Pre-print of the "EON 5" scheduled for the April 2005 OPT Journal

[Title page of OPT Journal]

INTRODUCTION [start of OPJ introduction]

The first sixteen pages are devoted to looking at and drawing implications from the immensely important *Wind Report 2004* from the large German grid operator E.ON Netz.

Wind Power and Electrical Demand (pp. 3-4) sums up the essence as simply as possible. The E.ON Netz report breaks new ground in giving data for electricity fed into the grid (this infeed is only 16% of the rated capacity of the wind turbines compared to a 21% German capacity factor). Germany is not likely to be typical of all situations, but as a guide to what to look for, it is immensely valuable. It becomes apparent that any future report needs to include sufficient data to be able to ascertain, in addition to the mean installed capacity, the following: (a) the annual infeed to the grid; (b) the peak of simultaneous power infeed to the entire system; (c) the mean infeed during the low-wind half of the year; (d) the maximum forecasting error as a proportion of the installed capacity.

Wind Power Objections (pp. 5-6) counters some objections that have been raised by laymen after reading the previous paper.

Wind Power and Natural Gas (pp. 7-10) deals with integrating wind power with natural gas-fired plant. It shows that integrating wind power in the UK increases gas consumption.

Wind Power with Coal and "dominant in-harness backup" (pp. 11-12) studies the combination of wind with coal-fired plant. At present, the conclusions are speculative, mainly because no datum is available for the efficiency achieved by coal-fired backup plant when it is having to vary its output and also keep running reserves available. Probably using wind has does not have much effect.

Wind and PV with and without fossil fuels (13-15) extends the argument to cover PV and then dwells on the problems of an 'all renewable energy' world. The postscript on page 18xx mentions some existing popular delusions about wind power.

WIND POWER AND ELECTRICAL DEMAND

by Andrew R.B. Ferguson

Abstract. Based on extensive data over the year 2003, we learn that were sufficient wind turbines to be installed so that, when winds over the whole area were optimum, 100% of peak electrical demand could be satisfied, then during the low-wind half of the year, that is during the 4380 hours of the year when the wind is lower, these same turbines could satisfy only an average 6% of peak electrical demand. For this reason, it is necessary to have sufficient conventional “shadow power stations” available to cover 100% of the peak output from the wind turbines. Other problems are dwarfed by that 6% figure.

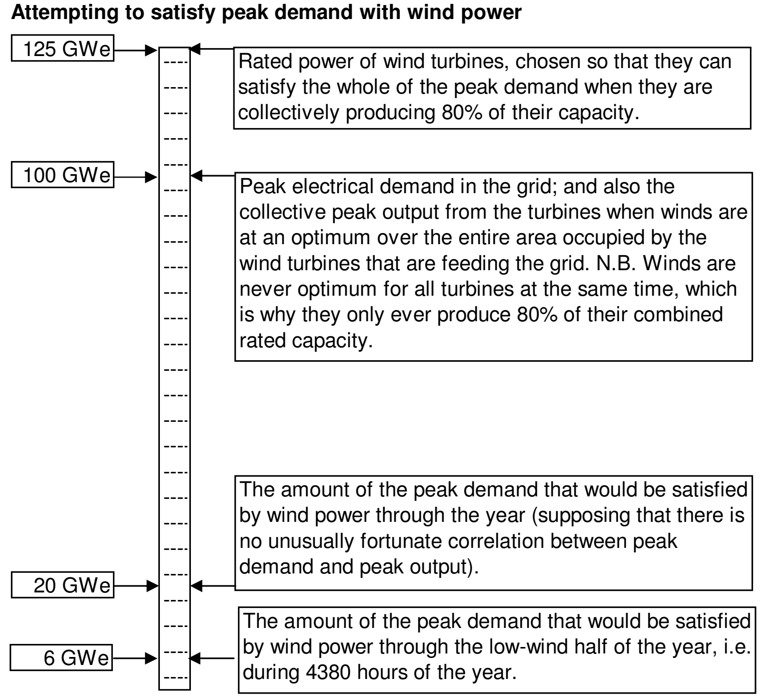
E.ON Netz GmbH operate an electricity grid in Germany extending from Austria to Denmark. The firm is responsible for 44% of the total installed capacity of German wind turbines. Their superbly detailed report, *Wind Power 2004*,[1] throws light on all aspects of the problems of using the output of wind turbines to run a national grid.

Problems are legion, but perhaps the kernel problem is to be found by noting the incompatibility between wind output and electrical demand. Figure 1 sums up the situation. Further explanation is needed on how the figures are arrived at. We will start with the 100 GWe (100 billion watts of electricity) figure, representing peak demand.

The 100 GWe, of Figure 1, could merely have been called 100% of the peak demand, but it is perhaps easier to think of that in terms of some actual power output.

The 125 GWe figure of Figure 1 is arrived at on the basis of the statement on page 5 of the report, “Simultaneous wind power infeed was maximum 4,980 MW, equivalent to just under 80 % of the installed capacity,” i.e. the maximum electrical infeed from the turbines rose to 80% of the combined rated capacity of the wind turbines when winds over the area of the grid network were at their overall optimum. Thus to have a chance of ever satisfying 100 GWe peak demand, 100 / 0.80 = 125 GWe of rated capacity is needed.

Figure 1. Attempting to satisfy peak demand with wind power



The 20 GWe of Figure 1 is based on the data provided in Figure 3 of the report (corroborated elsewhere in the report with *energy* figures), namely that the power supplied to and used by the grid was 969 MW, and the average annual installed wind turbine capacity was 5900 MW, which makes the load factor 969 / 5900 = 16%. Thus, as a mean figure, the output would be 16% of the installed 125 GWe, equal to 20 GWe, as shown.

In making further comments on its Figure 3, the report says that, “Over half the year, the wind power fed-in was less than 11% of the wind power capacity installed in the yearly average.” Figure 3 shows a sloping line for the output below 11%, which is not quite a straight line to zero, so the mean infeed can be estimated at 5% of rated capacity, for the low-wind half of the year, that is during those 4380 hours of the year. 5% of the installed 125 GWe is 6 GWe, which explains the 6 GWe figure of Figure 1. Of course, sometimes during this low-wind half of the year, the wind turbines would be able to contribute 14 GWe (i.e. 11% of 125 GWe), but at other times it would be less than 6 GWe, so as to make the average contribution 6% of the 100 GWe peak demand.

As was stated at the beginning, this 6% of peak demand for half of the year is the kernel of the problem of wind intermittency. A 6% average clearly means that the “shadow power stations,” as they are termed by E.ON Netz — or backup power stations— must cover the whole of the 100 GWe; that is 100% of the peak output, or 80% of the installed capacity. This is confirmed on page 7 of the report, which says, “The characteristics of wind make it necessary for these ‘shadow power stations’ to be available to an extent sufficient to cover over 80% of the installed wind energy capacity.”

Forecasting problems

Another huge problem with wind arises from the difficulty of making accurate forecasts. The report’s Figure 9 shows that it is possible to forecast electrical demand on the basis of past experience with such accuracy that the lines between demand and forecast demand can hardly be separated. However, on the same graph, the lines between wind supply and forecast wind supply are widely separated, as the following figures imply: “In 2003, the average negative forecasting error for the E.ON control area was -370 MW, and the average positive forecasting error was 477 MW. However, during individual hours the deviations reached much higher levels of up to +/- 2,900 MW. This was equivalent to just under half the installed wind power capacity.” Furthermore, as the E.ON report makes clear, one cannot predict when forecasts will be good and when they will be bad, so reserves have to be available on the basis of ‘today’ being the day when the very worst forecasts are going to occur. This is obviously a huge problem, but it is hardly necessary to dwell on it, since the 100% (of peak wind infeed) requirement for cover by backup — with the backup plant needing to vary its output to accommodate wind variations — is the kernel of the problem, especially as it probably means that integrating wind power will result in using more fossil fuel than would be used by foregoing wind power. However the latter assertion is complicated to prove, and will be left to other papers.

E.ON Netz “Wind Report 2004” as paradigm.

Germany may not be typical, but the E.ON Netz report sets a paradigm for reporting on wind. Any future report needs to include sufficient data to be able to ascertain, in addition to the mean installed capacity, the following: (a) the annual infeed to the grid; (b) the peak of simultaneous power infeed to the grid; (c) the mean infeed to the grid during the low-wind half of year; (d) the maximum forecasting error as a proportion of installed capacity.

1. The web address of E.ON Netz GmbH is http://www.eon-netz.com; for English pdf version: http://www.nowhinashwindfarm.co.uk/EON_Netz_Windreport_e_eng.pdf

WIND POWER OBJECTIONS

by Andrew R.B. Ferguson

Abstract. Several objections have been voiced to the points raised in the previous paper *Wind Power and Electrical Demand*. This paper shows why the objections are not valid, and also clarifies one possible point of confusion.

The "objections," to which the title refers, relate to the previous article, *Wind Power and Electrical Demand*. Doubtless objections will arise in the minds of some people as they read the article, only to be rapidly resolved. Others will feel that their objections are valid. Naturally I think that they are not valid. This short paper is intended to respond to the objections, or points of puzzlement, which readers have raised with me.

Objection 1. Surely it is misleading to contemplate installing sufficient wind turbines to satisfy the peak of electrical demand. Roughly speaking, the top third of demand is varying anyhow. It makes no sense to try to satisfy that with an inflexible power source like wind. It would be essential to use a 'flexible' (also called 'demand-following') plant to satisfy that fluctuating part of total demand. Thus the sensible aim would be to install only enough wind turbines to produce an amount of electricity such that when the wind turbines are all producing at their peak, they can satisfy the low points of demand.

Response 1. That is perfectly true; my example was for simplification. But following the policy you suggest only shrinks the problem. Suppose we limit the peak infeed from the turbines to 60 GWe, instead of the 100 GWe that we took as an example. That would reduce the amount of demand which would be satisfied by wind power from 20 GWe in Figure 1, to 20 x 0.60 = 12 GWe, and it would reduce the amount of demand that would be satisfied by wind power through the low-wind half of the year, from the 6 GWe shown in Figure 1, to 6 x 0.60 = 3.6 GWe. It is clear that the problem has shrunk, but not gone away, because the suppliers would be faced with trying to even out the fluctuating output from the wind turbines using a 'flexible' backup power source. That 'flexible' power source would operate much less efficiently because of the need to fluctuate, and because of the need to hold power in reserve because of the difficulty of forecasting the wind accurately.

Objection 2. OK I'll accept that point, but there is another thing that bothers me. Although you don't try to explain it fully in this paper, you remark, in passing, that integrating wind power will result in using *more* fossil fuel than would be used by foregoing wind power. Can you give me some sort of insight into how that could be so?

Response 2. Let us take the 100 GWe of Figure 1, but now think of it as the amount that is needed to satisfy electrical demand at the *low points of demand*, as you wisely suggested. If we try to run that in conjunction with wind power, then because of the varying infeed from the wind turbines, we have to use 'old fashioned' gas turbines, which can easily vary their output, but are less efficient (at about 40%) than the highly sophisticated Combined Cycle Gas Turbines (CCGTs). But the 'old fashioned' turbines would not be able to maintain even 40% efficiency when required to both vary their output and to keep a running reserve of power. 35% would probably be an optimistic estimate for efficiency.

On the other hand, CCGTs, when filling the base load (i.e. constant level part of demand) and so not needing to vary their output, are likely to achieve 60% efficiency. Thus the improvement in efficiency is (60 / 35) - 1 = 71%. Without doing the full calculation, which is the subject of another paper, you can see that such a significant improvement is likely to be more important than the fact that the wind can supply 20%.

Objection 3. In your Abstract, you mention that during the low-wind half of the year the wind turbines will be producing only a mean 6% of their peak output, and yet you also say that it will be necessary to have shadow power stations to cover only 80% of the rated capacity of the wind turbines. I would have thought that the figure should be 94%, i.e. the difference between 100% and 6%.

Response 3. The key words, of which you are taking insufficient note, are "rated capacity." You must bear in mind that the E. ON Netz wind turbines, taken as a whole, never produce more than 80% of their rated capacity. This is because over the whole geographical area of the turbine network, the winds cannot everywhere be optimum. There is an alternative way of expressing the fact that shadow power stations need to be able to cover 80% of the *rated capacity* of the combined wind turbines. That alternative way is to say that the shadow power stations need to be able to cover 100% of *the peak output that is likely to be achieved* from the wind turbines as a whole. By connecting up the wind turbines over a total distance of 800 km, E.ON Netz have reduced the peak output to 80% of the rated capacity of the entire group of wind turbines. Ideally one would connect the wind turbines over such an incredibly wide area that their output would remain steady throughout the year, at the 16% of rated capacity which is the mean infeed that these wind turbines are achieving, but if connection over 800 km only reduces the peaks to 80% of rated capacity, and allows the infeed to drop to zero at times, the hope of getting anywhere close to a steady output of 16% of rated capacity obviously belongs to dreamland.

That is one of the key findings of the E. ON Netz report. Complicated statistical calculations have been made to show that over a wide area wind speeds are chaotic, which the people who made the calculations thought to be sufficient evidence to deduce that strong winds in one place will always be balanced by low winds in another, provided the connection area is wide enough. E. ON Netz has produced the empirical evidence to show that the statistical calculations are misleading, since 800 km is probably approaching the region of a practical limit for transmitting electrical energy from one place to another. Transmission losses and costs of transmission are likely to become a barrier to connecting up over a much greater distance.

Remember, too, that the 6% figure you mentioned is only a *mean* figure, and at times the output would be close to zero, which is why it is no exaggeration to say that the shadow power stations must cover 100% of the peak output of the combined wind turbines, rather then the 94% that you suggested. To sum up, the situation with wind turbines is perfectly simple: if a group of wind turbines which are sharing their infeed capacity to the grid occasionally produce some specified output (e.g. 80% of rated capacity), then it is necessary to build shadow power stations to produce that same specified output. The fact that the capital cost is thereby approximately doubled is obviously serious, but not as serious as the point we discussed previously, namely that integrating the wind turbines with gas-fired plant will increase rather than decrease the use of fossil fuel.

WIND POWER AND NATURAL GAS

by Andrew R.B. Ferguson

Abstract. *Wind Report 2004*, published by the German electricity suppliers E.ON Netz GmbH, further clarifies the proportion of the rated capacity of wind turbines which is fed into the grid. In the whole of Germany (as in the E.ON area which contains about 44% of the wind turbine capacity of Germany), that proportion is 16%. E.ON's data allow an analysis of the fossil fuel energy costs of operating wind turbines. The present paper does not allow for the considerable inputs required (a) to build the wind turbines and access roads; (b) to extend the transmission capability of the grid — the need for which is stressed by E.ON; or (c) to build backup capacity (termed "shadow power stations" by E.ON). Without accounting for these inputs, it is shown that in the UK, where the wind is good and natural gas is used for producing electricity, combining wind turbines with gas-fired plant *increases* the use of fossil fuel by a *minimum* of 20%. Needless to say, if allowance were made for the inputs, then the additional fossil fuel cost of incorporating wind turbines would be greater.

Until *Wind Report 2004*[1] was published, the best evidence about the practical problems of operating wind turbines came from Denmark. A report was produced by the *National Association of Neighbours to Wind Turbines* recording the Danish experiences.[2]

One of the main problems is that Denmark makes extensive use of CHP (combined heating and power), and good wind conditions often coincide with weather that produces a lot of electrical power from the CHP plant. The upshot of this is that although Denmark was — at the time of the study — producing 21% of its electrical energy from wind turbines, it was having to export about 40% of it to other nations. Moreover, it could only manage to do this because of the availability of hydro power in adjacent countries: the hydro output could be switched off to give precedence to the wind output. This option, as well as being expensive, is not available to all countries. The Danes had to give away a considerable amount of the energy they generated as recipients only took it grudgingly. The problems in particular regions were highlighted in this letter in The *Scotsman,* 28 December 2004:

> During 2003, in west Denmark, the annual production of renewable energy (mostly windpower) in the region was numerically equivalent to about 20.7 per cent of demand. But at its time of generation, about 84% of the wind power was surplus to local demand and had to be exported to the much larger power systems of Norway, Sweden and Germany, primarily to maintain stability of frequency and voltage in the Danish grid.

Despite the comprehensive referencing of the Danish report from the *National Association of Neighbours to Wind Turbines*, some people might suspect that its provenance suggests a likely anti-wind bias in reporting. There is no such problem with the recent *Wind Report 2004*, which was published by the German electricity suppliers E.ON Netz GmbH. The firm is responsible for the electricity grid of the E.ON Group. With over 32,500 kilometres of high-voltage and extra-high voltage lines, it has responsibility for about 44% of Germany's installed wind power capacity, and serves 20 million customers over an area which stretches across Germany for 800 km, from Austria to the Denmark. The tone of the report is well balanced, especially in view of the severe difficulties that are clearly arising. There is no plea for the government to remove this burden from their shoulders — even if the present study suggests that there should be one!

The data in the report make it possible to provide a reasonable estimate for something that has long been a problem with assessing wind turbines; to explain that point we must start with definitions. In the wind turbine business, terms are often used without precise definition. In the definitions which follow, I am not exactly adopting accepted meaning. It is dubious whether, in the past, 'capacity factor' and 'load factor' have been always been used with precise meaning. I hope these definitions will continue to be useful, but they are intended mainly for this and the related papers.

Definitions

Capacity factor (CF) is the amount of electricity that is produced by one or more wind turbines divided by the amount of electricity that would be produced were those turbines to operate continuously at their rated capacity.

Infeed factor. (IF) is the amount of electricity that is fed into the grid by one or more wind turbines divided by the amount of electricity that would be produced were those turbines to operate continuously at their rated capacity. N.B. the wind turbines must be only feeding the grid, with output not being partly used in an adjacent building.

Load factor (LF) is intentionally ambiguous, allowing the reader to infer from the context if the reference is to 'capacity factor' or 'infeed factor'. 'Load factor' is useful when quoting figures from a source which has failed to be precise about meaning.

The first clear insight into the substantial difference between infeed factor and capacity factor came when the New Electricity Trading Arrangement (NETA) came into force in the United Kingdom. As reported in the OPTJ 2/2 (p. 38), this depressed the infeed factor by 14%. However, we do not know what the infeed factor was before that depression, and for quantification we need to turn to calculations by the Renewable Energy Foundation, based on the Renewable Obligations Certificates. These have monetary benefits based on input, so we have fair assurance that the data refer to actual infeed. The calculations show an average infeed factor of 24%. The British Wind Energy Association report that the UK mean capacity factor is 29%. This gives an approximate IF/CF ratio of 24 / 29 = 83%.

There is some confirmation from United States data. The wind records for the US are not as detailed as for Denmark, Sweden, Germany and The Netherlands, but the American Wind Energy Association use 30% as a typical capacity factor, and there is some evidence available from the *Windstats*[3] three monthly report that 30% is about the mean capacity factor that is being achieved in the USA. With regard to the load factor, Howard Hayden (2001, p. 21) gave these figures for the whole USA, for 1998: 3.5 billion kWh, or a mean 399 MWe from a wind turbine capacity of 1700 MWe. That calculates as a load factor of 23.5%. Assuming that is an infeed factor, which is likely, it suggests an IF/CF ratio of 23.5 / 30 = 0.78. However, that is a figure to be treated with some caution, because the 30% capacity factor is little more than a guesstimate.

E.ON's data is perhaps the most secure. For capacity factor figures we can turn to *Windstats* again. Capacity factors were given in month by month detail in the OPTJ 3/1 (p. 4). They can be condensed into yearly means as follows:

	Oct-98 to Sep99	Oct 99 to Sep-2000
Denmark	22%	24%
Germany	20%	22%
Netherlands	18%	20%
Sweden	22%	25%
Mean value	**20%**	**22%**

Denmark and Sweden's capacity factors benefit from more of their turbines being situated either offshore or close to the shore, so these figures, taken from the *Windstats Newsletter*, seem thoroughly plausible. We can thus estimate, from the above table, that Germany has a capacity factor of about 21%.

One bombshell contained in the E.ON *Wind Power Report 2004* is that even when spread over 800 km the infeed from the wind turbines varies from 80% of rated capacity to zero. The other bombshell is that taking either Germany as a whole, or the E.ON area by itself (it contains 44% of all the installed wind capacity), the infeed factor is 16%. That makes the IF/CF ratio 16 / 21 = 0.76.

The UK's 83% and E.ON's 76% are the most reliable measurements that we have of the IF/CF ratio, and we can be fairly confident that 80% is good general guide to the IF/CF ratio. We do not necessarily need to know the IF/CF ratio, but it could be useful where only one of the two factors is known.

As mentioned, we now have a calculation from the Renewable Energy Foundation (REF), of a 24% infeed factor for the UK (Scotland 25%; England 24%; Wales 23%); moreover Dr John Constable of the REF told me that the Department of Trade and Industry's statistics confirm that, showing an overall 24.1%

For this analysis, we can therefore proceed with some confidence on the basis of a 24% infeed factor — a considerable improvement on Germany's 16%. Since the British Isles borders the Atlantic ocean, such an improvement — with well placed wind turbines — is unsurprising.

At present, about 47% of the electricity which is generated from fossil fuels in the UK is produced using Combined Cycle Gas Turbines (CCGTs).[4] Unsurprisingly, these run on natural gas! It may well be argued that it is not wise to be using such a precious resource as gas for generating electricity, but then governments rarely act with foresight and wisdom, and we simply have to accept that the use of gas is the reality. Thus the simple question to address is this: will installing wind turbines use more gas than would be used by not installing them? As we will see, the answer is Yes.

The E.ON area extends over 800 km, so in extent it is comparable to the UK. E.ON found that the peaks of the wind system reached 80% of capacity. The significance of that is that if the aim is, for example, to produce 100 MW of steady output, 100 / 0.80 = 125 MW of capacity can sensibly be installed. At the 24% infeed factor we have for the UK, that means that 125 MW of capacity would deliver 125 x 0.24 = 30 MW of output. Thus to produce the target base load of 100 MW, 30 MW will come from wind turbines with 70 MW of electricity from gas turbines.

Because of the almost continuously fluctuating wind input, CCGT plant could not be used (they are highly complicated and expensive to repair and cannot accept continually varying load demands, see OPTJ 4/1. p. 23). It would be necessary to use conventional open cycle gas turbines instead. These normally have an efficiency of 40%, but because their output would have to be varied almost continuously, and also because of the need to have running reserve to cope with sudden wind changes, an overall efficiency of 35% — in terms of *useful* output — might be achieved. Thus the 70 MWe mean power to be supplied by these gas turbines would require 70 / 0.35 = 200 MWyr per year of natural gas.[5]

Now let us consider not building *any* wind turbines. As was recorded in OPTJ 4/1 (p. 23), CCGT plant is currently achieving 50% efficiency, and the best are running at 60% efficiency. Moreover Fred Starr, of *European Technology Development Ltd*, estimates that by 2020 they will be running at 70% efficiency. However, let us be not quite as optimistic as Fred Starr, assuming instead that by time a significant number of wind turbines could be installed, the mean efficiency of CCGT plant will have increased only to the level of the best that are operating now, i.e. 60%.

In the wind-turbine-free scenario that we are presently contemplating, we are planning to produce all 100 MWe from CCGT plant. To supply 100 MWe of mean power would require 100 / 0.60 = 167 MWyr per year of natural gas.

We can therefore conclude that with infeed factors in the region of the 24%, as for the UK, and with natural gas being the alternative power source, substantial savings in natural gas will be achieved by not building wind turbines. Put the other way round, in the above example, the *minimum* additional fossil fuel cost of combining wind turbines with gas-fired plant is (200 / 167) - 1= 20%, or an increase in gas use, over the non-wind option, of 20 MWyr per year of natural gas.

That is a *minimum* additional fuel cost because we have not taken the inputs into account, that is the inputs needed to build the wind turbines, and the "shadow power stations" as the E.ON report calls them, and to enhance the transmission capacity. So the actual addition to fossil fuel cost by incorporating wind turbines would be significantly greater.

These calculations do not apply to nations where the alternative power source is coal-fired plant. That will be considered in the next paper.

Neither do they apply to the situation in which there simply is no fossil fuel available at an acceptable cost. In that situation, the question to ask is whether it will be possible to sustain the whole process of building and maintaining a wind power grid system based on renewable energy, using 'flexible' energy derived from renewable sources. That is also the subject of separate papers (see pp. xx). Nothing about renewable energy is simple!

Some dyed-in-the-wool optimists have seen wind power as the solution to all the problems of overpopulation. From the above analysis it does not appear to fill that role at all well, so let us strive to do better.

Trying to improve the results

From Figure 3 in the E.ON analysis, we can see that the turbines spend only about 250 hours in the year, 3% of the time, above 60% of rated capacity . Perhaps there's a possibility of improving the results by allowing any output over 60% of rated capacity to go to waste. That would involve allowing the strongest wind power to go to waste, but from Figure 3 it looks as though wastage would probably only amount to just over 10% of the total. While that 10% reduction would reduce the infeed factor — 24% to 21.6% for the UK — it would have the advantage that we are aiming only to produce a steady supply of 60% of rated capacity instead of 80%. That would mean that to provide 100 MWe of mean power we could build 100 / 0.60 = 167 MWe of rated wind power. At 21.6% infeed factor, that would produce 167 x 0.216 = 36 MWe, leaving only 64 MWe to be produced from gas turbines (an improvement over 70 MWe). At 35% efficiency, the 64 MWe would require 64 / 0.35 = 183 MWyr per year of natural gas.

Recalling that to supply 100 MWe of mean power from CCGTs would require 100 / 0.60 = 167 MW of gas, the *minimum* additional fuel cost of combining wind turbines with gas-fired plant would be (183 /167) - 1 = 10%, or 10 MWyr per year of natural gas.

That appears to be an improvement over the 'unimproved' 20%, but note that that we have increased the required inputs in relation to the output, because we need to install 167 MWe of rated wind power capacity instead of 125 MWe; also we have increased wastage, because the infeed factor is putatively reduced to 21.6%. So there is less output to provide the required input. Overall it seems dubious that we can achieve much improvement with this '60% cap' policy. It might seem unnecessary to have carried out this 'variation analysis', but a frequent suggestion of wind fantasists is that we could let a bit of wind go to waste, when the peak wind output exceeds total demand, which could of course easily happen with a substantial use of wind power, because of the large difference between a peak infeed of about 80% and a mean infeed — in the case of the UK — of 24%. The meaning of 'substantial', just mentioned, is sufficient to impinge on the lowest demand of the total electrical system, i.e. the opposite of the peak demand.

Another favourite idea of energy fantasists is to overcome intermittency with pumped storage. Problems associated with that are here confined to endnote 6.

Conclusion

For those who are generating electricity from natural gas, there is no escaping the fact that the result of installing wind turbines, and the related equipment, would be to use substantially more gas than would be used by *not* installing them, and that is true even without accounting for the energy cost of installing them and their related equipment.

References

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Endnotes

1. Wind Report 2004 from E.ON Netz GmbH is a 16 page report on the experiences of the company in 2003. The web address of E.ON Netz GmbH is http://www.eon-netz.com; for English pdf version: http://www.nowhinashwindfarm.co.uk/EON_Netz_Windreport_e_eng.pdf
2. See http://www.naboertilvindmoller.dk/English/danishdelimma.doc
3. WindStats Newsletters are issued every three months, but are very hard to come by, being held only by the British Library according to Reading University Library. The way in which "capacity factor" may have many meanings can be illustrated by an excerpt from a WindStats Newsletter. The preface to its tables says that to be included turbines: "must have reported for all three months of the quarter; and must not have had more than ten percent downtime during any month of the quarter."
4. 134,414 GWhe from CCGT and 150,685 GWhe from conventional thermal, as given in the National Statistics Annual Abstract 2004 edition, No. 140.
5. Electrical energy is usually given in terms of mean power, MWe, with the time of a year often being implicit. However, it is somehow against intuition to regard gas in the same terms, so I use the energy term MWyr per year. 1 MWyr/yr = 1 x 10^6 x 24 x 365 = 8760 MWh/yr, or 31.5 x 10^{12} joules/yr.
6. The amount of water need to generate 1 kWh when raised by the nominal height of 50 m is 8.6 tonnes or 8.6 m^3, which calculation goes thus.
   1 kWh = 3.6 x 10^6 joules. 1 J = 0.1019 m kg, so 3.6 x 10^6 joules = 0.1019 x 3.6 x 10^6 = 366,840 m kg.
   So the weight of water required, if raised 50 m, is 366,840 / 50 = 7337 kg = 7.34 m^3.
   Estimating that transformation of the potential energy of the water into electrical energy is 85% efficient, that would require 7.34 / 0.85 = 8.64 m^3 of water.
   If the drop were say 200 m, then the water required would be (7.34 x 50 / 200) / 0.85 =2.16 m^3, which could also be arrived at as 8.64 x 50 / 200 = 2.16 m^3.
   The amount of energy that needs to be stored to allow seasonal shifting, from the high wind months to the low wind months is about 10%. Thus for a mean 600 MW output (i.e. that of a normal power plant) storage for 60 MWyr is required. Water 10 m deep would need to cover 21 km by 21 km.

WIND POWER WITH COAL, and "DOMINANT IN-HARNESS BACKUP"

by Andrew R.B. Ferguson

Abstract. This paper is closely related to the previous paper, *Wind Power and Natural Gas*. This analysis — for coal-fired plant — is necessarily different from that for gas-fired plant. Contrary to natural gas, the results are far from clear cut. The analysis is only a ballpark appraisal: the broad conclusion is that there can be no assurance that there will be saving in energy by using wind turbines in conjunction with coal-fired plant, so there is an essential need for better data. It is suggested that only when the flexible power source is given an appropriate name — *dominant in-harness backup* — does it become apparent just how pervasive are the problems of integrating wind power and photovoltaics.

Although this paper is designed to be printed together with *Wind Power and Natural Gas*, that may not always happen, so here is a repeat:

Definitions

Capacity factor (CF) is the amount of electricity that is produced by one or more wind turbines divided by the amount of electricity that would be produced were those turbines to operate continuously at their rated capacity.

Infeed factor. (IF) is the amount of electricity that is fed into the grid by one or more wind turbines divided by the amount of electricity that would be produced were those turbines to operate continuously at their rated capacity. N.B. the wind turbines must be only feeding the grid, with output not being partly used in an adjacent building.

Load factor (LF) is intentionally ambiguous, allowing the reader to infer from the context if the reference is to 'capacity factor' or 'infeed factor'. 'Load factor' is useful when quoting figures from a source which has failed to be precise about meaning.

There was no need to consider the energy cost of the inputs when dealing with natural gas, because even without including those energy costs, it was evident that natural gas can be saved by *not* incorporating the use of wind turbines. When coal is the energy source used to provide backup power for wind turbines, the situation is more finely balanced.

We need first to consider the differences from natural gas. It must be said that the figures used here are not by any means firm. What follows is mainly an illustration of the factors that need to be taken into account; nevertheless the figures chosen are my best guess at reflecting reality. As will be apparent at the end, the only thing that is certain is that better data are required before it will be possible to give a definitive answer.

The big difference with coal, as compared to gas, is that is cannot be used to run the super-efficient Combined Cycle Gas Turbines (CCGTs). Thus we are forced back to the much lower efficiency of converting coal to electricity, about 30%.

Differences between gas and coal

Gas has another advantage. A graphic from the National Grid shows open cycle gas turbines having a *2 minute* response time; CCGT 6 hours; Small Coal 12 hours; Large Coal 24 hours. With such a slow response time, coal-fired power stations need to keep large amounts of spinning reserve available. For that reason, it may be in the ball park to estimate that the overall efficiency of coal-fired plant, *including the losses incurred by keeping spinning reserves to cope with wind variability*, will be significantly more than the

13% (i.e. the drop from 40% to 35%) that we assumed for gas turbines when they have to operate in conjunction with wind power. A 16% drop for coal-fired plant operating as backup for wind, compared to what it would be operating under constant output, would seem to be a minimum change from 13%. A 16% drop would reduce their 30% conversion efficiency to 25%. Perhaps I should stress that my hunch is that the reduction will be far greater than 16% because of the need to keep more spinning reserves available, but the 25% efficiency figure will give us something to work from.

Inputs required.

Since everything is more closely balanced in the coal-fired backup situation, we need to consider inputs. Some analyses have put the *inputs* required to install and maintain wind turbines and their related equipment at very low fractions of the *output*. But there are many weaknesses in those analyses. The problems may be listed as:

a) In making an energy balance calculation, the electrical *output* is uprated to its thermal equivalent, making it worth about three times as much. For some purposes that is legitimate, but not always when assessing the inputs against output. Electrical *inputs* are normally uprated to thermal equivalents, which is perfectly fair, but no uprating is applied to liquid inputs (e.g. gasoline and diesel). As oil and gas become scarce it is arguable that those inputs should be uprated due to the difficulty of producing 'liquid' energy from electricity. (We could pursue a more detailed analysis of this input/output energy balance conundrum, but let us just say that it is problems of this type which bedevil — and make dubious — all energy balance analyses, when applied to an all-renewable energy world).

b) Some of the energy balance analyses do attempt to include the inputs needed for upgrading and then maintaining the grid transmission system, but I doubt that they make adequate allowance for the need for the very wide-area transmission which E.ON Netz has found to be necessary to cover an 800 km range.[1]

c) The energy balance analyses have been based on optimistic load factors, usually of the order of 30% (making inputs appear as a small fraction of the output), whereas, as we see from E.ON's data, the infeed factor in Germany is 16%. This roughly doubles the ratio of input to gross output.

d) The energy balance analyses do not take into account the additional inputs needed to build the "shadow power stations," as E.ON term them, also called backup, to match the peak output of the wind turbine system.

Taking all those factors into account, it would seem to be a reasonable estimate that, if we uprate the output of the wind turbines to its thermal equivalent, we can estimate that 20% of that output will be needed to provide energy for the construction and operation of the wind turbines, including all the plant which is directly related to the operation of the wind system and to providing a backup for it.

Wind plus coal versus coal

We can now follow the same type of analysis that we did for natural gas, but this time we need to extend it to make an allowance for inputs. Let us continue with the 24% infeed factor that we used for the UK.

With the same wide-area wind situation as reported by E.ON Netz, in which the peaks of output were no higher than 80% of rated capacity, then in order to achieve 100 MWe of output, we can sensibly install 100 / 0.80 = 125 MWe of rated capacity. With our assumed 24% infeed factor, 125 x 0.24 = 30 MWe will be provided by the wind turbines, and the remaining 70 MWe by coal-fired power stations. Note, too, that the 20% that we have estimated as input amounts to 30 x 0.20 = 6 MWe. Thus the coal-fired power stations need to produce 70 + 6 = 76 MWe. At the above 25% efficiency, the fuel needed would amount to 76 / 0.25 = 304 MWyr per year of coal.[2]

We can compare that result with producing all 100 MWe from coal-fired plant operating at 30% efficiency. The fuel needed would be 100 / 0.30 = 333 MWyr per year of coal.

It looks, from those figures, that by operating the wind turbines we are saving 9% of the fuel that would otherwise be used. However almost no trust can be placed in that result. The only conclusion is that we must withhold judgement until we know, (a) how much less efficiently coal-fired plant operates when it has to change its output almost continuously, and sometimes rapidly (E.ON Netz report a six hour period when infeed was dropping at a rate of 600 MW per hour); and (b) how much fuel is used up in the process of keeping running reserves available to cope with errors in forecast winds.

"Dominant in-harness backup"

It is clear by now that much of the faith that has been placed in wind power has been misplaced. I would suggest that a substantial reason is the deceptive nature of the word "backup." Even the alternative phrase "shadow power station" somewhat obscures what it is that flexible power plants are required to do when operating in conjunction with intermittent power sources, particularly with wind turbines and photovoltaics. The "backup" plant is in fact the *dominant* source of power and it has to work "*in harness*" with the varying output of the wind turbines or PV. Thus a more suitable phrase would be "dominant in-harness backup," or "dominant backup" for short.

Dominant backup is in fact *very* dominant. With the wind in Germany, it has to supply about 100 - (100 / 0.80) x 0.16 = 80% of the energy, and in the UK it has to supply 100 - (100 / 0.80) x 0.24 = 70% of the energy. With PV in Germany, where the infeed factor would be about 10%, the dominant backup would have to work in-harness with the PV to provide 100 - (100 / 0.80) x 0.10 = 87% of the energy. As soon as it is fully appreciated that introducing wind or photovoltaic energy into the system is bound to put a fearful burden on the *dominant in-harness backup*, then the negative assistance given by both of these intermittent power sources when using them with gas, and the doubts about the existence of any assistance when combining them with coal-fired plant, is surely what might be expected, without doing any calculations at all.

Conclusion

The only things which are certain about the wind integrated operation is that we will need to build exactly the same amount of coal-fired plant as would be needed without the wind turbines, and to that will be added the cost of installing and maintaining the wind turbines, and of enhancing the transmission capacities of the grid, all of which will result in a significant increase in the cost of electricity. We therefore need to be sure that we have the data available to know whether we are going along a sensible path before we proceed too far along it.

Endnotes

1. Wind Report 2004 from E.ON Netz GmbH is a 16 page report on the experiences of the company in 2003. The web address of E.ON Netz GmbH is http://www.eon-netz.com; for English pdf version: http://www.nowhinashwindfarm.co.uk/EON_Netz_Windreport_e_eng.pdf
2. Electrical energy is usually given in terms of mean power, MWe, with the time of a year often being implicit. However, it is somehow against intuition to regard coal in the same terms, so I use the specific energy term MWyr per year. 1 MWyr/yr = 1 x 10^6 x 24 x 365 = 8760 MWh/yr, or 31.5 x 10^{12} joules/yr.

WIND AND PV WITH AND WITHOUT FOSSIL FUELS

by Andrew R.B. Ferguson

Abstract. In related papers, it has been demonstrated that incorporating wind turbines into the production of electricity from natural gas, even with favourable UK winds, results in a *minimum* 20% increase in the use of gas. After reviewing those results, this paper shows that by incorporating PV into the production of electricity from natural gas in similar circumstances, there is an increase in the use of natural gas of a *minimum* 50%. It has also been shown that combining coal-fired power stations with wind turbines will remain a dubious proposition until better data are available. This paper shows that when PV is combined with coal, the lower infeed factor of PV — 8% instead of 24% for wind (both figures for the UK) — tips the balance, so that combining PV with coal-fired plant is likely to increase the use of coal. The outstanding question is whether it will be possible to use wind turbines (or any other intermittent energy source) without fossil fuels. This paper suggests that the level of uncertainty means it would be wise to start immediately to reduce the size of populations to levels which might be supportable in the post fossil fuel era.

On a theoretical basis, it has been clear for some time that using wind power in conjunction with gas-fired plant is likely to increase the use of gas (OPTJ 4/1, April 2004, pp. 23). These intimations have been firmed up by meticulously collected empirical evidence. For this we can thank the firm E.ON Netz, the operators of a transmission grid extending across Germany from Austria to Denmark. Their superb report *Wind Power 2004*,[1] shows that the problem is significantly more dramatic than the earlier estimates had foreshadowed. As was demonstrated in *Wind Power and Natural Gas* (p. xx), even for the UK, where wind conditions are markedly better than Germany, integrating wind turbines will increase fossil fuel use by a *minimum* of 20%. Far less clear cut is the combination of wind power with coal-fired plant as backup; the situation remains to be resolved by better data.

Since this present paper may be circulated separately from the two that precede it, I will briefly encapsulate the intended meaning of *capacity factor* — it refers to the electricity *produced* by wind turbines or photovoltaics. *Infeed factor* refers to the electricity *fed into the grid*. In both cases the numerators are divided by the rated capacity (usually called peak capacity in the case of PV) to arrive at the appropriate factor.

From a recent news item, it seems that Germany is also a leader in the empirical study of photovoltaics. The German Solar industry says that, in 2004, sales of new PV capacity are expected to amount to over 200 MWe (peak capacity).[2] Having noted that the use of PV in Germany is substantial, we will continue to look at the UK situation.

We will apply the same type of analysis to PV as we did for the combination of wind power and natural gas. Then, without doing a full scale analysis, we will revise the analysis contained in *Wind Power with Coal* for using PV with coal-fired backup.

The Rule of Thumb (OPTJ 4/1, pp 28-31) for determining the 'capacity factors' of PV is actually designed, *according the terminology being used here*, to determine 'infeed factors' (it estimates the electricity delivered to the grid).[3] Insolation was measured at Reading, Berkshire over many years, and the figure was close to 110 W/m^2 (watts per square metre). Thus the Rule of Thumb indicates an infeed factor of (110 / 1000) x 0.70 = 8%.

For this analysis, we will again consider installing sufficient plant to produce 100 MWe (million watts of electricity) as a mean output. As with wind power, we need to know what the peaks of output would be when the PV output is connected over a wide area, say as wide as the E.ON network, stretching over 800 km. It is hard to know whether there would be more regularity with PV than with wind. Perhaps on occasions the whole of the region could be experiencing strong sunshine at the same time, but let us give PV the benefit of the doubt, and assume that the *mean* peaks would reach only 80%, as they do with wind. That indicates that there is a possibility of installing 100 / 0.80 = 125 MWe of peak capacity without exceeding the 100 MWe steady load that we are aiming to provide.

The 8% load factor would provide 125 x0.08 = 10 MWe; the remaining 90 MWe, of the 100 MWe, would be provided by gas turbines operating at 35% efficiency, because of the need to vary their output continuously. Thus the 90 MWe mean power to be supplied by these turbines would require 90 / 0.35 = 257 MWyr per year of natural gas.[4]

By *not* using PV, and so producing all 100 MWe from natural gas (using Combined Cycle Gas Turbine plant), the gas requirement would be 100 / 0.60 = 167 MWyr per year of natural gas.

We can therefore conclude that, with a PV infeed factor in the region of 8% (as would obtain in the UK; it would be about 10% in most of northern Europe), and assuming that natural gas is the alternative power source, then more natural gas will be used by operating plant in combination with PV. In the above example, the *minimum* additional fuel required to integrate the PV system would be (257 / 167) - 1 = 54%. We need hardly repeat that the figure is *minimum*, because we have made no allowance for the inputs which in the case of PV modules are likely to be greater, in proportion to their output, than for wind turbines.

PV and coal

Little would be gained from going through a wind-type calculation to analyse using coal-fired power stations in combination with PV. It is easier to simply recall the broad estimate that better data are required to know where the balance of advantage lies when wind power is combined with coal-fired plant. For PV the situation is clear cut to the extent that, even without doing calculations, an 8% infeed factor for PV, compared to 24% for wind, will sufficiently shift the balance to make it advisable not to combine PV with coal-fired plant. The end result of integration would be to use more coal.

Wind turbines and PV without fossil fuels

Having shown, in this paper and the two earlier ones, that it is unwise to try to combine the use of either wind turbines or PV with gas-fired power stations and that it is also unwise to integrate PV into the operation of coal-fired plant, and it may be unwise to incorporate wind turbines into coal-fired power stations, we are now faced with what is probably the most important question, namely what is to be done when fossil fuels become so scarce that they can no longer be used. Could wind power (or PV, wave power, or something else) have a role to play in that situation? If our concerns extend beyond the immediate future, there could hardly be a more vital question.

What are the alternatives for a ‘flexible’ renewable power source? The part that biomass can play is limited, because its power density is so low (OPTJ 3/1, pp. 11-15). The extent of the need for a flexible power source is obvious from the 70% requirement from a flexible energy source shown in the wind analysis, and 90% for PV. Thus a great deal hinges on whether we can store electrical energy and thereby make use of the relatively high power density of wind. Perhaps the meaning of a ‘flexible’ power source needs defining. A ‘flexible’ power source is one that can be varied according to human requirements, either to satisfy increased *demand*, or — very important with intermittent renewables — to compensate for lack of *suppl*y.

The most thoroughly studied method of storing electricity is to produce hydrogen and then to regenerate electricity, possibly using fuel cells. However, problems have already been encountered in running electrolysers on an intermittent basis. Moreover the whole process, starting with generating electricity at the wind turbines, looks alarmingly inefficient. If we start with a 30% capacity factor, then after electrolysis (70% efficient) and regeneration using fuel cells (60% efficient), the 'final load factor' would be 0.30 x 0.70 x 0.60 = 13%. That means that for each 100 MWe of mean 'flexible' power to be made available, we need to have 100 / 0.13 = 769 MWe of rated wind turbine capacity. There is also the need for electrolysers and fuel cells. With so much plant to construct, the inputs would be large in proportion to the output. Nearly all engineers doubt whether the project would be feasible, especially in a world where energy is expensive.

Pumped storage comprises pumping water into reservoirs for later use. It requires 8.6 m^3 of water to be raised 50 m to store 1 kWh (endnote 5 to *Windpower and Natural Gas* shows why). To store 10% of the supply of a plant capable of producing 600 MW, thus requiring 60 MWyr to be stored, would need a reservoir elevated by 50 m, say, and able to accept a 10 m depth of water extending 21 km by 21 km. Obviously in most places there is an insuperable problem in find suitable places for reservoirs which would accommodate the amount of water required for seasonal shifting.

Another idea is CAES, compressed air energy storage. To my knowledge, the problems associated with that have not been sufficiently investigated to be able to say anything definite.

Capturing energy in liquid form at an *acceptable power density* is at least as problematic as producing an on-demand supply of electricity. With the prospects of success in doubt, we should start without delay to move in the direction of a much smaller population. Whether world population will need to be reduced to 2 billion, UK to 20 million and the USA to 200 million, as OPT think, can be left open for some time, so long as we commence to move in the right direction.

Some people may be troubled by the disparity between the above, and the general ambience of optimism about wind power in the media. To try to understand that better, the next page to this section — the postscript *Popular Delusions* — takes a look at just one of the many attempts, both in the academic world and outside it, to paint a rosy picture, wildly at variance with reality.

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OPTJ 4/2. 2004. *Optimum Population Trust Journal*, Vol. 4, No 2, October 2004. Manchester (U.K.): Optimum Population Trust. 32 pp.

1. The web address of E.ON Netz GmbH is http://www.eon-netz.com; for English pdf version: http://www.nowhinashwindfarm.co.uk/EON_Netz_Windreport_e_eng.pdf
2. This report appeared on page 24 of the Natta (Network for Alternative Technology and Technology Assessment) Newsletter, RENEW Vol. 152, Nov/Dec 2004. 'Peak capacity' is the output at which the modules are rated, so it is another name for 'rated capacity'.
3. As of 7 December 2004, Minnesotans for Sustainability have a small spreadsheet to facilitate calculation of output from PV; it is at http://www.mnforsustain.org/energy_photovoltaic_calc_output.htm
4. Electrical energy is usually given in terms of mean power, MWe, with the time of a year often being implicit. However, it is somehow against intuition to regard gas in the same terms, so I use the specific energy term MWyr per year. 1 MWyr/yr = 1 x 10^6 x 24 x 365 = 8760 MWh/yr, or 31.5 x 10^{12} joules/yr.

A postscript on popular delusions

Readers will have observed the disparity between the foregoing analysis and the view of wind enthusiasts, who think that wind energy could replace fossil fuels. Some of that enthusiasm is spurred on by scientific papers. It may be helpful to take a look at one such paper, to see how it serves to strengthen the delusion. The paper I choose is *Assessment of the global and regional geographical, technical and economic potential of onshore wind energy* by Monique Hoogwijka, Bert de Vriesb, and Wim Turkenburga, published in 2004 (*Energy Economics* 26 (2004) 889– 919) This is the first quotation:

> As illustrated, there is recently a large policy interest in wind energy based on various arguments. First, wind energy reduces dependency on and payments for imported fuels. Second, it diversifies energy carriers for the production of electricity. Furthermore, it can increase the flexibility of the electricity system as demand changes and it saves fossil fuels for other applications and future generations. Finally, wind electricity reduces pollution and emissions, such as NOx and CO2, that are produced by conventional energy systems.

The study is mainly quoting the judgement of others there, but note that it is only able to entertain such beliefs because it does not take into account the need to supply the greater part of the energy from a 'flexible' energy source. When that is taken into account, all the above assertions are false.

The study is realistic in terms of capacity factors as we see here:

> Various combinations are possible between the generator and the rotor diameter, leading to different full-load hours for the wind turbine. The aim is to achieve a cost-effective optimum, which is attained at full-load hours around 2000 h.

2000 load hours per year = 2000 / 8760 = 23% capacity factor. That indicates an infeed factor of around 23 x 0.76 = 17.5%, which is not far from Germany's achieved 16%.

An essential factor in the type of assessment being made in this paper is the power density, that is the MW of output per area of land (although for wind turbines I often also use the reverse ratio, ha/MW). This is what the study says:

> This value [4 MW km $^{-2}$] corresponds to the power density assumed in this study

4 MW km^{-2} is 25 ha/MW of *output*. About the closest positioning of wind turbines that has been recorded is 25 ha/MW of *capacity*. At a realistic capacity factor of 22%, which gives a likely infeed factor of 22 x 0.76 = 17%, a realistic power density would be 25 / 0.17 = 147 ha/MW of infeed power. In other words, insofar as it assumes a power density of 25 ha/MW of infeed power, the study is in error by a factor of 6. However, it is not always absolutely clear what power density is assumed. This is what the paper says in one reference to a "global average":

> As a global average, we calculate a slightly higher figure, 0.37 MW km^{-2}.

That is 270 ha/MW of output. That may be plausible on a global basis. However even for a global assessment the paper appears to sometimes use 25 ha/MW, as here:

> To supply this technical potential [96 PWh/yr for the world], an area of 1.1 Gha is required assuming a power density of 4 MW/km^2. This is similar to the total global grassland area or the size of about China. The regionally highest technical potential is found in the USA (21 PWh year $^{-1}$)"

As noted, the 4 MW/km^2 (25 ha/MW of output) is unrealistic, while the other figure that the study mentions, 0.37 MW/km^2 is possibly realistic. That increases the area to 1.1 x 4 / 0.37 = 12 Gha, yet the total area of ice free land is only 13 Gha! Other studies of the potential for wind power in the USA have put the figure at 10 PWh/yr, but they too took no account of the need for 'flexible' backup power. That is the fundamental flaw which underlies most attempts at analysing the potential of intermittent power sources.