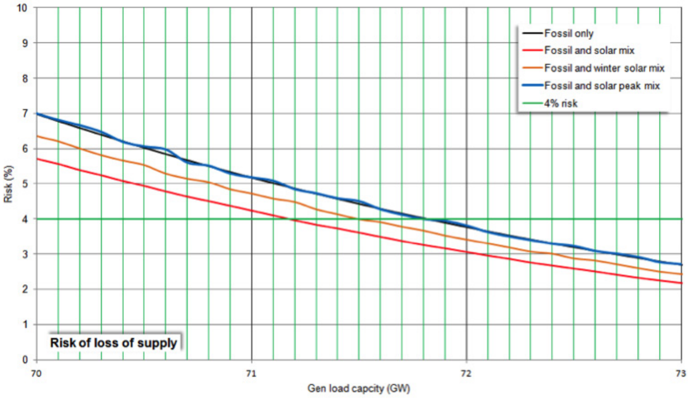


FIGURE 31B: RISK ASSESSMENT FOR THE FLEET'S PRODUCTION IN WINTER MONTHS



9. Intermittency

Intermittency of generation refers to there being long periods when the output of a generation fleet falls below certain limits.

In Section 5 the capacity factor result for the winter period is a mere 4.8% (Table 7) and daily energy production falls below 600MWh. (Figure 11). In Section 6, using the power production curve for solar generation, I have listed the summed duration of low output from the solar fleet as follows:

i. Power output was below 20% of installed capacity for 6,629 hours (39 weeks) per annum.
ii. Power output was below 10% of installed capacity for 5,790hours (35 weeks) per annum.

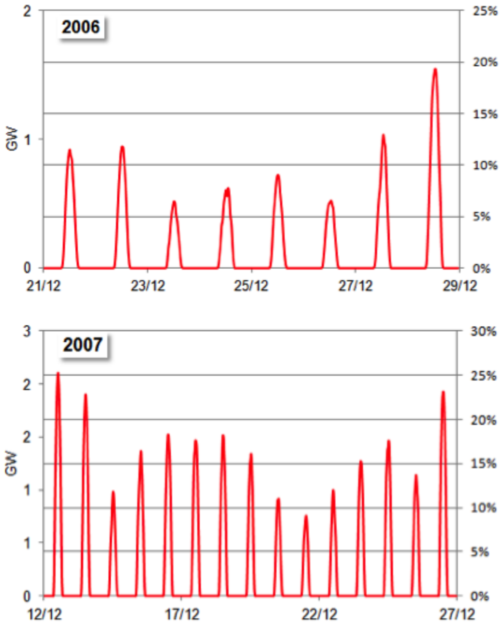
Further analysis reveals that:

i. Of the 6,629 hours when the power output of the UK solar fleet is below 20% of installed capacity, all outpput occurs over periods longer than 12 hours.
ii. Of the 5,790 hours when the power output is below 10% of installed capacity, all occur over periods of 6 hours or more.

In Section 8 we see that solar generation provides negligible capacity credit throughout the year and especially during the winter peak load period. These observations confirm that solar generation is intermittent at diurnal and seasonal timescales. There are hopes and claims that the adoption of higher efficiency solar panel technology will make this a more cost-effective renewable technology, but this will do nothing to remove the intermittency of this technology. Claims that solar power may operate under moonlight skies are nothing more than moonshine!

Figures 32a and 32b show a period in 2006 when the solar power output was below 10% of installed capacity for 118 hours, and a period in 2007 when it was below 20% of installed capacity for 309 hours.

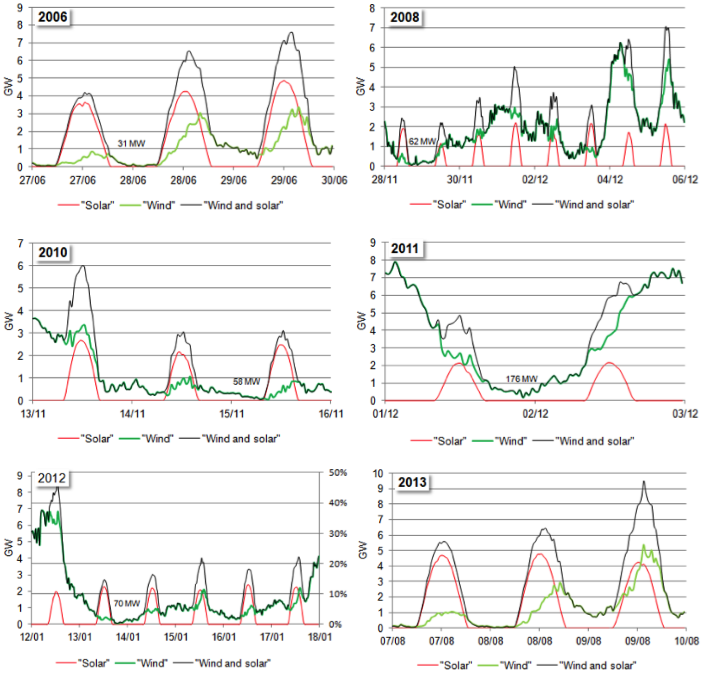
FIGURES 32A AND 32B: SOLAR POWER OUTPUT BELOW 10% AND 20% OF INSTALLED CAPACITY



In *Wind Power Reassessed* I demonstrated the degree of intermittency for the wind fleet.[3, 4] It is therefore no surprise that if we combine the power generation results for the wind and solar fleets, we see strong evidence of intermittency. Figure 33 illustrates several instances of low power output for the combined renewables fleet. The plots for 2006 and 2013 (both summer plots) show the lowest power outputs experienced: 31 and 62MW respectively. In 2012 there were five consecutive days when the power was below 25% of installed capacity. 2011 experienced a roller-coaster ride through the intermittency of the wind and solar fleet.

These graphs imply that the building of the two renewable energy fleets (at very high cost and environmental impact) cannot displace the requirement for building fossil and nuclear fleets of exactly the same size prior to wind and solar build.

FIGURE 33: INSTANCES OF LOW POWER OUTPUT FROM THE COMBINED WIND AND SOLAR FLEETS

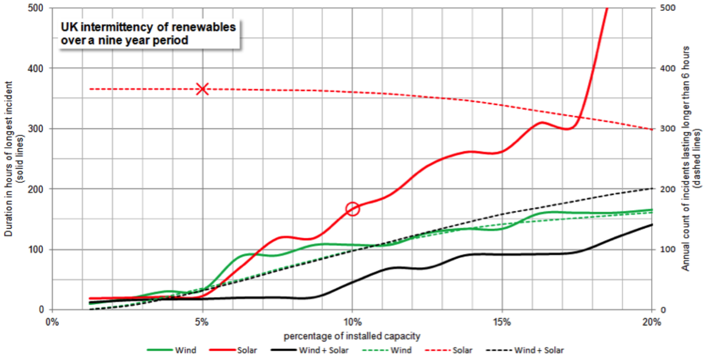


We have had an example of prolonged low output from renewables recently. On a mild day in November (Wednesday 11th 2015), National Grid declared a state of ‘inadequate capacity margin’ and requested certain industries to shed load. The lack of power had two causes: multiple failures of coal and gas generation plants, and a lack of wind generation. Given the time of year little could be expected from the solar fleet. Mark Lynas, writing in the Guardian, claimed that this “notification of inadequate system margin [NISM] had nothing to do with wind power, as any of the writers quoted above could have discovered had they taken the trouble to call the National Grid and ask”.[17] This claim ignores the more obvious point that in the last ten years we have installed 13.533GW of wind generation plant, and 7.769GW of solar at a cost probably exceeding £20 bn. In the same period we have built no new gas fired stations. The unavoidable question must be 'have we spent our money wisely?' Clearly we haven't. Perhaps we should learn from this warning.

None of the graphs of Figures 32 and 33 give any impression of the number and size of incidents when the power output of our various renewables falls below some lower limit. Figure 34 is an attempt to display the frequency and length of intermittency we can expect from the UK's various renewable fleets. The basis of the plots is the detection of periods of low fleet power output at an increasing fraction of the fleet installed power output. For each fleet type (solar, wind, combined solar and wind) there are two plots:

a. Solid lines (left-hand vertical axis) which show the longest duration intermittency power gap as a function of test power.
b. Dashed lines (right-hand vertical axis) which show the annual incidence of intermittency gaps lasting six hours or more as a function of test power.

FIGURE 34: THE SCALE OF RENEWABLE INTERMITTENCY



The modelled fleet sizes are solar: 8.4GW; wind 10GW. The production data for the solar and wind fleets has been analysed to reveal periods when their output fell below a varying percentage of installed fleet capacity for 6 hours or more. The solid lines show the longest duration of such incidents that occurred during the nine year sampling period (scale: left vertical axis). The red open circle shows that the longest continuous period of solar production below 10% of installed capacity was 167 hours. The dashed lines show the annual incidence of incidents longer than 6 hours (scale: right vertical axis). The red cross shows (reading from the right hand vertical scale) that the average annual count of incidents when solar output was below 5% of installed capacity for 6 hours or more was 365–every night. The steps in all plot plots are a result of the stepped nature of the METAR observations.

Figure 34 captures the almost daily occurrence of solar over-night intermittency not experienced by wind power. For the combined renewable fleets it gives a view of the high incidence of intermittency and its duration across a range of power levels, as shown in Table 9:

TABLE 9: MODELLED UK RENEWABLES FLEET INTERMITTENCY OVERVIEW

	FLEET POWER OUTPUT AS PERCENTAGE OF INSTALLED CAPACITY			
	5%	**10%**	**15%**	**20%**
Annual incidence	32	97	158	201
Duration (hours)	6-18	6-46	6-92	6-141

Intermittency of renewable generation within an island grid will constrain the scale of renewable implementation. Can intermittency be resolved? There are three potential solutions to the problem:

a. Electrical generation time shifting through the use of energy storage (hydro, batteries).
b. The use of interconnectors to the continental grid.
c. Conversion to other forms of energy which allow easier storage (hydrogen production, for example).

The first two possible solutions are discussed in Sections 9.1 and 9.2; the third possibility usually fails because the conversion efficiency to and from the chosen alternate energy degrades the already low renewable capacity factor to a level that is not sensible. In Section 9.3 I examine whether simply diverting all the renewable energy in a one-way conversion to space and water heating for domestic customers could contain the intermittency problem with the distribution grids.

9.1 SOLVING INTERMITTENCY USING ENERGY STORAGE

The problem of intermittency can be solved by the use of energy storage and if achieved would make renewable energy very much more attractive to consumers (provided the storage does not add significantly to the overall cost). The storage facility built for the modelled renewables fleet must be correctly sized for both power output and energy storage capacity. The former can easily be gauged from the span of the daily energy output plots; here that would imply about 10GW. The storage requirement cannot be calculated directly but only estimated by system modelling. In *Wind Power Reassessed* I gave results for a rolling energy deficit analysis for the wind fleet assuming a power rating equal to the capacity credit (2,300MW) a storage requirement as high as 250,000MWh was shown.[3, 4]

To improve the accuracy of the storage estimate, and to investigate the viability of storage as a means of reducing intermittency, I have simulated a pumped storage plant coupled to the renewable fleets solely for this purpose. The simulation objective was to establish an operation regime such that the extreme variability of production shown in Figure 35 was removed. (Note the high incidence of prolonged low output (ringed red) that occurs in winter). If this is achieved then power output should stabilise somewhere close to the capacity factor of the combined fleets. The model has adjustable parameters for maximum power output, pumping capacity taken as equal to that of generation output, storage capacity, and fractional target storage. The model operates in three stages.

1. A daily, renewable energy production predictor for the forthcoming fortnight. Here that is simply a summation of the solar and wind fleets' modelled production for the look-ahead period (implying perfect forecasting; this can easily be randomised to give some semblance of reality). This predictor generates a projection for the day ahead half-hourly power outputs.
2. An energy storage control loop which looks at the error between present storage and target storage. The error signal modifies the predicted generation into a target output for the whole system for the forthcoming half hour. The gain of this loop is adjustable. Provision was made for integral gain in this loop, but it was not required.
3. A load control routine which delivers the stipulated power output within the confines of available storage and maximum power. In this section the turn-round efficiency for storage was set at 75% and with the pump efficiency slightly lower than that of the turbines.

The model was run repeatedly tuning the various parameters. The resulting power output from the coupled wind, solar and pumped storage system is shown in Figure 36. Note the following performance aspects of this simple scheme:

a. There is only one instance where the system fails to deliver any power (December 2006).
b. The number of high power peaks shown in the unregulated scheme has been considerably reduced. All the remaining peaks happen when the energy store is full; they could be removed by increasing the storage (and costs) further.
c. The capacity factor of the system before linking to the pumped storage scheme was 19.81%; with the pumped storage scheme it is 18.4%, implying a storage efficiency of 92.9%. If all of the wind and solar production had passed through the pumped storage scheme the final capacity factor would have been 19.81*0.75, i.e. 14.86%. Clearly, a great deal of the production has passed to the supply network and not through the pumped storage scheme.
d. The storage scheme has given the two renewable fleets a semblance of base load generation. It would now be possible to decommission 2GW of baseload plant.

Aspects of this system could be changed:

a. No attempt has been made to shift the periods of energy production towards meeting the afternoon demand peak. This could be done, attracting a higher price for the production in those periods, but would require a more complex control algorithm for the pumped storage plant.
b. The storage scheme could include some battery storage. However, the energy store experiences a high and rapid variation of stored energy which will reduce both battery storage cycle

efficiency and battery life (pumped storage has a nearly constant cycle efficiency and can be cycled almost indefinitely).

c. The pumped storage/battery store can be built gradually.

d. If built as a pumped storage facility with typical hydro power units of weight and operational units seen at Dinorwig (each with a 670 ton stator and turbine runner, 500 rpm) then the problem of low grid inertia associated with all wind and solar plant would be mitigated to a high degree. This would not happen with battery storage.

There are, however, difficulties with using an energy store to mitigate renewable intermittency:

a. The scheme requires pumped storage plant with 300GWh of storage capacity (30 times larger than Dinorwig) and a maximum output of 10GW (5 times larger than Dinorwig). Dinorwig was costed on completion in 1984 at £440m; indexed to 2014 this would be £1.25bn. The storage scheme proposed here does not require a station of the sophistication of Dinorwig. Dinorwig has plant hidden underground which may not be a necessity elsewhere and it is engineered to deliver very fast ramping of power output for the purposes of delivering a grid fast response service. Nonetheless, the cost of building this energy store would likely exceed £20bn and probably exceed the capital cost of the renewable fleets. If we allow £1bn per annum as pumped storage operating costs, then over a 30 year period the total expenditure would be £50bn. Over that period the renewable fleet could generate approximately 890TWh (with no allowance for solar ageing), implying that this reduction of intermittency would cost of £56 per MWh of renewable production.

b. There are not many locations in the UK that are suitable for large pumped storage schemes.

c. Dinorwig took over ten years to build. Most of this time was spent on civil engineering, not the installation of the generating plant. This solution to the renewable problem would therefore take a long time to come into operation and may be redundant when it does.

d. Even though pumped storage would be expensive, it still has the advantages of cheapness (capital and operational) and longevity compared to batteries. But both options would be very expensive.

FIGURE 35: YEARLY POWER DELIVERY PLOTS FOR WIND PLUS SOLAR

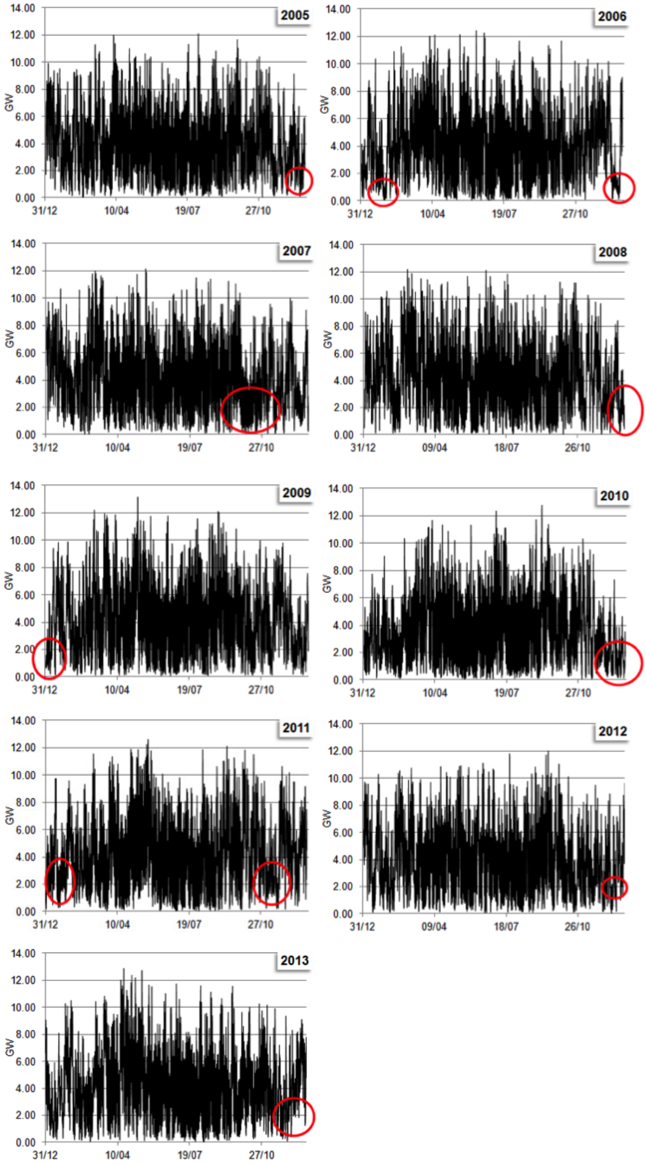
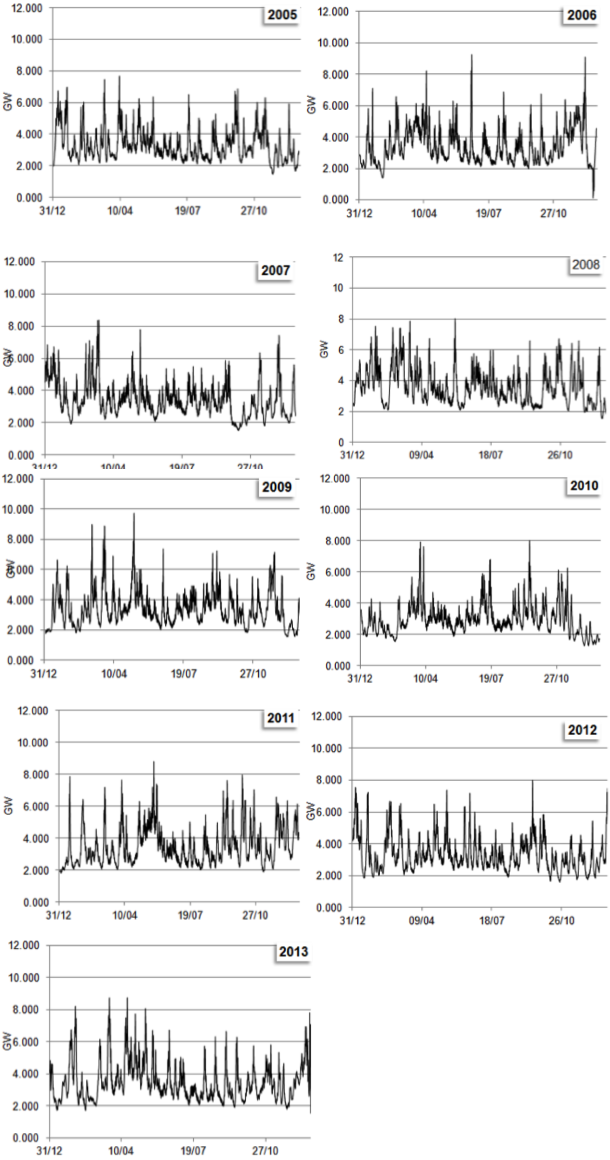


FIGURE 36: YEARLY POWER DELIVERY PLOTS FROM WIND PLUS SOLAR COUPLED TO PUMPED STORAGE



9.2 CAN INTERCONNECTORS SOLVE RENEWABLE INTERMITTENCY PROBLEMS?

> Interconnection makes it easier to bring higher levels of intermittent renewables, such as wind and solar, to the grid, says Mott Macdonald's chief economist Guy Doyle. "If you put greater renewables on the system then you tend to make it harder for the grid to manage its situation," he says. "Interconnectors offset that and help make it easier." Because interconnections open up new electricity supplies and potential buyers, they make it easier to shift power around on a minute-by-minute basis when there is a surplus or a shortfall.
>
> *power-technology.com*

> By connecting and integrating geographically disperse wind farms across Europe, each experiencing a different phase of the region's weather system, electricity is pro¬duced wherever the wind is blowing and transported to regions of demand, ensuring a reliable and predictable source of energy.
>
> *Airtricity*

The two observations quoted above imply that the intermittency of renewables varies between countries and that by interconnecting them any country experiencing a gap or surge in domestic renewable generation can draw or drain power from or to other countries experiencing different weather patterns. But this claim can only be correct from a UK perspective if:

i. Falls in renewable energy production in the UK coincide with times when the continent has a surplus of power.
ii. The continent is not experiencing its own crisis of renewable intermittency at the same time as the UK which would likely drawdown most or all of the continental, dispatchable-power reserve.

In *Wind Power Reassessed* I partly examined this claim for the wind fleets of the UK, Ireland and the northern European plane and concluded that the interconnected fleet would indeed have reduced intermittency, but the intermittency problem was far from resolved.[3, 4] The combined system with an available power output of 48.8GW had long periods of very low power output:

i. power would be below 20% of available power for 4,596 hours (27 weeks) per annum.
ii. power would be below 10% of available power for 2,164 hours (13 weeks) per annum.

This analysis did not address whether or not the continent is likely to have a surplus of dispatchable power generation, nor did it include the solar fleets of the UK and the continent.

To examine the power system inclusive of solar generation I have extended the modelling study to include solar stations across the north European plane, details of which are given in the Appendix section. I have not conducted a solar study for Ireland (as I did previously for wind) since it has little installed solar generation. The countries included in this study are Belgium, The Netherlands, Denmark and Germany, all of which have large solar power fleets. I have extended the Germany METAR station selection of the previous paper southwards to give coverage of the whole country, see Figure A1 and Table A1.

9.2.1 THE SCALE OF RENEWABLE GENERATION IN NORTHERN EUROPE

Germany has the largest installed generation capacity of these countries and Figure 37 profiles the generation capacity mix over the last thirty years. Germany electricity consumption has increased from 460TWh in 1980 to 580TWh in 2012, during which fossil fuel generation declined by 40TWh. Nuclear power expanded in the early 80s to reach 150TWh, continuing at that level until 2005. The Chernobyl accident prompted a planned closure of nuclear power which was later cancelled, and then later confirmed to be completed by 2022. By 2012 nuclear power had fallen to 16% of Germany's electricity generation. If the closure of the nuclear fleet is not to increase emissions, then the present wind and solar fleets will have to expand such that they can deliver another 90TWh per annum. Since the present wind and solar fleets deliver 47TWh and 25TWh respectively, then the wind fleet will have to expand from a capacity of 31GW (2012) to 70GW, and solar from 38GW to 86GW. This large increase in intermittent renewable generation will exacerbate the existing intermittency problems seen by Germany (and Denmark since it has considerable renewable generation), and increasing their dependence on adjacent countries and grids (such as those of the Nordic countries and France) for mitigating power inputs and exports to stabilise generation to meet the load profile.

Figure 38 plots the production data in terms of percentages by sector, and projects events to 2022. It is obvious that switching from nuclear generation to renewables will do nothing to cut the total emissions of Germany's electricity generation.

Figure 39 contrasts the daily generation mix seen in 2012 with that projected for 2020. In 2020 there will be no requirement for any baseload. Fossil fuel generators will be required to cycle output on a daily basis and shut down frequently. At times, there will be little inductive inertia connected to the German grid. Germany will be heavily dependent of import/export electricity flows to/from adjacent countries and for frequency control.

Thus it seems unlikely that the UK will be able to use any interconnection it has with the European grid to mitigate intermittency whilst competing against the large requirements expected from within north Europe.

FIGURE 37: GERMANY'S GENERATION PRODUCTION - EIA DATA

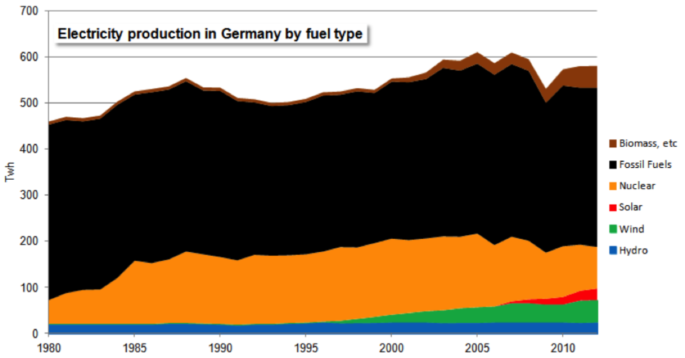


FIGURE 38: GERMANY'S ELECTRICITY PRODUCTION BY SECTOR PERCENTAGE, PROJECTED TO 2022

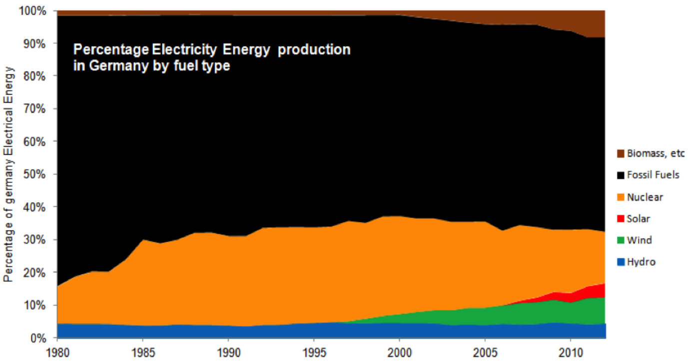


FIGURE 39: CONTRASTING DAILY GERMAN ELECTRICITY PRODUCTION ENERGY MIXES FOR 2012 AND 2020

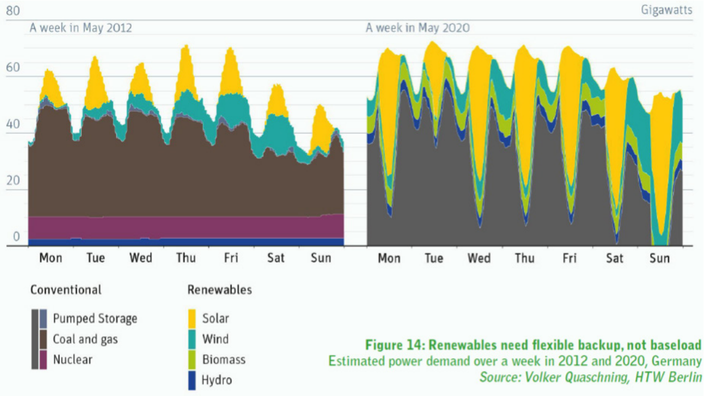


Figure 14: Renewables need flexible backup, not baseload
Estimated power demand over a week in 2012 and 2020, Germany
Source: Volker Quaschning, HTW Berlin

9.2.2 NORTHERN EUROPEAN RENEWABLE GENERATION INTERMITTENCY

Figures A3 and A4 show solar production across northern Europe to be very similar to that seen in the UK. Obviously, there's no generation at night, and very little in winter. The energy production curves for solar (Figures 40 and 41) are similar to those for the UK. Tables 10 and 11 show the monthly and seasonal solar capacity factors.

TABLE 10: PERCENTAGE MONTHLY CAPACITY FACTORS FOR SOLAR POWER ACROSS NORTHERN EUROPE

Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
3.9%	6.1%	9.8%	13.1%	14.0%	14.5%	14.6%	13.4%	11.4%	8.1%	4.6%	3.2%

TABLE 11: SEASONAL CAPACITY FACTORS FOR SOLAR POWER ACROSS NORTHERN EUROPE

Winter	Spring	Summer	Autumn
4.3%	12.3%	14.2%	8.0%

Figures 40 and 41 show the daily energy production and power scatter plots for solar generation in northern Europe.

Figures 42 and 43 show the daily energy production and power scatter plots for wind generation in northern Europe.

Figures 44 and 45 show the daily energy production and power scatter plots for solar and wind generation in northern Europe.

FIGURE 40: NORTHERN EUROPE DAILY SOLAR ENERGY PRODUCTION

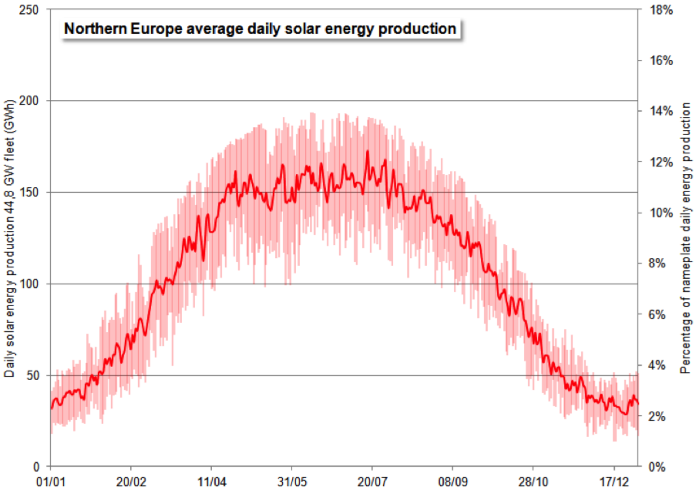


FIGURE 41: NORTHERN EUROPEAN SCATTER PLOT OF SOLAR POWER PRODUCTION

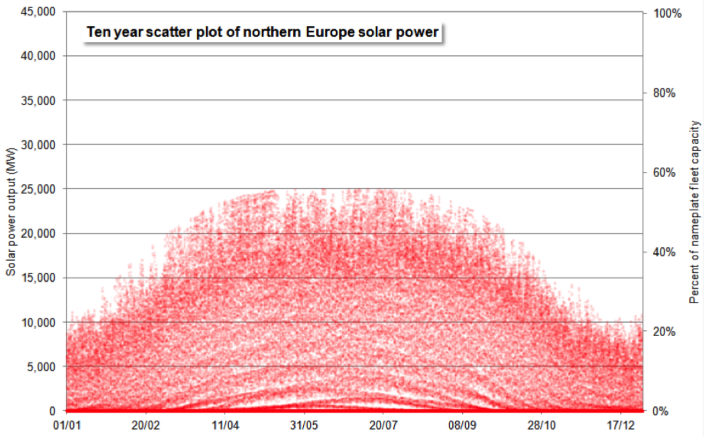


FIGURE 42: NORTHERN EUROPEAN AVERAGE DAILY WIND ENERGY PRODUCTION

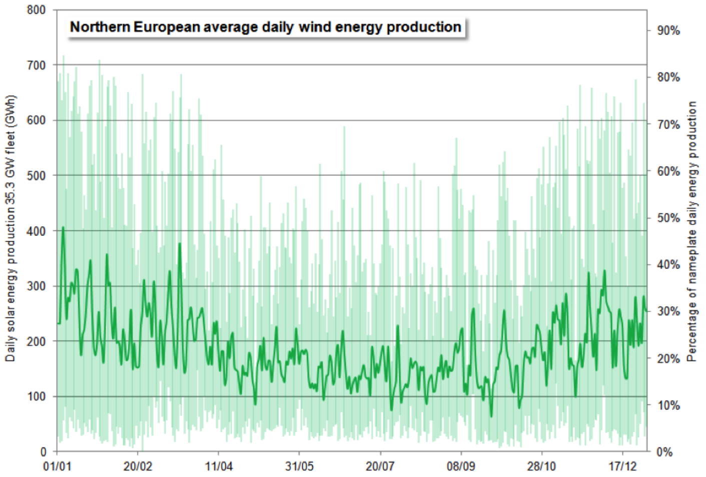


FIGURE 43: SCATTER PLOT OF NORTHERN EUROPEAN WIND POWER PRODUCTION

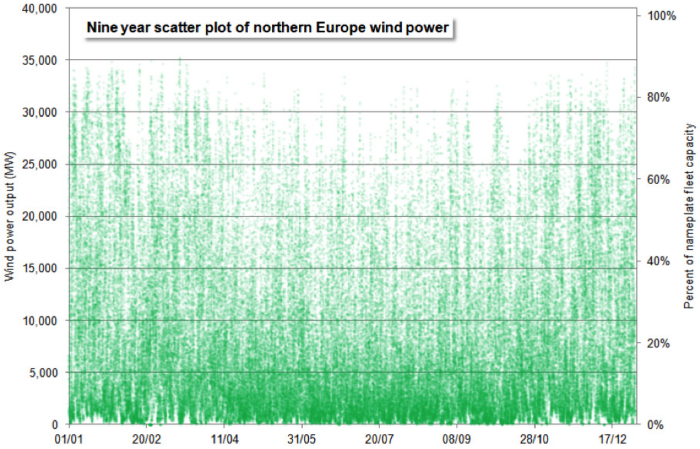


FIGURE 44: NORTHERN EUROPEAN AVERAGE DAILY SOLAR AND WIND ENERGY PRODUCTION

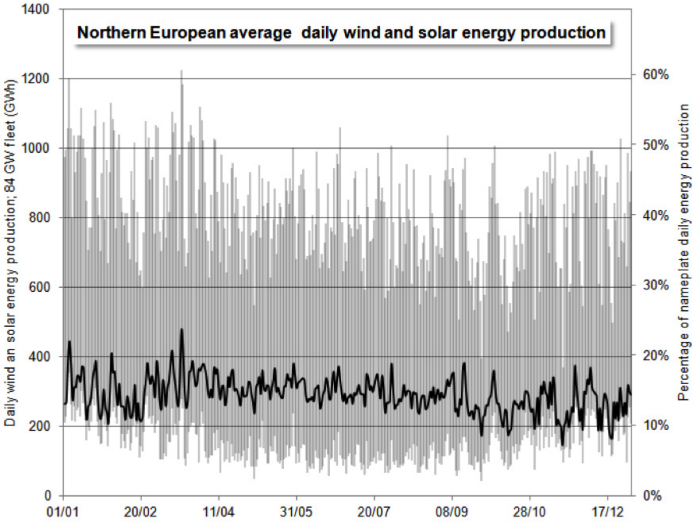


FIGURE 45: SCATTER PLOT OF NORTHERN EUROPEAN SOLAR AND WIND POWER PRODUCTION

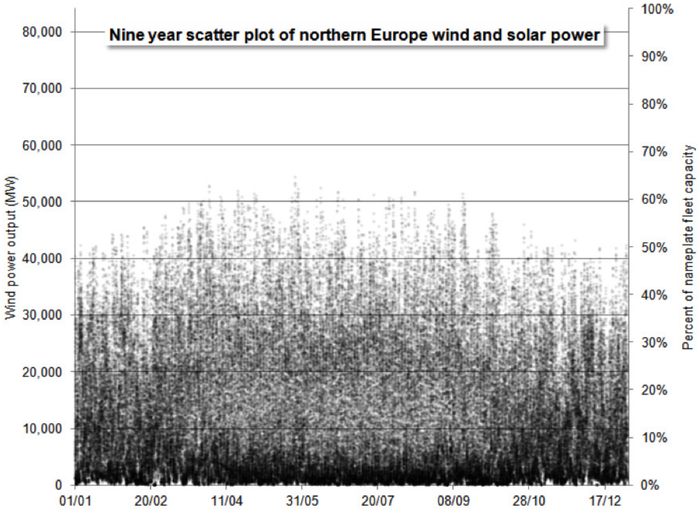


Figure 46 shows one example of the variability and intermittency experienced with the northern Europe renewable fleet.

FIGURE 46: EXAMPLE OF NORTH EUROPEAN RENEWABLES INTERMITTENCY

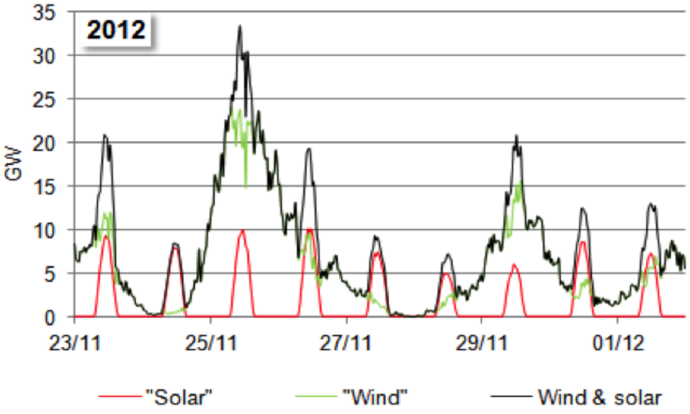


Figure 47 provides an overview of the incidence and duration of intermittency, summarised in Table 12.

FIGURE 47: INTERMITTENCY DURATION AND INCIDENCE FOR THE NORTH EUROPEAN GRID

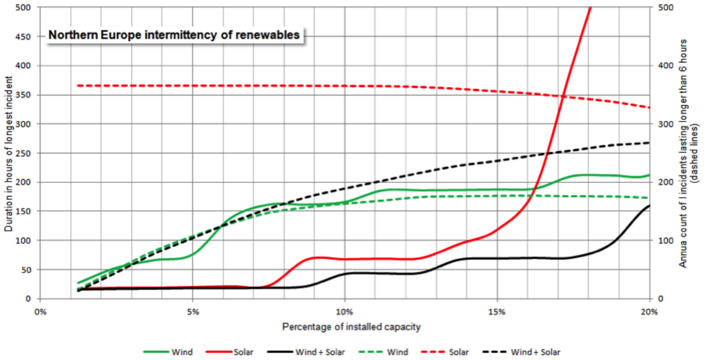


TABLE 12: MODELLED NORTH EUROPEAN RENEWABLES FLEET INTERMITTENCY OVERVIEW

	FLEET POWER OUTPUT AS PERCENTAGE OF INSTALLED CAPACITY			
	5%	**10%**	**15%**	**20%**
Annual incidence	104	189	237	268
Duration (hours)	6-19	6-43	6-69	6-159

9.2.3 A PAN EUROPEAN RENEWABLES GRID – A CURE FOR INTERMITTENCY?

We can now attempt to answer the question posed at the beginning of Section 9.2: can the use of the European grids interconnection or rather, increased number of interconnections and better links to outliers such as the UK and Ireland mitigate the intermittency of renewable energy generation?

In my previous study of the wind fleets of the UK, Eire and northern Europe I concluded that interconnection:

> . . . reduced the number and duration of prolonged wind power breaks, but it [did] not eliminate them.

It is possible to combine all the modelled power outputs together for each individual timestamp since the METAR observations are time coincident. Studying this combined power grid for intermittency we have Figure 48 as an overview of European renewable intermittency. Table 13 gives summary data for the intermittency for this fleet.

FIGURE 48: INTERMITTENCY DURATION AND INCIDENCE FOR THE WHOLE EUROPEAN GRID

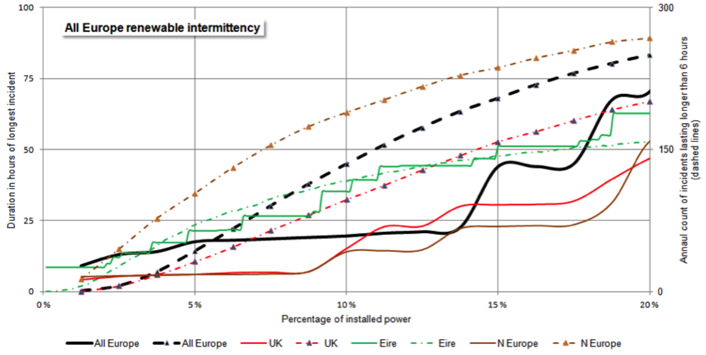


TABLE 13: MODELLED EUROPEAN RENEWABLES FLEET INTERMITTENCY OVERVIEW

	FLEET POWER OUTPUT AS PERCENTAGE OF INSTALLED CAPACITY			
	5%	**10%**	**15%**	**20%**
Annual incidence	43	135	204	250
Duration (hours)	6-18	6-20	6-44	6-71

Considerable intermittency of the European fleet still remains. The additional solar fleets are strung out east-west across a 6° span of latitude and ~20° of longitude and will see the passage of insolation noon spread over little more than 80 minutes. We cannot expect that interconnectors will be of much use in handling any intermittency of the solar fleets since the pan European solar fleet will have much the same temporal generation profile. Like the UK, the north European solar grid will do nothing to help with the peak load experienced in early winter evenings. Simple observation of the incidence of pan-European high-pressure regions will show us that periods of low wind generation output across the whole region will be frequent. If we then consider that the German grid is likely to be experiencing difficulties meeting capacity requirements (see Section 9.2.1) up to 2022, then it is likely that the drawdown of fossil-fuel/nuclear/hydro supply from Poland, France and the Nordic countries will be considerable, leaving little or no possibility of power delivery to the UK.

Thus the UK interconnection companies are very unlikely to be able to eliminate the intermittency of the UK renewable fleets. Moreover, the interconnectors would bring no increase in much-needed grid inertia since they all depend on DC links with inverters at either end.

9.3 SOLVING INTERMITTENCY BY DIVERTING RENEWABLE ENERGY TO DOMESTIC AND COMMERCIAL HOT WATER HEATING

Solving the renewable intermittency problem using a pumped energy storage would probably cost too much, and pose too much of a threat to the environment. Given expected developments in electricity generation technology (especially in nuclear fission and fusion) which would reduce or even extinguish the need for solar and wind generation, we run the risk of premature obsolescence of pumped storage plant with considerable value wasted in its long lifetime (at least 100 years).

There is another possibility: load management through the use of water and space heating as a 'dump' for intermittent generation. This has been done before, very successfully, in New Zealand in a scheme called 'Ripple Control'.

> "[In] the 1950s, New Zealand has had a system of load management based on ripple control, allowing the electricity supply for domestic and commercial water storage heaters to be switched off and on, as well as allowing remote control of nightstore heaters and street lights. Ripple injection equipment located within each local distribution network signals to ripple control receivers at the customer's premises. Control may either be done manually by the local distribution network company in response to local outages or requests to reduce demand from the transmission system operator, or automatically . . ." [18]

An alternative scheme for solving the problem of intermittency could therefore be formed by diverting the energy output from intermittent renewables away from the electricity supply system (which requires secure, dispatchable, stable frequency delivery) into the supply of domestic space and water heating for those house holders not connected to the gas grid. (This scheme would not apply to rooftop solar installations as it is not required – see next page).

In the DECC report *UK Housing Energy Fact File 2013* the following facts emerge:[15]

a. Households are responsible for one quarter of the UK's greenhouse gas emissions.
b. Domestic electricity usage accounts for 41% of greenhouse emissions.
c. There are 27 million homes in the UK.
d. Space heating accounts for 60% of domestic energy use.
e. Water heating accounts for 18% of domestic energy use.
f. 25 million homes are central heated, 22.5 million of which by gas, the remainder are electric and oil heated.
g. 2.5 million homes are not centrally heated and mainly use electric heating.

Those 4.5 million homes that do not use gas heating are probably not on the UK gas grid and concentrated in rural areas. The annual energy production of the present solar and wind fleets is typically 26TWh which could supply 5.8MWh per annum to each non-gas household. This would increase to about 10MWh per annum if we include the offshore wind fleet.

This is not sufficient to meet the entire space and water heating needs of the non-gas customers (unless they use heat pumps). It is indicated, however, that this is an adequate, cheap, heat dump that could solve our intermittency problem. Given that New Zealand was able to contain much of its intermittent renewable generation (hydro power) within distribution grids as early as the 1950s, it should be easy and cheap to achieve the same without using any concept of smart metering. The New Zealand system does not require the use of smart meters, merely signalling between hydro generators (in the UK case, solar or wind parks) to inform the local distribution centre about the level of renewable generation within the local grid. The local signalling is simply the injection of a high frequency tone (between 100 and 1,600 Hz) onto the local power wires to turn on the reduced tariff to customers.

A 4kWp roof-top installation should deliver the entire average domestic hot water heating requirements of each house (3.5MWh/annum). The majority of rooftop installations will be in urban areas so there will be sufficient homes on the local distribution grid to take local, surplus solar generation.

This method of solving renewable intermittency has several significant advantages over other possible methods:

i. It has no impact on the local rural environments already damaged by the intrusion of renewable generation.
ii. It is solved entirely by control engineering which is usually far cheaper than other engineering disciplines, and could be designed with future adaptation in mind.
iii. It should be quick to implement. Little or no technical innovation is required; it is merely a ‘design and build’ solution.
iv. It solves the problem of declining grid inertia since it implies that for the electricity transmission system low CO2 emission electricity generation will have to be sourced either from nuclear fission or gas-fired generation, both of which have high inertia.

10. Conclusions

This study has had to rely on data derived from weather reports generated for the aviation industry and not from insolation data that the UK Meteorological Office has collected over the years, funded by the public purse. MET Office data would provide a greater time-span, and perhaps have greater reliability and accuracy than the aviation data, but it is not freely available to private individuals. Aviation data has enabled the construction of two models to predict historic wind and solar energy production for Britain and northern Europe. I reported the findings of the wind energy modelling previously; this paper reports the performance of the solar generation industry and goes on to assess the performance of European renewable generation.

10.1 THE UK SOLAR FLEET

This study of solar generation in the UK has shown that, as currently implemented, the solar fleet produces less than 2.5% of UK electricity generation, has especially low production in winter months, has no capacity credit, is highly variable, and is intermittent on a daily basis.

The capacity factor for solar generation varies year-to-year between 9 and 10.5%–when the solar panels are new. A literature review of solar panel ageing indicates a yearly decline in output of 1% (varying between 0.5 and 2%). Taking the central estimate, the capacity factor will fall to 7% after 25 years, and the lifetime capacity factor could be as little as 8%. The modelled 8.4GW solar fleet has the same energy delivery capability as an 882MW CCGT (which would cost less than £1m to build). A 5MW solar park will have a lifetime generation of 92GWh; this can be matched by a 2.5GW nuclear station generating for a mere 36 hours. The lifetime production of the present UK solar fleet could be matched by the same nuclear station in 7 years. The ground-mounted solar fleet occupies 100 square kilometres of UK farmland; the nuclear power station will occupy approximately 200 hectares.

Most of the solar energy is produced in summer months. The winter capacity factor drops to 4.8% and has a minimum of 3.6% in December. Figure 14 shows the daily average, maximum and minimum solar energy production over the ten year model period and how scarce production can be in winter. No generation occurs overnight and solar generation can make little or no contribution to meeting the UK maximum demand period which occurs in the winter months between 4 and 8 p.m. each weekday.

Solar power production is strongly correlated across the UK. This is hardly surprising since the dominant variable controlling production is solar elevation and the latitude and longitude spread of the sites studied is quite limited.

National Grid have stated that the rapid change in solar power output that occurs about noon is manageable but it will force dispatchable plant to change load rapidly, almost certainly lowering their production efficiency and increasing their maintenance costs. National grid also state that any additional, low grid-inertia renewables on the UK grid may lead to instability while loading and unloading plant to meet solar power variability. The extent of solar variability is discussed in Section 7 and portrayed in Figure 22a-c.

A conventional assessment of capacity credit for the solar fleet predicts a value of 650MW but because this is certain to be unavailable at peak demand is considered to be zero.

The solar fleet suffers long periods of zero or low production; it is very intermittent. From the production probability curve and the power duration curve we observe that:

i. Power never exceeds 70% of installed capacity.
ii. Power exceeds 60% of installed capacity for 7 hours per annum.
iii. Power exceeds 50% of installed capacity for 210 hours per annum.
iv. Power is below 20% of installed capacity for 6,629 hours (39 weeks) per annum.
v. Power is below 10% of installed capacity for 5,790 hours (35 weeks) per annum.
vi. Power is totally absent for 5,074 hours (30 weeks) per annum.

The scatter plot of solar power output over the ten year model period portrays the high incidence of low power output from the solar fleet. The majority of the solar fleet's periods of low generation occur in episodes of long duration:

i. Of the 6,629 hours when the power output of the UK solar fleet is below 20% of installed capacity, all of them occur over periods longer than 12 hours, and
ii. Of the 5,790 hours when the power output is below 10% of installed capacity, all of them occur in events where that condition is maintained for 6 hours or more.

Figures 32 and 33 show incidences of long duration low power output, and Figure 34 offers a novel portrayal of the maximum duration and incidence of these low power events for a range of percentage power outputs. (Figure 34 also shows the intermittency of the wind and combined renewables fleets).

Solar power is therefore NOT generating for the majority of the time. The generation mode (the most frequent output condition)for solar power lies at zero. We can say that solar panels will dependably not generate any power whatsoever overnight, every day.

10.2 THE UK WIND FLEET

In *Wind Power Reassessed* I carried out a similar analysis for the UK wind fleet of 10GW with a plant availability of 90%. What follows is a summary of that paper's findings.

i. The yearly capacity factor varied between 25 and 35%.
ii. Wind power production across the UK was not random but showed a degree of correlation between sites.
iii. Seasonal and monthly variation of wind production was observed but was much less that that for solar.
iv. The power production mode was at 8% installed capacity.
v. A capacity credit of 2,300MW was calculated.
vi. Power output was highly variable but not in the ordered fashion seen for solar power production.

vii. The power production curve revealed that:
  - **a.** Power exceeded 90% of installed capacity for only 17 hours per annum.
  - **b.** Power exceeded 80% of installed capacity for 163 hours per annum.
  - **c.** Power was below 20% of installed capacity for 3,448 hours (20 weeks) per annum.
  - **d.** Power was below 10% of installed capacity for 1,519 hours (9 weeks) per annum.

viii. Production gaps were commonplace and could be extremely long:
  - **a.** Of the 3,448 hours when the power output of the UK wind fleet is below 20% of maximum, 2,653 hours (77%) occur in events when that condition continues for 12 hours or more;
  - **b.** Of the 1,519 hours when the wind fleet power output is below 10% of maximum, 1,178 hours (78%) occur in events when that condition continues for 6 hours or more.

ix. Many of the low power events occur during periods of prolonged, cold weather.

In this study I have included new graphs of daily, average energy production (Figure 15) and a power production scatter plot (Figure 21) for the wind fleet to illustrate the production variability and intermittency of the wind fleet.

10.3 THE UK SOLAR AND WIND FLEETS COMBINED

The combined fleets have a installed capacity of 18.4GW. The wind fleet was taken to have 90% plant availability (solar 100%). The capacity factor for the combined fleet is approximately 20% when new. This will fall over the plant lifetime due to solar panel ageing and wind turbine plant difficulties and premature failure.

The power production mode of the wind fleet at 8% of installed capacity shifts in the combined wind and solar fleets shifts to a weaker mode at approximately 4% of installed fleet capacity.

The power production curve for the combined wind and solar fleet reveals that:

- **i.** Power never exceeds 70% of installed capacity.
- **ii.** Power exceeds 60% of installed capacity for 30 hours per annum.
- **iii.** Power exceeds 50% of installed capacity for 257 hours per annum.
- **iv.** Power is below 20% of installed capacity for 4,940 hours (29 weeks) per annum.
- **v.** Power is below 10% of installed capacity for 2,743 hours (16 weeks) per annum.

Figure 34 shows the variation of incidence and duration of low power output for the combined fleet as a function of fractional installed capacity for the combined fleet, which is also summarised in Table 9. From this latter we have:

- **i.** Power output was below 5% of installed capacity (920MW) 32 times every year, for periods of between 6 hours and 18 hours.
- **ii.** Power output was below 10% of installed capacity (1,840MW) 97 times every year, for periods of between 6 hours and 46 hours.
- **iii.** Power output was below 15% of installed capacity (2,760MW) 158 times every year, for periods of between 6 hours and 92 hours.
- **iv.** Power output was below 20% of installed capacity (3,680MW) 201 times every year, for periods of between 6 hours and 141 hours.

There is weak, positive correlation between the variability of solar and wind (Figure 27).

The capacity credit will be the same as that for the wind fleet: 2,300MW, although this assumes that there is sufficient wind to support that level of generation.

10.4 SOLVING THE RENEWABLES INTERMITTENCY PROBLEM?

I have examined two of the often claimed solutions to the intermittency of renewables:

- **a.** Storage (as either pumped storage or batteries);
- **b.** The use of interconnectors to the continent.

Due to the very high costs and very high environmental disruption of pumped storage facilities, that first strategy cannot be considered as a solution to the problem of renewable generation intermittency. The present sized UK renewable fleet could achieve a smooth, dispatchable output of approximately 3,500MW through the construction of pumped storage with a power capacity of 10GW and a storage capacity of 300GWh. A very conservative cost estimate for this solution (using zero i.e. Sternian discounting rates) is £56/MWh of renewable production. The environmental impact of this construction would be high and it would be very difficult to find sufficient sites in the UK for pumped storage plants equal to 30 Dinorwigs. Switching to battery storage is probably impossible since the storage reservoir experiences deep cycling which would decrease battery life.

To examine the use of interconnectors the model was extended to cover solar fleets in northern Europe. The continental wind fleet has a lower production level than the UK's, whereas the solar fleets are slightly better. Eire has very little solar generation. The combined fleets also experience periods of intermittency and when combined with the UK fleet of renewables will still produce considerable periods of very low power output. Given that Germany will be retiring all its nuclear fleet by 2022 it seems unlikely that the UK will have a strong claim to draw energy from the continent to mitigate renewable intermittency.

Finally, I consider solving the intermittency problem by diverting renewable generation into low-tariff supply to the space and water heating of domestic customers close to the renewable generators, thus diverting renewable generation away from the transmission system and ‘confining’ it to the distribution system. This technique was successfully employed during the 50s for New Zealand hydro schemes. Such a scheme could be achieved using smart control systems attached to renewable generators, distribution centres and customers’ appliances and/or meters. It would be at a far lower cost than either storage or interconnectors, have no environmental impact, and would be adaptable to changing market conditions. It could be selectively applied in rural, non-gas-mains communities as a form of rural assistance.

Appendix

NORTHERN EUROPEAN SOLAR FLEET

The modelled solar fleet for northern Europe was based on the data collected for the previous wind study, but extended to included locations in the sunnier, south of Germany. Table A1 and Figure A1 (overleaf) give details of these stations.

TABLE A1: NORTHERN EUROPEAN AIRFIELDS ISSUING METARS USED IN THIS STUDY

NAME	ICAO	LATITUDE	LONGITUDE	SIZE OF SOLAR FARM (MW)
Ostend	EBOS	N51º11’59”	E02º51’49”	1,035
Lille	LFQQ	N50º33’48”	E03º05’13”	1,035
Brussels	EBBR	N50º54’05”	E04º29’04”	1,035
Amsterdam	EHAM	N52º18’29”	E04º45’51”	500
Eelde	EHGG	N53º07’30”	E06º35’00”	500
Dusseldorf	EDDL	N51º17’22”	E06º46’00”	2,200
Cologne	EDDK	N50º51’57”	E07º08’34”	2,200
Manheim	EDFM	N49º28’21”	E08º30’51”	2,200
Esbjerg	EKEB	N55º31’33”	E08º33’12”	1,100
Frankfurt	EDDF	N50º02’00”	E08º34’14”	2,200
Bremen	EDDW	N53º02’15”	E08º47’12”	2,200
Billund	EKBI	N55º44’25”	E09º09’07”	1,100
Stuttgart	EDDS	N48º41’24”	E09º13’19”	2,200
Hannover	EDDV	N52º27’39”	E09º41’06”	2,200
Hamburg	EDDH	N53º37’49”	E09º59’28”	2,200
Augsburg	EDMA	N48º25’31”	E10º55’54”	2,200
Erfurt	EDDE	N50º58’47”	E10º57’29”	2,200
Nurnburg	EDDN	N49º29’55”	E11º04’41”	2,200
Munchen	EDDM	N48º21’14”	E11º47’10”	2,200
Roskilde	EKRK	N55º35’08”	E12º07’53”	1,100
Leipzig	EDDP	N51º25’26”	E12º14’11”	2,200
Rostok	ETNL	N53º55’06”	E12º16’42”	2,200
Berlin	EDDB	N52º22’43”	E13º31’14”	2,200
Dresden	EDDC	N51º08’04”	E13º46’05”	2,200
Stettin	EPSC	N53º35’05”	E14º54’08”	2,200

The size of the solar farms at each site is such that each country has a total solar fleet size approximately equal that countries’ reported, installed capacity at the end of 2014. The modelled fleet sizes are:

i. Germany 37,400MW,
ii. Denmark 3,300MW,
iii. Belgium 1,0.35MW, and
iv. Netherlands 1,000MW.

Even power distribution of solar generation across the METAR stations has been taken for each country.

The analysis described for the UK solar fleet was then repeated for this north European fleet. The results of the capacity factor analysis and the monthly and hourly production levels are shown in Figures A2 to A4. Table A2 highlights the low solar production seen in winter months. Given the massive scale of investment in solar power in Denmark and Germany it was surprising to see capacity factors that were similar to those in the UK. The daily maximum production for northern Europe occurs approximately 45 minutes before that in the UK.

FIGURE A1: NORTHERN EUROPE INSOLATION MAP AND AIRFIELD SITES

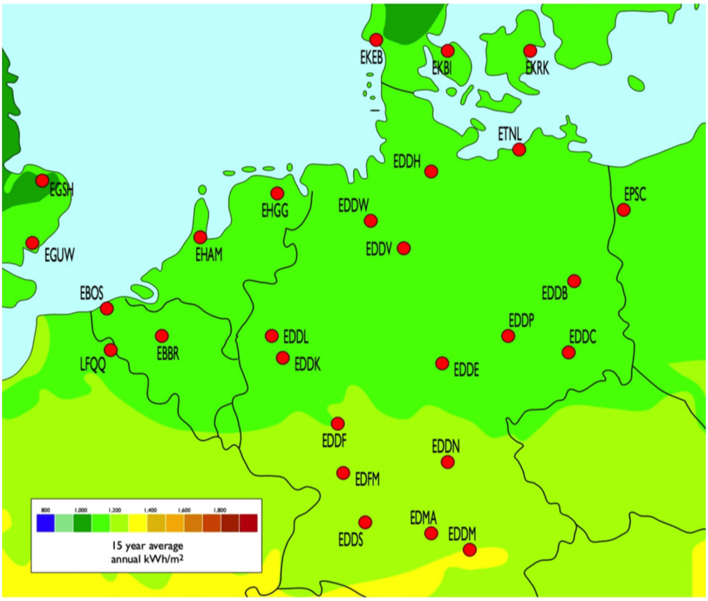


FIGURE A2: NORTHERN EUROPEAN SOLAR CAPACITY FACTORS

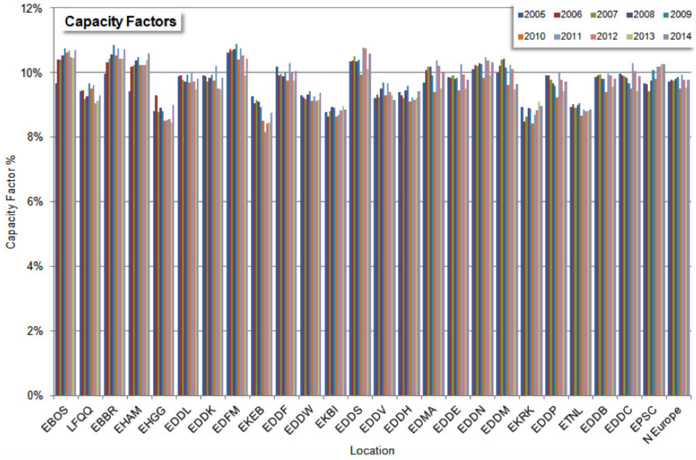


FIGURE A3: MONTHLY SOLAR POWER OUTPUT FOR THE NORTHERN EUROPEAN SOLAR FLEET

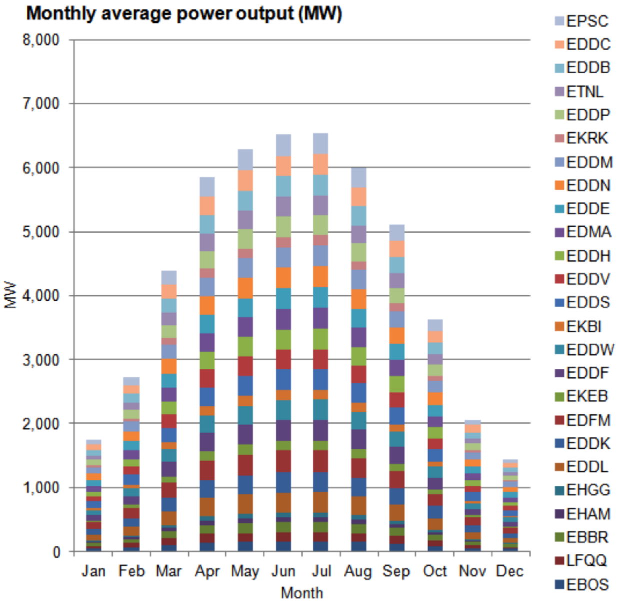


TABLE A2: MONTHLY CAPACITY FACTORS FOR THE NORTHERN EUROPEAN SOLAR FLEET

Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
3.9%	6.1%	9.8%	13.1%	14.0%	14.5%	14.6%	13.4%	11.4%	8.1%	4.6%	3.2%

FIGURE A4: HOURLY POWER OUTPUT OF THE NORTHERN EUROPEAN SOLAR FLEET

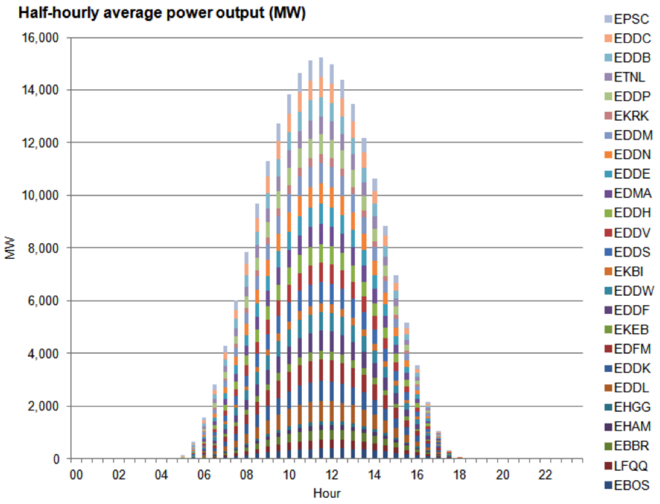


Figure A5 shows the production duration for this fleet.

FIGURE A5: NORTHERN EUROPE RENEWABLES PRODUCTION CURVES

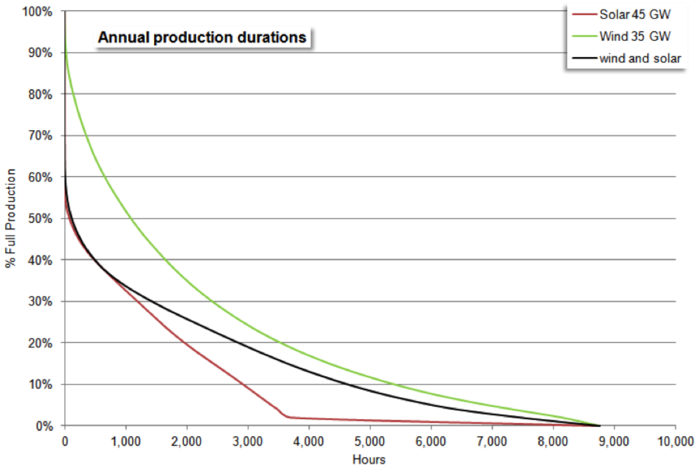


Figure A5 supports the following statements for the solar fleet:

i. Power never exceeds 60% of installed capacity.
ii. power exceeds 50% of installed capacity for 78 hours per annum.
iii. Power exceeds 40% of installed capacity for 488 hours per annum.
iv. Power is below 20% of installed capacity for 6,796 hours (40 weeks) per annum.
v. power is below 10% of installed capacity for 5,841hours (34 weeks) per annum.
vi. Power is unavailable for 5,052 hours (30 weeks) per annum.

This performance is similar to the poor performance seen for the UK solar fleet.

Figure A5 supports the following statements for the combined wind and solar fleet:

i. Power never exceeds 70% of installed capacity.
ii. Power exceeds 60% of installed capacity for 9 hours per annum;.
iii. Power exceeds 50% of installed capacity for 118 hours per annum.
iv. Power is below 20% of installed capacity for 5,909 hours (35 weeks) per annum.
v. Power is below 10% of installed capacity for 4,124 hours (25 weeks) per annum.

Figure A6 shows the Germany energy production levels for different fuel types between 1980 and 2012. This could be viewed as solar and wind generation replacing the fall in zero-carbon emission nuclear generation, with other (presumably biomass, etc) displacing traditional fossil fuels.

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About the author

Dr Capell Aris first worked in the Electricity Supply Industry as reactor physics specialist at Wylfa nuclear power station. He later took up a role in the control and instrumentation section of both Dinorwig and Ffestiniog pumped storage stations, later taking up additional responsibility for information technology systems. He holds a private pilot's license and is a Fellow of the Institute of Engineering and Technology.

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