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WIND/BIOMASS ENERGY CAPTURE: AN UPDATE

An article by Andrew Ferguson - OPT Research Director
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Abstract. Wind energy suffers from *short term* unpredictability, giving problems of integrating the output with a time-independent source. Moreover, *long term* variability means that a substantial proportion of the energy required to satisfy consumer demand must come from a time-independent source (in the context of renewable energy this means biomass). We also see that wind energy can have only a small effect in raising net energy-capture from the mean figure of 1.5 kW/ha, available from the whole biomass spectrum, up to the figure of 3 kW/ha which is assumed for eco-footprinting. The importance of a realistic assessment of net energy-capture is apparent from the fact that biomass alone could support only a fraction of the present population.

It is demonstrated that if the USA develops all its wind resources, the related composite wind/biomass system would cost about $700 billion, and would provide at most 18% of *primary energy* (enough to satisfy 16 years of population growth). Fuel for the biomass-fired generating stations would require 180 million hectares of land—not likely to be available. In UK (and barring off-shore production), to provide 22% of national *electricity* from a wind/biomass system could require 33% of its ecologically productive land: an amount that is certainly not available.

The precursor to this article, pages 38-40 of the October 2002 issue of the *OPT Journal*, was not a complete analysis, since it took into account only the short term variability of wind. This update extends the analysis to cover long term variability. It has been made possible because Morten Lintrup, of the Danish carrying capacity organization DROS, kindly sent me wind data taken from eight issues of the admirable *WindsStats* newsletters (see Table 1).

In order to make this paper complete in itself, some of the text from the preceding article is repeated. In following in the path of that article, we also aim to keep wind power within the wider perspective of all types of renewable energy.

Capacity factor means 'production as a proportion of rated output'. At the time of writing the previous article, the only annual national capacity factor figure I had available was 25% for the UK. The UK appears to be well situated to catch Atlantic winds, so I was not sure that this figure would be representative. It is possible to be more confident about the four nations shown in Table 1, Denmark, Germany, the Netherlands and Sweden. As it happens, the difference in capacity factors is not great: over the two years of Table 1, these four nations achieved a mean capacity factor of **22%**.

The October 2002 issue of the *OPT Journal* (pp. 33-37) showed that photovoltaics cannot play a significant part in the quest for renewable energy because of expense. The April 2002 issue, pp. 11-13, showed that the problem with wind power is that it is limited in scope. Later we will consider

Table 1: Monthly, and hence yearly, capacity factors from Wind Stats Newsletter, Oct-98 to Sep-99

		Oct-98	Nov-98	Dec-98	Jan-99	Feb-99	Mar-99	Apr-99	May-99	Jun-99	Jul-99	Aug-99	Sep-99	mean/total
Denmark	Capacity MW being reported.	545.0	546.7	566.5	573.8	490.4	485.2	523.9	564.3	533.6	557.2	550.1	548.7	540.9
Germany	"	1134.3	1098.3	1094.0	1160.6	1167.2	1134.3	1278.2	1231.5	1201.6	1372.7	1342.7	1102.1	1193.6
Netherlands	"	182.0	196.7	196.7	281.7	281.5	281.6	216.3	178.7	187.2	280.3	279.1	276.3	236.3
Sweden	"	147.8	156.5	161.5	176.0	156.5	169.3	173.3	176.0	135.6	177.4	187.5	190.5	167.5
US (VT)	"										5.5	5.5	5.5	5.5
US (TX)	"										6.6	6.6	6.6	6.6
Denmark	Production MWh.	174,612	60,681	119,453	128,509	89,219	78,841	93,634	73,947	54,503	48,849	47,981	60,212	1,030,441
Germany	"	332,135	108,267	240,303	259,735	233,426	153,468	183,750	105,478	105,478	132,337	129,500	109,920	2,093,797
Netherlands	"	42,296	18,212	35,660	59,938	54,510	32,088	24,135	19,683	16,857	24,432	19,557	23,598	370,966
Sweden	"	44,893	16,921	36,753	36,930	31,102	36,753	29,168	21,865	13,637	17,387	14,837	23,120	323,366
US (VT)	"										827	545	583	1,955
US (TX)	"										1,496	843	1,273	3,612
Denmark	Therefore capacity factor.	43%	15%	28%	30%	27%	22%	25%	18%	14%	12%	12%	15%	22%
Germany	"	39%	14%	30%	30%	30%	18%	20%	12%	12%	13%	13%	14%	20%
Netherlands	"	31%	13%	24%	29%	29%	15%	15%	15%	13%	12%	9%	12%	18%
Sweden	"	41%	15%	31%	28%	30%	29%	23%	17%	14%	13%	11%	17%	22%
US (VT)	"										20%	13%	14%	16%
US (TX)	"										30%	17%	26%	25%
													Mean for all 4 nations Oct-98 to Sept-99	20%

Table 2 : Monthly, and hence yearly, capacity factors from Wind Stats Newsletter, Oct-99 to Sep-2000

		Oct-99	Nov-99	Dec-99	Jan-00	Feb-00	Mar-00	Apr-00	May-00	Jun-00	Jul-00	Aug-00	Sep-00	mean/total
Denmark	Capacity MW being reported.	608.1	534.5	490.0	441.8	608.4	624.1	611.3	550.2	477.7	659.2	711.6	679.3	582.9
Germany	"	1460.6	1461.0	1393.3	1470.4	1503.2	1434.0	1550.5	1612.4	1301.0	1809.1	1761.9	1738.9	1542.0
Netherlands	"	318.5	318.5	319.2	256.2	251.5	252.7	233.1	229.0	190.1	335.2	338.7	335	281.9
Sweden	"	183.9	185.6	195.6	212.6	212.1	210.0	136.2	136.3	195.6	214.4	209.2	213.2	192.0
Denmark	Production MWh.	116,351	93,814	130,807	125,356	164,041	147,420	59,339	68,175	73,021	70,001	82,922	107,646	1,238,893
Germany	"	279,579	220,283	398,647	369,610	398,212	339,413	164,004	173,468	170,095	174,764	111,107	184,276	2,983,458
Netherlands	"	50,254	52,453	77,873	51,944	60,719	52,373	24,453	27,260	20,967	32,076	18,004	30,679	499,055
Sweden	"	42,311	38,900	56,845	60,293	53,972	49,820	14,509	17,861	21,661	20,075	21,255	29,661	427,163
Denmark	Therefore capacity factor.	26%	24%	36%	38%	39%	32%	13%	17%	21%	14%	16%	22%	24%
Germany	"	26%	21%	38%	34%	38%	32%	15%	14%	18%	13%	8%	15%	22%
Netherlands	"	21%	23%	33%	27%	35%	28%	15%	16%	15%	13%	7%	13%	20%
Sweden	"	31%	29%	39%	38%	37%	32%	15%	18%	15%	13%	14%	19%	25%
													Mean for all 4 nations Oct-99 to Sept-2000	23%
													Mean for all 4 nations over 2 years, Oct-98 to Sept-2000	22%

26 Sept 2002; af-wind2.xls

the ramifications of this limited scope, but first we will focus on the implications of the short and long term variability of wind strength, and its effect on land requirements.

Table 1 shows that there are some months of the year when the capacity factor drops to low levels, for example below 8% for Germany and the Netherlands in August 2000. Not apparent from the table, but common knowledge, is the variation in wind strength which occurs from one day to another, or one week to another. While the monthly variability shown in the table provides an interesting background, and illustrates the imperative need for back-up, what chiefly concerns us, in this analysis, is the mean capacity factor achieved for all four nations over two years. That figure, as already mentioned, and as shown at the bottom right of Table 1, is 22%.

Now we can address the question of how to run a composite wind/biomass energy system to satisfy normal consumer demand. Let us, by way of an example, consider a system using wind turbines with a rated capacity of 100 MW_e (megawatts of electrical power). At the aforementioned mean capacity factor of 22%, this would produce 22 MW_e. But not quite all this 22 MW_e could be utilized, because those running the system would need to have some warning of what to expect from the wind system, within the next few hours, to allow time to adjust the output from the time-independent (biomass) power plants.

Some clues on the importance of this short term variability came from an article by science editor, Peter Bunyard, in *The Ecologist*, April 2002, pages 51-53. He told us that, in 2001, the UK energy department produced a new energy trading arrangement (NETA). This demands that the wind power generator should predict, four and a half hours in advance, the exact amount of electricity that is to be produced. Financial penalties apply for getting the figure wrong. We have a clear indication of how difficult the wind power operators found it to make predictions four and a half hours in advance, because output to the distributors fell by 14% as a direct consequence of NETA. We can thus expect that of the 22 MW_e which the wind turbines would generate, 14% would be lost due to the unpredictable nature of the supply. This reduces the usable power output to **18.9** MW_e.

The biomass-fired power plants would make up the difference, in order to satisfy consumer demand. But where should we set the limit of demand that the composite system should cover? Over a fairly extensive system of wind turbines, it is unlikely that all of them will, at the same time, be running close to their full rated output. Thus, trying not to overstate the problems for wind, we might assume that the *maximum* output from the entire turbine system would be only 80% of the rated capacity of the wind section. Later we will consider the effects of varying this assumption.

So we need to design a composite system which will deliver 80 MW_e. On occasions this might be delivered entirely by the wind turbines, and on other occasions by a time-independent back-up system (biomass being the only plausible renewable energy source).

As with any conventional power station, the electricity which is actually delivered from the system is never the full capacity of the system, because of the variability of consumer demand. A coal-fired power station operates in the region of 60% capacity. Thus even though, as explained, the system would be capable of developing 80 MW_e to satisfy peak demand, over the year we would expect this mooted composite system to actually deliver about 0.60 x 80 = **48** MW_e. Since the wind would deliver a usable 18.9 MW_e, this leaves 29.1 MWe to be supplied by the biomass-fired power plant. Using 33%

as the conversion efficiency, heat to electricity, this would require 29.1 / 0.33 = **88** MW_{th} of biomass energy.

It is generally agreed that a sustainable yield of biomass, over large areas, averages 3 dry t/ha/yr, which approximates to 60 GJ/ha/yr, or 2 kW_{th}/ha. This means that supplying the 88 MW_{th} would require **44,000** hectares.[1]

Because wind turbines, including the required access roads, actually occupy only a small area (about 2-5% of the area over which the turbines are deployed), their energy-capture is high. In terms of primary energy equivalent, 1100 kWth/ha is a sound estimate. Additionally, a proportion of the wind turbines would be situated off-shore, or on land that was not biologically productive. Thus — accurately enough for our purposes — we may put the energy-capture of wind turbines as high as 3000 kWth/ha of productive land required. This means that the wind turbines would *monopolize* **19** hectares of productive land.[2]

We now have the data to calculate the energy-capture of the composite system. In primary energy terms, the total power output of 48 MW_e is 145 MW_{th}.[3] Dividing this by the biologically productive land required, 44,019 ha, gives an energy-capture of 3.30 kW_{th}/ha.[4]

It is evident why we did not need to be too careful with our estimate of the energy-capture of wind itself: had we guesstimated 4000 kW_{th}/ha, instead of 3000, 14 hectares would have been required for the turbines instead of 19 — with a negligible overall effect.[5]

Since this 3.30 kW/ha is only marginally above the 3 kW/ha assumed for eco-footprinting (OPT 2/2, October, p. 2), it is going to have only a small effect on raising the mean up to 3 kW/ha, from the 1.5 kW_{th}/ha which is the rough estimate of the energy-capture available from biomass (some of which needs to be used to produce energy in liquid form, as explained on page 17 of the *OPT Journal*, October 2002). Later we will see exactly how much effect the composite wind system has on mean net energy-capture.

Generalising the analysis

Having followed through the example of a wind system rated at 100 MW_e, which contributes, on average, 22 MW_e, when integrated into a composite system that is capable of delivering 80 MW_e, we can set the matter out in general terms, relating everything to the output of the turbines, which we might designate 'T' (with a value of 22 MW_e in this example).

The rated capacity of the turbines would, of course, be 1 / 0.22 = 4.55 times T. The composite system should be designed for a peak production of 3.64 times T. With our assumption of operation at 60% capacity factor, the composite system would *actually produce* 2.18 times T. Since 86% of the output T is usable, the wind turbines *usefully* supply 0.86 times T. This leaves the biomass component to supply 1.32 times T.[6] Those factors can, of course, be checked in the previous example by using them to multiply the assumed value of T, 22 $_{Mwe}$.

The situation in the United States of America

It will be recalled (*OPT Journal*, October 2002, p. 17) that the chief limitation on wind power in the U.S. was that if the full wind potential were to be exploited, producing 777 billion kWh/yr, this would still only replace 8% of U.S. primary energy demand (or more like 6.5% if allowance is made for inputs). We can now alter that picture to contemplate a composite system able to accommodate variations in consumer demand.

777 billion kWh_e/yr, or 89 million kW_e, is the output from the turbines. The amount that a composite system would produce, that is one properly integrated with this turbine output, is 2.18 x 89 = 194 million kW_e. At our calculated 3.3 kW/ha, the ecologically productive land required for this composite system would be (194 / 0.33) / 3.3 = 180 Mha.[7]

180 Mha is hardly feasible, since the U.S. has, depending on definition, 500 - 740 Mha of biologically productive land, a large proportion of which is in use. Moreover, in a renewable energy situation a lot of land would be required to supply biomass for direct heating.

Of equal note is the fact that the *amount* of energy captured by the composite wind/biomass system that we are envisaging is not going to contribute *a large part* of the total energy demand. To put figures on it, the composite system would produce 2.18 x 89 million kW_e = 194 million kW_e. That is about 50% of the total electricity consumed in the United States.[8] While 50% of electricity may seem encouraging, the energy captured is not large within the overall picture of energy demand. Converted to primary energy terms, the 194 million kW_e represents about 18% of the total energy used in the U.S.. Rate of energy growth in the U.S. exceeds population growth, *but even ignoring that fact*, 16 years of population growth would suffice to cancel out the huge effort of deploying about 400,000 1 MW turbines, building 3,200 biomass-fired power plants each with a capacity of 100 MW, and using 180 Mha of land to supply them. Since the total cost of building the composite system would be in the region of 700 billion dollars, it must be doubtful if it would be completed before being overtaken by population growth.[9]

The implications of the preceding paragraph are so stark that it is only incidental to the analysis — but nevertheless we should not lose sight of the fact — that a substantial part, perhaps a fifth, of the output of the turbines would be needed as input to build and maintain them. One of the problems of developing a large wind system is that, for many years, the input is greater than the output.

Thus a *composite system based on wind power* is only going to contribute 18%, at most, to the whole of U.S. energy demand; and its output seems unlikely to keep pace with 16 years of population growth. Moreover, there is little else, amongst renewables, of sufficient magnitude, and with a high enough energy-capture, to make a significant contribution.

As has already been observed (see page 17 of the October 2002 *OPT Journal*), the mean energy-capture that can be achieved when providing heat and liquid fuels, from renewable sources, is unlikely to exceed 1.5 kWh. Now we can take a representative sample of the whole energy supply, this time of say 1000 kWth. Of this, let us *hope* (for we have ignored the inputs) that 18%, 180 kW_{th}, would come from wind/biomass. It would require 180 / 3.3 = 54.5 ha, while the remaining 82%, 820 kW, would require 820 / 1.5 = 546.7 ha. Thus, overall, energy-capture would be 1000 / 601 = **1.66** kW/ha. In other words, our wind/biomass energy system would have raised the mean energy-capture figure, from 1.5 kW/ha, by only 0.16 kW/ha.

This result makes it clear why, in order to reach eco-footprinting's assumed energy/land ratio of 3 kW/ha, it will probably be necessary to assume *some* input from fossil fuels (probably mainly coal), with perhaps some contribution from tar sands and shale. It is only on that basis, that the 3 kW/ha figure can be honestly defended as coming within a description of being 'not excessively optimistic'.

Sensitivity to varying the parameters

There is room for doubting some of the parameters used above. Let us vary them slightly to see how sensitive the final result is to such variation. Suppose that the U.S. mean capacity factor were to be 25% instead of 22%. This would raise the composite energy-capture from 3.3 kW/ha to **3.6** kW/ha. Suppose *additionally* that instead of 14% of the output of the turbines being lost due to short term variability, that figure could be reduced to 7%. That would raise the composite energy-capture to **3.9** kW/ha. Suppose, *additionally,* that the wind turbine system never produces more than 70% of its rated capacity, so that we only need a composite system capable of producing 70% of the rated capacity of the wind turbines, instead of 80%. This would raise the composite energy-capture to **4.5** kW/ha.[10] Keeping to our approximation that the composite system would produce about 18% of total energy, this 4.5 kW/ha would raise the mean energy-capture from 1.5 kW/ha to **1.70** kW/ha — a hardly significant improvement over the previous figure of **1.66** kW/ha. In conclusion, the result is not sensitive to reasonable changes in the parameters.

A lesson from a wind project in northern Britain.

Peter Bunyard mentioned plans for the "world's largest wind farm, with a capacity of 600 MW, on the Isle of Lewis," adding that this "one project alone would meet nearly 0.5 per cent of the UK's electricity needs." The figure seems encouraging, perhaps suggesting the thought that were this project to be repeated 20 times, it would provide 10% of the UK's electricity needs. However, from our previous considerations, this amount of energy from wind turbines would require a composite system which would actually deliver 2.18 x 10% = 22% of the UK electricity. The total area of biologically productive land needed to produce that amount (satisfying consumer demand as required) would be 6.7 million hectares.[11]

That area constitutes 33% of the UK's biologically productive land, and is a ludicrous figure in the context of the UK's present population and its wood production.[12] Although the UK is gradually increasing the amount of timber grown at home, a peak is expected around 2025. By that time, the UK will be producing a *third* to a *half* of its present wood consumption; moreover UK citizens are not presently burning much wood for heating — they are merely using it for products of various kinds.

On page 103 of *Tomorrow's World*,[13] Duncan McLaren and his co-authors said that 190 billion kWh/yr was their "optimistic" estimate for electricity from wind power in the UK by 2050. Perhaps it would be wise to apply a reality check to that figure before considering the land implications, in the context of a fossil-fuel-free society.

The UK has a land area which is 2.6% of that of the United States. The American Wind Energy Association estimate a potential wind output of 675 billion kWh/yr for onshore turbines. Thus on the basis of land area, the UK might get 18 billion kWh/yr. High in thrall to optimism, we can pass over the fact that difficulties may arise from the UK being far more built-up than the US.

Off-shore is more difficult, but the UK has a coastline of roughly 2000 km compared to 6000 km for the US. On that basis, the UK should, pro-rata, be able to get a third of the estimated offshore potential of 102 billion kWh/yr of the US. That makes a total of 52 billion. Thus, leaving a margin for error, 65 billion kWh/yr would seem a better figure, in order to keep optimism within bounds! So how much land would be needed to supply 65 billion kWh/yr from wind/biomass? 65 billion kWh/yr is 22% of the UK's electrical supply, and we have already seen that that would require 33% of the UK's ecologically productive land.

Implications

Drawing data from a wider canvas than this paper, we should note that the *really intractable* problem of renewables lies in changing current sunshine into '*liquid* sunshine'. Despite the problems demonstrated here, producing electricity is the *easier* task. The USA and the UK serve as examples from which the following general conclusions can be drawn. It is hard to capture 'current sunlight' in quantities which — in relation to the amounts of energy used by modern civilization — are significant. Thus the present human population of six billion has to be seen as a temporary bubble, made possible by relatively easily access — over the past century or so — to 'ancient sunlight'. So what can be done?

It would be unreasonable to anticipate that all nations will become aware of what the future holds soon enough to take appropriate action. It is, however, possible that some might both see and act. Europe's indigenous population would contract without net immigration.[14] In the United States, about seventy percent of the population expansion is the result of net immigration. With balanced migration, and a small change in popular mood, the US could achieve the same downward trend in population that Europe would be able to achieve with balanced migration. Thus both Europe and America *could*, by taking appropriate action, go some way toward getting their populations in line with sustainable use of biocapacity.

It is hard to exaggerate the importance of getting this message across, especially in view of the almost boundless optimism about renewable energy which emanates from various environmental 'experts', who almost unanimously present wind energy as a sovereign remedy for an energy-hungry world. The truth is, whether we look at wind alone or the whole scene of renewable energy, fulfilment of our hopes for a tolerable future for the human race must depend upon achieving a smaller population.

WHY NOT JOIN OPT NOW
Tel: 07976-370 221

Optimum Population Trust Ltd
(Membership Secretary)
12 Meadowgate, Urmston
Manchester M41 9LB, UK

E-mail: info@optimumpopulation.org

Endnotes

1. 29.08 MW$_e$ = 29.08 / 0.33 = 88.12 MW$_{th}$.

2. 18.92 MW$_e$ = 18,920 / 0.33 = 57,333 kW$_{th}$.
   At 3000 kW$_{th}$/ha this requires 57,333 / 3000 = 19.11 ha.

3. 48,000 kW$_e$ = 48,000 / 0.33 = 145,455 kW$_{th}$. (Note that, for general statistics, the output of hydro and nuclear plants is expressed as the amount of primary energy that would be required, used in conventional power plants, to generate the output of hydro and nuclear plants).

4. Composite energy-capture 145,455 kW$_{th}$ / (44,060 + 19) = 3.2999 kW$_{th}$/ha.

5. At 4000 kW$_{th}$/ha, land monopolized by turbines would be 57,333 / 4000 = 14.33 ha.

6. Let Raw turbine output be T (i.e. amount actually generated).
   With a 22% capacity factor, the rated capacity of the turbines would be (1 / 0.22) T = **4.545** T. The composite system would be designed for a peak production of 80% of this, i.e.(1 / 0.22) x 0.80 T = **3.636** T.
   Operating at 60% capacity factor, the system would actually produce 3.636 x 0.60 T = **2.182** T.
   With 14% of output wasted, due to short term variability, usable output from turbines = T x 0.86. Since the wind turbines supply 0.86 T, biomass supplies 2.182 - 0.86 = **1.322** T.

7. 777 x 10^9 kWh$_e$/yr = 777 x 10^9 / (24 x 365) = 88.70 x 10^6 kW$_e$.

   ± Using the parameter 2.182 of previous endnote:
   The amount of electrical power produced by a composite system able to handle this output from the turbines, would be 2.182 x 88.70 x 10^6 kW$_e$ = 193.54 x 10^6 kW$_e$.
   The thermal equivalent of this is **193.54** x 10^6 / 0.33 = 586.49 x 10^6 kW$_e$.
   At 3.30 kW$_{th}$/ha the ecologically productive land needed is 586.49 x 10^6 / 3.30 = **177.7** x 10^6 ha. Slightly more long-winded, but perhaps more transparent, is to calculate the areas individually. The output of 777 x 10^9 kWh$_e$/yr = 777 x 10^9 / (24 x 365) = 88.70 x 10^6 kW$_e$ = 88.70 / 0.33 = 268.78 x 10^6 kW$_{th}$.
   At 3000 kW$_{th}$/ha, this requires 268.78 x 10^6 / 3000 = 89,595 ha = 0.09 Mha.

   ± Using the parameter **1.3218** of previous endnote:
   The biomass output supply required would be 1.3218 x 88.70 x 10^6 kW$_e$ = 117.24 x 10^6 kW$_e$. The thermal equivalent of 117.24 x 106 kW$_e$ = 117.24 x 106 / 0.33 = 355.28 x 106 kW$_{th}$.
   At 2 kW$_{th}$/ha, this requires 355.28 x 10^6 / 2 = 177.64 x 10^6 ha.
   Thus the composite area of ecologically productive land required = 177.64 x 10^6 + 0.09 x 10^6 = 177.7 Mha

8. In the year 2000, US electricity consumption was about 3.5 x 10^{12} kWh$_e$/yr.
   194 x 10^6 kW$_e$ = 194 x 10^6 x (24 x 365) = 1.70 x 10^{12} kWh$_e$/yr.
   This is 1.70 / 3.5 = 49% of the total electricity supply.

9. With a 22% capacity factor, the rated capacity of the turbines would be (1 / 0.22) T = 4.545 T; so the rated capacity of a system capable of producing 777 x 10^9 kWh/yr is:
   (777 x 10^9 x 1000 / (24 x 365)) x 4.545 = **403.1** x 10^9 W (or 403,100 turbines each of 1 MW).
   The capital cost of turbines is about US$1 per watt of rated output, so cost would be $403 billion. The composite system would be designed for a peak production of 80% of the rated power of the turbines, that is **3.636** T (see endnote 6.).
   Since the backup must at times produce nearly all the power, the backup must be able to provide:
   (777 x 10^9 x 1000 / (24 x 365)) x 3.636 = **322.5** x 10^9 W (this checks since 322.5 is 80% of 403.1).
   The capital cost of a conventional power plant is again about US$1 per watt of rated output, so cost would be 322 billion dollars. (Note that 100 MW would be fairly large for a biomass powered plant, and 322,000 MW would probably indicate 3220 plants each of 100 MW capacity).
   Thus total cost of the composite system would be 403 + 322 = 725 billion US dollars.
   That the output is about 18% of current U.S. total energy use is estimated as follows:
   In 2000, U.S. energy use (estimated from 1995 data) = 93.97 [quads] x 1.0112^5 = 99 quads = 99 x 1.055 x 10^{18} = 104.8 x 10^{18} J, or 104.8 EJ.
   Primary energy required to generate 193.54 x 10^6 kW_e (see endnote 6.) = 193.54 x 10^6 x (24 x 365) / 0.33 = 5.138 x 10^{12} kWh_{th} = 5.138 x 10^{12} x 3.6 x 10^6 = 18.5 x 10^{18} J or 18.5 EJ.
   So wind could replace 18.5 / 104.8 = 17.7% (say 18%) of the total energy use.
   The DOE reported a nearly 40% increase in energy between 1970 and 2000, making an annual growth rate of 1.127%, say 1.12%
   However, ignoring that, growth of population alone, at the rate of the three closing decades of the last century, 1.06% per year, would increase demand over 16 years by 1.0106^{16} -1 = 18.4%

10. As well as the calculations shown above, the logic was followed through on a spreadsheet, thus making it easy to vary the parameters.

11. Using the parameter **2.182** (see endnote 6.), the composite system which would make use of this raw output of 10% of UK electricity from wind turbines would be a system which would actually deliver 2.182 x 10% = 21.8% of UK electricity.
    UK's electrical consumption is about 295 billion kWh/yr.
    21.8% of this is 0.218 x 295 = 64.31 billion kWh/yr = 64.31 x 10^9 / (24 x 365) = 7.34 x 10^6 kW. The primary energy equivalent is 7.34 x 10^6 / 0.33 = 22.2 x 106 kW_{th}.
    Thus at 3.30 kW/ha, the biologically productive land required = 22.2 x 10^6 / 3.3 = 6.74 Mha.

12. According to the spreadsheet for *Ecological Footprints of Nations*, the UK has 20.3 Mha of ecologically productive land, thus 6.74 Mha is 6.74 / 20.3 = 33%.

13. McLaren, D., S. Bullock, Y. Nusrat. 1997. *Tomorrow's World*. London: Earthscan.

14. Data from PRB 2002 data sheet: whole of Europe, 7.26 M births, 8.15 M deaths per year.