

Note

A modern Danish 600 kW wind turbine will recover all the energy spent in its manufacture, maintenance, and scrapping within some three months of its commissioning.

Within its 20-year design lifetime a wind turbine will supply at least 80 times the energy spent in its manufacture, installation, operation, maintenance and scrapping.

The scrapping of a turbine requires energy. But recycling the metal parts will recover slightly more energy than what is required for the scrapping process.

This note contains new energy balances for the most modern coal-fired power stations which take due account of the energy used for transporting coal to the power plant.

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THE ENERGY BALANCE OF MODERN WIND TURBINES

This paper calculates the energy balance in the manufacture, operation, maintenance and scrapping of a typical modern wind turbine.

The *energy balance* is the ratio between the amount of energy used for manufacturing, operation, maintenance, repairs, and scrapping of a wind turbine – and the energy which the turbine will supply throughout its lifetime. Modern wind turbines have a design lifetime of 20 years.

The basic calculation method is input-output analysis using the energy matrices published by *Danmarks Statistik* (Danish Central Bureau of Statistics).

Danmarks Statistik publishes an annual report of sources and uses of 25 different energy goods and their flow through 117 industrial sectors.

In addition to its own use of energy each sector needs supplies of goods and services manufactured in other sectors which in turn use energy and supplies of goods and services from other sectors.

It is possible to calculate *direct and indirect use of energy* for each and every sector in the chain of production which ends up in the final output of the sector we are investigating.

If we make the assumption that deliveries from foreign countries on average are manufactured using the same amount of energy as deliveries

from domestic (Danish) suppliers one may calculate *the global direct and indirect use of energy* in the production process. We shall be using this concept to estimate the use of energy in wind turbine manufacturing.

The precision in the calculations in this paper is not as large as the number of significant digits would seem to imply. However, one may safely use *the tendencies and orders of magnitude* in the results.

The method being used is roughly the same as the one used in a three year older study from Risø National Laboratory, although the present calculations have been performed using much more disaggregated and newer data.

In addition, this note also calculates the energy balance in the scrapping of wind turbines.

One of the results is, that the energy balance in the scrapping-recycling process is *positive*, since a substantial amount of energy from the original manufacture of metal components may be recovered in the subsequent manufacture of metals.

The data in this paper is consistent with the publications from the Danish Energy Agency, the publications from Risø National Laboratory, and the publication *Employment in the Windpower Industry*, *WindPower Note no. 1*, published in March 1996 by the Danish Wind Turbine Manufacturers Association.

1 BASIC ASSUMPTIONS

1.1 Global direct and Indirect Use of Energy

This report estimates *the global direct and indirect use of energy* in the manufacture, installation, operation, maintenance and scrapping of a wind turbine, i.e. the energy which directly and indirectly has been used domestically or abroad throughout the life cycle of a wind turbine.

1.2 The Components of a Wind Turbine

The basis for the calculations is a modern Danish 600 kW wind turbine manufactured in 1995. The cost of the components of the turbine and the costs due to the installation of the turbine have already been published in *Employment in the Wind Power Industry, WindPower Note no. 1*, published in March 1996 by the Danish Wind Turbine Manufacturers Association.

1.3 Turbine Installation

The calculations also account for the installation of the turbine.

The basis for cost calculations is the cost of wind turbine installation for private individuals as analysed in *Rapport om privatejede vindmøllers økonomi*, Energistyrelsen (Danish Energy Agency), January 1994.

Power companies may have somewhat lower costs than those indicated here since they usually place turbines in wind parks.

These calculations only account for grid reinforcement costs to the extent that they include the transformer which is needed to connect the turbine to the high voltage grid (usually at the 10-20 kV level).¹⁾

This assumption has been made even if the power companies may need to extend the high voltage grid in order to accommodate another wind turbine. The reason for this assumption is that the power companies may reuse the reinforced grid to serve future customers and/or handle an increase in electricity demand. Furthermore, the cost of grid reinforcement is usually relatively modest, probably about 5 to 6 per cent of installation costs, and the net result on the calculations will be in the order of magnitude of 2 to 3 per cent. Finally, when comparing

with conventional electricity generation, we have not included the cost of the high voltage grid when calculating energy use in that connection.

1.4 Turbine Operation

Annual costs of operation and maintenance are assumed to be at the level of 3 per cent of the price of the turbine. This corresponds to historical Danish experience cf. *Redegørelse om den teknisk-økonomiske udvikling på vindmølleområdet, Status primo 1993* published by Risø National Laboratory.

The assumption is probably outdated for the largest wind turbines today. A figure of some 1.5 - 2.5 per cent would appear more reasonable since larger turbines should imply lower maintenance cost per kW installed power, in any case. The basic reason is, that some costs and the corresponding energy use (for transportation, oil replacement etc.) would appear to be relatively independent of the machine size.

1.5 Scrapping of a Turbine

Wind turbines can often be made to work somewhat longer than their design lifetime by a major overhaul, e.g. replacing the gear box or other major components like the generator. In addition there is a market for used turbines in developing countries.

In this paper, however, we assume that wind turbines have a lifetime of 20 years corresponding to the design lifetime, and that the foundations are not reused for another wind turbine.

The energy balance may therefore be slightly better than indicated in this report.

In connection with the scrapping of the turbine we assume that all components except for the transformer are destroyed and that the material is not reused but only recycled to the extent that this is economical.

2 ENERGY USE IN THE MANUFACTURE AND INSTALLATION OF A 600 kW WIND TURBINE

2.1 Gross Value Added for a Wind Turbine

The domestic market price of a 600 kW Danish

1) Any high voltage grid has a limited transmission capacity. This is both a question of the amount of electrical power it can transmit (thermal limit), and a question of the *power quality* (voltage and power stability) which is acceptable. *Grid reinforcement* is the upgrading of the grid which may be necessitated by the addition of another wind turbine (or electricity consumer) to the grid.

wind turbine was on average 3.0 million DKK (excluding VAT) at the end of 1995.

The estimated ex factory value of the different components of a wind turbine are given in table 1, while table 2 shows the installation cost. Table 3 gives the cost of operation and maintenance of the turbine.

2.3 Energy Multipliers

Danmarks Statistik (The Danish Central Bureau of Statistics) publishes so-called *energy multipliers* each year for each of the 117 sectors of the Danish economy. These multipliers indicate the average direct and indirect global use of energy per 1 million DKK of gross value added.

Energy consumption is registered as its *gross value*, i.e. for electricity, district central heating, and gas works gas, the total amount of fuel which has been used to manufacture the energy in question is registered. (In electricity production only part of the energy use is transformed into electricity, the rest of the energy is wasted through heating cooling water, through losses in the electrical grid etc.).

Energy consumption per million DKK is shown in table 1 to 3 in Terajoule per million DKK gross value added in the years 1987 and 1991 in 1987 and 1991-prices respectively.²⁾

The figures in the last row of the table have been computed weighing the multipliers with the percentage weights given in column 2 of the table.

It is obvious that there is some uncertainty in both the calculation of the energy multipliers

and the implicit assumption that the energy use in the production of wind turbine components corresponds to the average energy use per million DKK of gross value added.

However, this method has many important advantages compared to engineering calculations of energy use in the manufacture of different products.

Firstly, the input-output method accounts in great detail for the energy use in subcomponents and raw materials. Secondly, the tables have been constructed to ensure that the sum of energy use per sector and in total corresponds exactly to deliveries from other sectors. We are therefore on much firmer ground than if we had applied various engineering methods.

The substantial amount of detail in the 117 subsectors of the economy furthermore enables us to make calculations on the basis of individual components of the turbines.

The advantage of this method is that we eliminate several potential sources of bias if wind turbine components differ from the average in the fabricated metals sector. Potential errors at the detailed sectorial level would tend to cancel out, in any case.

Consequently, there is good reason to give a substantial amount of credibility to the *totals* rather than the subtotals for individual components, as economists familiar with input-output analysis will be aware.

2.4 Forecasting Energy Multipliers to 1995

Detailed sectorial tables of energy multipliers are published by *Danmarks Statistik* with a delay of 4

Table 1. Direct and Indirect Global Gross Energy Use Manufacturing a Danish 600 kW Wind Turbine in 1995

GDP at factor cost, Share of turbine value per cent	No.	Component Manufactured in sector <i>Manufacture of...</i> 1995 mill. DKK	Global direct & indirect gross energy multiplier			Global dir. & indir. gross energy use per turbine TJ	
			1987	1991	1995*)		
Generator	4	38398 Other electrical supplies	0.120	0.91	0.70	0.54	0.065
Gearbox	12	38238 Industrial machinery	0.360	0.96	0.73	0.56	0.202
Rotor (blades)	18	35600 Plastic products n.e.c.**)	0.540	1.44	1.07	0.80	0.432
Tower	18	38138 Structural metal prod.	0.540	1.35	1.00	0.74	0.400
Brakes, hydraulics	1.5	38238 Industrial machinery	0.045	0.96	0.73	0.56	0.025
Electronic controller	4	38320 Telecom equipment	0.120	0.82	0.65	0.52	0.062
Nacelle (remainder)	42.5	28238 Industrial machinery	1.275	0.96	0.73	0.56	0.714
I alt	100.0	3.000	1.11	0.84	0.63	0.63	1.900

*) Computed values cf. section 2.4.

**) In the publication *Employment in the Wind Power Industry, WindPower Note No. 1*, this sector has been classified as *Construction Industry*, since the manufacturing process is relatively labour intensive. Considering the use of energy, it is more appropriate to use the present classification, *Manufacture of plastic products n.e.c.*

2) 1 Joule = 1 Watt second. 1 Terajoule (TJ) = 10¹² Joule. 1 Gigajoule (GJ) = 10⁹ Joule. 1 Megajoule (MJ) = 10⁶ Joule.

years. If we were to use the energy multipliers directly, our calculations would show the energy use producing a wind turbine using 1987- and 1991-technology (and 1987 and 1991 prices).

The multipliers consequently have to be updated to 1995 to be applicable to the gross value added figures, which obviously are given at a 1995 price level. Furthermore, we have to account for the fact that energy efficiency in production has been increasing over time.

Thus, we have chosen to forecast the multipliers from 1991 to 1995 using the same annual growth rate as during the period 1987 to 1991, i.e. the previous four-year period.

2.5 Gross Energy Use per Wind Turbine

The last column in tables 1 through 3 show the total energy consumption in the manufacture, installation and operation and maintenance of a 600 kW wind turbine. The figure is the product of the costs and the relevant 1995 multiplier.

3 OPERATION AND MAINTENANCE OF A 600 kW WIND TURBINE

Operation and maintenance includes transportation, man-hours, oil etc., and spare parts. We have chosen the same method as Risø National Laboratory i.e. using the sector *automobile repair*

services when calculating the energy content in O&M, since that sector is as close as we can get at something resembling wind turbine service.

The method used to build the table is otherwise the same as the one used for table 1 and 2.

4 SCRAPPING OF A 600 kW WIND TURBINE

All Danish wind turbines of the 600 kW size have rotor blades made of glass fibre reinforced polyester (GRP) or epoxy. The towers are usually tubular steel towers. The foundations are armed concrete.

As an alternative to dumping the used rotor blades, the blades may be shredded and used in the manufacture of certain plastics or concrete. Alternatively, they may be incinerated at a high temperature. This note assumes that the incineration method is used, but the amount of energy thus recovered is very modest, in any case.

Concrete foundations may be fragmented and used in the manufacture of concrete or as land-fill. The amount of energy recovered in these processes is approximately zero.³⁾

Gear oil may be recycled or burned. This note assumes that it is burned.

The rest of the turbine consists of mostly steel, iron and copper which may be sorted, shredded,

Table 2. Direct and Indirect Global Gross Energy Use Installing a 600 kW Danish Wind Turbine in 1995

GDP at factor cost, Share of turbine value per cent	No.	Manufactured in sector	Component value Manufacture of... 1995 mill. DKK	Global direct & indirect gross energy multiplier			Global dir. & indir. gross energy use per turbine TJ	
				1987	1991	1995*)		
Developer & legal costs	1.9	83509	Business services	0.057	0.55	0.44	0.35	0.020
Foundations	4.5	50000	Construction	0.135	1.04	0.89	0.76	0.103
Electricity installation	1.9	50000	Construction	0.057	1.04	0.89	0.76	0.043
Connect., kiosk, cable	10.9	50000	Construction	0.327	1.04	0.89	0.76	0.249
Transformer	2.6	38398	Other electrical supplies	0.078	0.91	0.70	0.54	0.042
Remote surveillance	0.6	38320	Telecom equipment	0.018	0.73	0.61	0.51	0.009
Road construction	1.3	50000	Construction	0.039	1.04	0.89	0.76	0.030
Total	23.7		0.711		0.98	0.82	0.70	0.495

*) Calculated values, cf. section 2.4.

Table 3. Direct and Indirect Global Gross Energy Use during 20 years of operation and maintenance 600 kW Danish Wind Turbine in 1995 prices

GDP at factor cost, Share of turbine value per cent	No.	Manufactured in sector	Component value Repair of... 1995 mill. DKK	Global direct & indirect gross energy multiplier			Global dir. & indir. gross energy use per turbine TJ	
				1987	1991	1995*)		
Oper. & Maintenance	60	95130	Motor vehicles	1.800	0.66	0.53	0.43	0.774
Total	60		1.800		0.66	0.53	0.43	0.774

*) Calculated values, cf. section 2.4.

Table 4. Energy Use in Scrapping a 600 kW Danish Wind Turbine

Process	Gross energy use total		Source
	kWh	TJ	
Disassembly, crane, 8.5 t fuel	100 000	0.360	<i>Kehrbaum</i>
Cutting, fragmentation, pyrolytic treatment	20 000	0.072	<i>Kehrbaum</i>
Truck transport 25 000 tonne kilometer	25 000	0.090	<i>Kehrbaum</i>
Total	145 000	0.522	

Sources for energy data, see note 3.

Table 5. Recovered Energy from the Scrapping of a 600 kW Danish Wind Turbine

Material	Saved gross		Saved gross energy total		Source
	Weight energy per kg		kWh	TJ	
	kg	kWh/kg			
Steel	57 000	2 205	125 685	0.452	<i>Stålvalseværket</i>
Copper ⁴⁾	3 000	7.0	21 000	0.076	<i>Niels F. Gram</i>
Aluminium	300	75.0	22 500	0.081	<i>Dansk Metallurgisk Selskab</i>
Reinforced polyester/epoxy	4 500	4.5	20 250	0.073	<i>Kehrbaum</i>
Gear oil	200	12.0	2 400	0.009	<i>Kehrbaum</i>
Transformer *)	11 667	0.042	
Total	65 000		203 502	0.733	

Sources for energy data, see note 3.

*) The transformer is considered 100% recovered, since its lifetime is substantially longer than that of the turbine, probably around 50 years.

refined and recycled. The scrap value of the metal is approximately 50 000 DKK. (More than 75 per cent by value is copper).

During the past ten years the weight of Danish wind turbines per kW nameplate electrical power has been halved. That obviously contributes significantly to energy balance improvement. Danish 600 kW wind turbines on average weigh approximately 60 metric tonnes plus 4.5 tonnes weight for the rotor blades.

A comparable German 600 kW Tacke turbine weighs some 90 tonnes plus 4.5 tonnes of rotor blades. If we account for differences in tower height, and look at turbines with 50 metre tower height only, it would appear that Danish turbines weigh one third less than the German turbine.

4.1 Energy Use for the Scrapping Process

Dismantling and shredding/fragmenting wind turbine parts and transporting them to their final processing location requires energy.

We have not used input-output analysis for this particular calculation, since these very

specific processes are not adequately covered by any particular sector in the available tables.

We have therefore used an engineering calculation which deliberately has added some extra energy use to account for indirect energy use in this process.

Table 4 shows the energy use for dismantling, shredding, fragmenting, and transportation of a disused wind turbine.

4.2 Recovered Energy from the Scrapping Process

Recoverable energy from the scrapping of a Danish 600 kW turbine has been accounted for in table 5.

A substantial amount of process energy is saved through the recycling of steel, copper, and aluminium scrap metal if one compares with average energy use in the iron and metals processing sector.

Copper and aluminium are assumed to be recycled, but not refined to the same uses as was formerly the case (that would be uneconomic at present prices). In the case of aluminium 95 per cent of the energy can be recovered. Roughly the

3) Energy data in table 4 is from *Kehrbaum*. Table 5 uses a number of other sources, since our calculations show that *Kehrbaum*'s figures for steel and copper are too high. An interview with *Eyvind Rasmussen*, *Stålvalseværket* in Frederiksværk, Denmark, shows that the primary energy use recycling iron and steel scrap metal is 1 750 kWh/t against 3 955 kWh/t spent in the reduction of iron ore in a classical smelter. Strictly speaking, we ought to account for the share of metal normally recycled in the metal industry. (In the case of copper the figure is rather high, about 30-40 per cent.) However, we have another bias in the opposite direction, since here we do not account for indirect energy use, as we do in the input-output calculations.

4) In table 4 the amount of copper has been reduced after a communication from *Kehrbaum*.

Tabel 6. Energy Use During the Life Cycle of a 600 kW Danish Wind Turbine

Gross energy use, total	
TJ	
Manufacture of wind turbine, cf. table 1	1.900
Installation of wind turbine cf. table 2	0.495
Operation and maintenance cf. table 3	0.774
Total excluding scrapping	3.169
Scrapping, energy use cf. table 4	0.522
Scrapping, recovered energy cf. table 5	- 0.733
Total including scrapping	2.958

same figure holds for the recycling of copper scrap metal.

Cf. table 1 and 2 manufacture and installation of a turbine required 2.395 TJ (Terajoule) of energy. Approximately 31 per cent, i.e. 0.773 TJ can be recovered as indicated in table 5.

5 THE ENERGY BALANCE FOR A 600 KW DANISH WIND TURBINE

Table 6 summarises the results of the calculations in the previous part of this paper. The table shows the total gross energy use. Logically, recovered energy is indicated as a negative figure.

The annual electricity output from a 600 kW wind turbine according to *Vindmølleoversigten, September 1995* amounts to 1.393 gigawatt hours (GWh) in roughness class 1 on average. Annual production in roughness class 2 is 1.130 GWh.

The annual electricity production is shown in tables 8 and 9.

The same tables indicate how energy usage (use of primary fuel) is required in a conventional power plant to produce the same amount of electricity as the turbine produces in one year.

It would require 11.14 TJ, and 9.04 TJ respectively if the same amount of electricity were to be produced at a coal fired power plant with a thermal efficiency of 45 per cent.⁵⁾ This assumption corresponds to the assumptions in the publication *Redegørelse om den teknisk-økonomiske udvikling på vindmølleområdet, Status primo 1993*, by Risø National Laboratory.

The most recent coal fired power plant from ELSAM (Western Danish utility group) which is under construction at present, however, will have a thermal efficiency of 47 per cent.⁶⁾

5) On average, the thermal efficiency of Danish power plant was 40.8 per cent in 1994, cf. *Dansk Elforsyning Statistik 1994* from Danske Elværkers Forening.

Risø's *Omkostningsopgørelse for miljøeksternaliteter i forbindelse med energiproduktion (1994)* using ELSAM as a source obtains a figure for coal consumption of 0.39 kg/kWh corresponding to a thermal efficiency of 36 per cent.

6) Interview with *Bjarne Røjkjær*, ELSAMPROJEKT.

5.1 Accounting for Fuel Transportation in the Total Fuel Cycle

The analysis from Risø only accounts for the thermal value of coal used in a coal fired power plant. The analysis ought to account for indirect use of fuel in the fuel cycle, however, if the figures are to be strictly comparable to the input-output calculations

In particular, we need to account for the energy use in mining, local freight to a port, and shipment by sea, since we assume that the coal fired power plant is located at the seashore.

Information for that purpose may be found in another Risø publication, *Omkostningsopgørelse for miljøeksternaliteter i forbindelse med energiproduktion (1994)*.

One should be aware of the fact, however, that Risø's calculations in that report only accounts for direct energy use in the processes. Indirect energy consumption as used in input-output analysis is not included.

The results will consequently be biased towards a low estimate for the marginal energy use in a coal-fired power plant.

Note, that we account only for the fuel-related part of energy use at the power plant (fuel costs account for less than half of the total cost of building and operating a coal fired power plant).

Table 7 indicates the direct energy use in transportation of coal to Denmark.

5.1.1 Coal Mining

Risø assumes that 60 per cent of Danish coal imports consist of surface mined coal, while the remainder comes from coal pits.

The energy use in the two processes is 275 and 360 MJ/tonne respectively. The weighted average thus amounts to 309 MJ/ton.

5.1.2 Local Coal Freight

The same source estimates that coal on average has to be shipped 700 km by diesel train to the coast for subsequent transportation by sea.

According to Risø's *Energiforbrug og emission ved godstransport i 1990* one tonne km by train requires 0.69 MJ of energy. Assuming that the train returns empty total energy consumption may be estimated as $0.69 \cdot 1.5 \cdot 700 = 725$ MJ/

Table 7. Energy use in coal transport

	Direct gross energy use GJ/t coal
Coal mining	0.309
Train transport to harbour	0.725
Loading and unloading	...
Sea transport	1.035
Unloading	...
Total direct energy use for transport	2.069
Steam coal thermal energy content	25.700
Added energy use for transportation = 8.05 pct. tonne of coal.	

5.1.3 Coal Freight by Ship

Risø's paper *Energiforbrug og emission ved gods-transport i 1990* estimates that a large bulk carrier of 172810 DWT on average requires 1.15 grammes of fuel oil/tonne/nautical mile.

In the paper *Omkostningsopgørelse for miljøkster-naliteter* sea transport is estimated to amount to two times 8,500 nautical miles. (Energy data assumes that the bulk carrier sails fully loaded and returns empty). On the other hand we do not account for indirect energy use or energy use for loading and unloading trains and ships.

Fuel oil has an energy content of 40.6 GJ/tonne⁶⁾, giving a total energy use for sea freight of $2 \cdot 8500 \cdot 0.0000015 \cdot 40.6 = 1.035$ GJ/tonne of coal.

5.1.4 Energy Use for Coal Fired Power Plant is more than 8 per cent above the Thermal Energy Content of Coal

Cf. table 7 we obtain a total direct energy use of $0.309 + 0.724 + 1.035 = 2.069$ GJ/tonne of coal.

The energy content of steam coal is 25.7 GJ/

tonne.⁶⁾

Direct energy use for coal transport thus increases energy use by approximately 8 per cent.

The figure does not include indirect energy use in the coal firing process, including transportation of ash, lime, or other products used for combustion or smoke scrubbing.

6 ENERGY PAYBACK PERIOD FOR WIND TURBINES

The most modern coal-fired power plant under construction in Denmark (built by the ELSAM utility) will have a thermal efficiency of 47 per cent.

The 47 per cent are calculated on the basis of *direct fuel consumption* only. Thus we have to adjust for at least the *direct* energy use in transporting the coal.

The efficiency adjusted for coal transport becomes $0.47 : 1.0805 = 43.5$ per cent.

Table 8 has been included in this paper to enable a direct comparison with Risø's analysis from the beginning of 1993 which does not take the scrapping of the wind turbine into account.

The energy used for the manufacturing process in this paper is some 20 per cent lower than in the Risø paper. Annual electricity output is 8.5 per cent higher than for Risø's 500 kW wind turbine.

The new results indicate that the energy payback period is some 33 per cent lower than in the previous Risø study. (Risø found a payback period of 0.42 years in roughness class 1, and 0.52 years in roughness class 2).

Table 8. Energy Balance for a 600 kW Danish Wind Turbine excl. scrapping

	Electricity production from wind turbine per year	Primary energy use in power plant	Energy for manufacture and operation	Energy recovered in
	mill. kWh	mill. kWh	TJ	years
Roughness class 1	1.393	3.202	11.528	0.28
Roughness class 2	1.130	2.598	9.352	0.34

Table 9. Energy Balance for a 600 kW Danish Wind Turbine incl. scrapping

	Electricity production from wind turbine per year	Primary energy use in power plant	Energy for manufacture and operation	Energy recovered in
	mill. kWh	mill. kWh	TJ	years
Roughness class 1	1.393	3.202	11.528	0.26
Roughness class 2	1.130	2.598	9.352	0.32

6) Energy contents taken from *Brændselsprisforudsætninger for samfundsøkonomiske beregninger*, Energistyrelsen februar 1994.

Fig. 1. Energy use recalculated to kWh electricity (net energy)

Figure 1. Energy use recalculated to kWh electricity (net energy use)

The net efficiency of the coal-fired power plant is slightly lower than in the Risø analysis, although we use a plant with a slightly higher thermal efficiency. The reason, of course, is that we at least account partially for transportation of the fuel.

Table 9 gives the final results of this analysis, including the energy scrap value of the wind turbine.

8 CONCLUSIONS

Comparing table 8 and 9 we find that the scrapping of the wind turbine gives a net energy gain amounting to an average week of electricity production from the wind turbine.

The calculations assume operation and maintenance costs of 3 per cent of the price of the turbine, which is probably a somewhat exaggerated figure. Consequently the energy use for the operation of the turbine is biased upwards.

Grid losses for wind turbines must on average be assumed to be somewhat lower than for central power plant, since wind turbines are typically dispersed in the grid (embedded generation). For central power plant the grid losses are typically in the order of magnitude of 6 to 9 per cent.

Lennart Söder estimates that the grid losses for wind turbines are about two percentage points lower than for central power plant. Thus, in addition to what we added for coal transportation, we could have added another 2 percentage points.

A wind turbine will typically recover the

energy spent in its manufacture, installation, operation, maintenance, and scrapping, some 80 times over.

The annual electricity production from a wind turbine is approximately proportional to the energy content of the wind, i.e. it varies with the third power of the average wind speed on the site.

In e.g. the Cap Verde Islands, Southern Argentina, or Southern China, wind speed are on average some 30 to 50 per cent above the figures known from Denmark.

In these areas wind turbines may recover the energy spent on their manufacture and operation in one month. The alternatives to wind energy in these areas will usually be diesel generators or coal fired power plant with far lower efficiency. (cf. note 4).

Even if a 65 tonne wind turbine has to be shipped 10 000 nautical miles, it will only affect its net energy use by 1.5 per cent, cf. section 5.1.3.

Since 1992 the energy balance for wind turbines has improved dramatically.

Comparing with the analysis from Risø National Laboratory, one should bear in mind that Risø has calculated with older 500 kW wind turbines, with an older production technology, and without accounting for scrapping or the energy use in the transportation of coal.

These differences explain the difference between the present results and the results from the 1993 study from Risø.

Søren Krohn

The Energy Balance of Offshore Wind Turbines

Energy 21

The Danish Government published its very ambitious long term energy plan, *Energy 21*, in 1996. This plan intends to limit Danish CO₂ emissions by 50 per cent before the year 2030 (compared to the base year 1988).

Most of Danish electricity is presently generated using fossil fuels, although increasingly in CHP plant (combined heat and power generation). Base power load is provided by large coal fired power stations, although natural gas has increasingly been used in smaller local power plant and also in certain large power stations.

Offshore Plans in Denmark

By the end of 1997 some 1 000 MW of onshore wind power is online in Denmark, covering some 7 per cent of total electricity consumption.

Two pilot offshore wind parks, Vindeby and Tunø Knob of 5 MW each have paved the way for large scale offshore wind power in Denmark.

The Danish Government currently plans to have 4 000 MW of wind power installed offshore before the year 2030, in addition to 1 500 MW onshore by the year 2005.

Presently 75 per cent of Danish wind power is owned by individuals or wind co-operatives, but it is expected that the major part of offshore development will be done by the power companies as a *public service obligation* to provide lower CO₂-emissions.

In 1996-1997 a number of feasibility studies for offshore wind turbines have been performed in Denmark by the Danish Energy Agency, the two large Danish utility groups, ELKRAFT and ELSAM, plus a number of consulting engineering firms.

The following sections summarise a number of modifications to the previous conclusions made on the basis of these reports published by the study groups (cf. the last two publications in the

references list).

Megawatt Wind Turbines

Naively, one might assume that the »Square cube law« applies to wind turbines, i.e. that if we double the rotor diameter we get four times as high an energy output, and that the weight of the turbine will increase by a factor eight, because we need to multiply all lengths by two in each of the three dimensions.

Whereas the square law roughly holds, the cube law does not. Technology development means that new turbines are comparatively lighter than their predecessors.

If we take a three bladed pitch controlled 1.65 MW Vestas wind turbine with a 66 metre rotor diameter as an example, we find that the weight of the turbine per installed kW of power is roughly the same as for a 600 kW machine.

Tower Height

Although the machine in our example is normally delivered with hub heights of 60, 67 or 78 metres, an offshore version would probably be fitted with a lower tower.

This is due to the fact that offshore wind turbines will be placed in an environment with a very smooth surface in *roughness class zero* (in European Wind Atlas terminology) i.e. a roughness length of some 0.0002 m.⁷⁾

This implies that *wind shear* will be slight, i.e. wind speeds will not increase very much with tower height, since the wind is not braked very much by the sea surface.

The Danish power companies at the time of writing estimate that the optimal tower height would be some 55 metres for a 1.5 MW turbine with a rotor diameter of 64 metres.

Adding another metre to the tower height would increase annual energy production by

7) You may wish to consult the European Wind Atlas for definitions, or look at the web site www.windpower.dk for further explanations.

8) Estimated by the author on the basis of information from Vestas Wind Systems A/S on the weight of towers for land-based machines.

about 0.5 per cent, and the cost of a taller tower, plus stronger foundations would increase costs by roughly the same percentage.

The total weight of the 1.65 MW turbine in our example with a 55 metre tower would be approximately 158 tonnes, as shown in table 10.

The plans made by the Danish power companies call for a design lifetime for towers of 50 years.

Rotor blades

Interestingly, the weight of the rotor blades is almost exactly proportional to the increase in nameplate power of the machine from 600 kW to 1.65 MW, i.e. an increase from 1.5 tonnes per blade to 4 tonnes per blade.

This is definitely not what one would have expected, since the strength of the blades have to vary with the cube of their length.

Foundation Costs

The new Danish studies on cost optimization of offshore wind turbine foundations has led to engineers abandoning concrete foundations in favour of steel foundations.

The first two Danish offshore wind parks off the coast of Vindeby, and at Tunø Knob had concrete caisson foundation built onshore, floated out to sea, and subsequently filled with sand and gravel (The same principle used for building bridges).

These so-called *gravitational foundations* were manageable for turbines of 450 and 500 kW, but foundations for 1.5 MW turbines would be extremely heavy and would thus require heavy

duty sea cranes, raising the cost considerably.

Eventually, the consulting engineering firms opted for three different designs which turned out to cost roughly the same, as shown in figure 2 below.

Figure 2 does not include the cost of a boat landing for each turbine, although the previous offshore wind farms at Vindeby and Tunø Knob included mooring facilities for boats.

The reason for omitting the costs of a boat landing is that the power companies are considering building special boats which can operate without a classical boat landing.

In case boat landings would be necessary in the final project, their cost would be approximately 250 000 DKK per turbine.

Otherwise, the foundation costs include surveying costs, drilling, preparation of the bottom, design, manufacture, installation and erosion protection.

Corrosion protection to ensure a design lifetime of 50 years will be accomplished electrically.

Mono pile Foundations

This type of foundation is essentially a steel pole which is rammed or drilled into the seabed. In locations with e.g. chalk or other stable seabed this may be a suitable solution. From figure 2 it appears that mono pile foundations are less cost effective at larger water depths, particularly in areas where pack ice may be a problem.

Gravitational Foundations

Basically they perform the same function as the

concrete caissons mentioned above, but made of a steel enclosure which is subsequently filled with a high-density mineral (Olivine).

Tripod Foundations

This solution is particularly suitable for larger water depths (and cannot be installed at lower water depths). The basic structure resembles a typical offshore oil rig. This type of foundation is most cost effective at larger water depths, particularly in areas without pack ice.

Weight of Different Foundation Types

To check on our previous results, tables 10 and 11 give the weights for the steel structures involved for the three technologies for two different locations in Danish sea territory.

Finally, table 12 summarises the weight for a wind turbine placed on an average Danish offshore location

Table 10. Estimated Weight of Steel Foundations for a 1.5 MW Turbine, Baltic Sea at Rødsand (Ice Loads Dimensioning Factor)

Water depth	5m	8m	11m
	Metric tonnes		
Mono pile	98	120	155
Gravitational	80	90	100
Tripod	...	106	119

Source: *Vindmøllefundamenter i havet, Slutrapport.*

Table 11. Estimated Weight of Steel Foundations for a 1.5 MW Turbine, North Sea at Horns Rev (Waves Dimensioning Factor)

Water depth	5m	8m	11m
	Metric tonnes		
Mono pile	103	117	131
Gravitational	90	100	110
Tripod	...	100	102

Source: *Vindmøllefundamenter i havet, Slutrapport.*

Table 12. Estimated Weight of a Danish 1.65 MW Offshore Wind Turbine

	Weight
	Metric tonnes
Tower (55 m hub height)	80
Nacelle	55
Rotor Blades	12
Hub, other rotor parts	+11
Total Wind Turbine	158
Foundation (average 8 m depth)	100
	258

Source: Calculations of the author based on data from Vestas Wind Systems A/S, and *Vindmøllefundamenter i havet, Slutrapport.*

Energy Output Offshore

The energy production from wind turbines located offshore will be significantly higher than from turbines onshore.

Wind measurements and calculations for the major sites indicate annual production figures shown in table 14 (on the basis of the 1.5 MW turbines mentioned in the earlier part of this section).

Table 14. Estimated Energy Output/Year and Investment

Location	Installed	Full load	Energy	Investment
	MW	hours/yr	TWh/yr	DKK/MW
Gedser Rev	150	3 287	0.493	12.4
Gedser Rødsand	600	3 330	1.998	11.5
Omø	300	3 014	0.904	11.0
Læsø	600	3 380	2.028	11.7
Horns Rev	600	3 530	2.118	11.7
Subtotal	2250	3 352	7.541	11.6
Remainder, Læsø	1750	3 380	5.915	11.7
Total	4000	3 364	13.456	11.6

Source: *Havmølle-handlingsplan for de danske farvande.*

In table 14 we have included the planned sites, and for this calculation example chosen the very spacious area south of the island of Læsø for the remaining part of the 4 000 MW of offshore wind power planned to be erected before 2030.

On typical onshore locations in Denmark, (roughness class 1.25) wind turbines register 2223 full load hours per year. (I.e. annual electricity production is equivalent to 2223 times the nameplate power of the wind turbine).

In offshore applications the figure in table 14 becomes 3364 full load hours per year on average, i.e. 51 per cent more than on land.

Even if we are not comparing identical machines onshore and offshore, it seems fairly safe to use this comparison with the degree of precision we are working with here. In any case, the figures are reasonably close to the manufacturers' specifications, if we recalculate them to a 55 metre hub height.

We have included the investment per MW for each site in the last column of table 14.

Calculation Method

For the wind turbine itself it seems safe to up-scale the results from the 600 kW turbine to in the first part of this paper to 1 500 kW, when we look at the weights involved.

The price of 1.5 MW turbine for offshore

applications is not known at the time of writing. Danish electrical power companies, however, believe that prices will be in the region of 9-9.5 million DKK (in 1997) for an order of 50 to 100 machines of 15 MW each.

In order to make a conservative estimate we use the low figure of 9 million DKK per machine, and let the rest of the cost be attributed to the foundation, which is more energy intensive than the turbine.

We also use the 1995 energy multipliers in table 15 below, which means that we get an upward bias in the energy content, since energy intensity per DKK tends to decline over time.

We assume a maintenance cost of 0.08 DKK/kWh in accordance with power company estimates. Annual energy production in kWh comes from table 14, i.e. 3 364 full load hours.

Finally, in table 16 we show the energy use for manufacturing, installing, and maintaining the turbine.

The method is exactly the same as in table 8.

Conclusions

Offshore turbines with a lifetime of 20 years will recover the energy spent in their manufacture, operation, and maintenance slightly quicker than onshore turbines in roughness class 1. (Danish conditions).

The difference is small, but we should also take into account, that the calculations on this page have a bias towards high energy use, as explained above.

An onshore wind turbine will recover the energy spent in its manufacture and maintenance some 80 times over throughout its 20 year design lifetime.

If we account for the fact that offshore wind turbines would have a longer lifetime of 25-30 years (due to less turbulence at sea, and thus lower fatigue loads), we find that an offshore wind turbine will recover the energy spent on it more than 100 times over.

Table 15. Direct and Indirect Global Gross Energy Use for 1.5 MW Offshore Wind Turbines

Process	value	Global direct and indirect gross energy multiplier 1995	Energy use
	mill. DKK	TJ/mill. DKK	TJ
Turbine manufacturing	9.0	0.63	5.67
Foundation + installation	2.6	0.74	1.92
Operation + maintenance for 20 years	8.1	0.43	3.47
Total	...	0.65	11.06

Table 16. Energy Use During the Life Cycle of a 1.5 MW offshore wind turbine

Electricity production for wind turbine per year	Primary energy use in power plant	Primary energy use in power plant	Energy for manufacture and operation	Energy recovery	Energy recovery	
mill. kWh	mill. kWh	TJ	TJ	years	months	
Total	5.046	11.600	41.76	11.06	0.26	3.2

The Energy Balance of Danish Vintage 1980 Wind Turbines

The Legend

It has been an extremely persistent legend in Denmark that wind turbines would never recover the energy spent in manufacturing them, let alone operating and maintaining them.

After the analysis in the main part of this paper has become widely known, the focus of the debate has shifted to acknowledging that modern wind turbines have a very favourable energy balance. On the other hand some people still claim that there was an enormous energy waste in manufacturing wind turbines in the 1980ies.

The remaining part of this paper sets out to investigate that claim, using the same methodology as in the first part of this paper.

1980 Technology compared to 1996

Energy & Environmental Data has been publishing statistics on Danish wind turbine performance since 1980. It has a sample of 27 machines installed during 1980 with a total nameplate power of 942 kW, i.e. with an average size of 34.9 kW.

The average energy yield per m² rotor area in 1980 (normalised to an average wind year) was 475 kWh/m² (compared to 1037 kWh/m² in 1996). The increase in yield per m² is thus some 118 per cent, corresponding to an annual growth rate of 5 per cent.

The huge difference in yields is not only due to better aerodynamics and higher efficiency in the turbine drive train: Typical tower heights have increased from 19 m to 46 m, explaining 25 percentage points of the increase.

Higher, (and indeed economic) towers are, of course, part of the technology, so this improvement should also be credited technology development.

The methodology for siting developed by Risø National Laboratory and others in the *European Wind Atlas Method* accounts for another substantial share of the improvement in the intervening period. Siting methodology should also be considered as a very important part of wind energy technology.

A typical machine in 1980 would be a Nord-

tank 55 kW machine with a rotor diameter of 11 m, and a hub height of 20 m

In table 1 we have selected three typical machines from each of the two major suppliers at the time (Vestas and Nordtank).

Wind Turbine Prices in 1980

The Danish Wind Turbine Owners' Association has been publishing semiannual price lists for wind turbines throughout the 1980ies and 1990ies.

The list from July 1980 has been used in table 1. To compare with present-day machines, the list price of a 600 kW machine with 43-44 m rotor diameter and a hub height of 50 m is between 2.8 and 3.2 million DKK in 1997.

Installation Costs

Risø National Laboratory has done a number of studies on the costs of wind energy in Denmark. Using their early reports, we obtain an installation cost of around 30 per cent of the turbine price.

Global Direct and Indirect Energy Content in Manufacturing and Installation

As we demonstrated in the conclusions of the first part of this paper, one may safely use the aggregate energy coefficients for the fabricated metal products sector when estimating the energy content of wind turbines.

Danmarks Statistiks input-output tables give a figure for global direct and indirect (primary) energy content in 1980 of 2.02 TJ/million DKK for manufacturing of fabricated metal products, and 1.98 TJ/million DKK for construction.

Using an average of 2 TJ/million DKK for the whole investment, we obtain a total global direct and indirect energy content per machine listed in gigajoule (and converted to kWh) in table 1.

Global Direct and Indirect Energy Content in Annual Operation and Maintenance

In 1996 annual operation and maintenance costs for wind turbines of the 10-30 kW size was 0.13 DKK/kWh (1996 prices) according to an analysis published in the October 1997 issue of *Naturlig*

Energi, published by the Danish Wind Turbine Owners' Association.

Risø National Laboratory reports on operation and maintenance costs indicate cost in the order of magnitude of 3-4 per cent of purchasing price per year.

The warranty period for the turbines in 1980 was generally 1 year. In the case of Nordtank, 2 years.

In the case of the 1980 Vestas machines, a two year service contract was included in the purchase price of the machines.

Annual Energy Yield

Using the officially published power curves, and a siting in roughness class 2, based on European Wind Atlas data for Beldringe, Denmark, we have computed the average annual production figures listed in table 1. (In cases where power curves did not cover wind speeds all the way to the cutout wind speed, we have assumed a constant output beyond the last reading).

(You may verify the production figures and check the power curves using the Wind Turbine Power Calculator on the Danish Wind Turbine Manufacturers Association's web site www.windpower.dk).

We have verified the figures using the Danish Wind Turbine Owners' Association magazine, *Vindstyrke*, to check for errors, and make sure that our figures are reasonably realistic.

The primary energy required to produce electricity in 1980 may be assumed to be the number of kWh produced divided by 0.35, assuming an average thermal efficiency of 35 per cent for typical Danish coal or oilfired power plant in 1980.

Energy Payback Period for 1980 Vintage Machines

When we take the energy content of the turbine and divide by the amount of primary energy saved per year, (and multiply by 12) we get the energy payback period (in months).

In this calculation you should note that we have also accounted for an assumed average (poor) siting of the 1980 vintage machines.

Improvements in the Energy Balance of Danish Wind Turbines 1980-1995

Comparing with the first section of this paper, and considering the fact that present day tur-

bines on average are located on sites better than roughness class 1.25, we may deduce that the energy balance for wind turbines located in Denmark has been improved by a factor 2 to 4 since 1980.

One should bear in mind, that the improvement is some 15 per cent higher than the change in the number of months indicate, since we have assumed an extremely high thermal efficiency in modern coal fired power plant when analysing the energy balance for 1995 wind turbines.

Improvement in the Energy Balance of Danish Wind Turbines Since 1980

Looking at table 1, it is obvious that there is an enormous difference in energy efficiency between the 55 kW generation of wind turbines and the previous generations of 30, 22, and 15 kW turbines.

Tower heights matter a lot, however, if one compares with present day 600 kW machines.

The 55 kW 1980 vintage Nordtank machine would produce 36% more with a 50 m tower. Moving it to roughness class 1.25 would increase output by another 13%.

The total increase in production would be 54%. One should bear in mind, however, that such a tall tower would not be economic (and probably not very energy efficient) for such a comparatively small machine.

Conclusions

Wind turbines in 1980 had a typical energy payback period of around 8 months if one loosely takes a weighted average over the different machine sizes.

This is quite impressive compared to today's 2-3 months for a modern wind turbine, when one bears in mind the difference in hub heights, and the (average) relatively poor siting of turbines.

The 55 kW generation of wind turbines heralded a breakthrough in energy efficiency in turbine manufacturing with energy payback periods of some 6 months, even on relatively poor sites.

Table 1. Typical Danish Wind Turbines from 1980

Wind turbine brand	Power rating kW	Rotor diam. m	Hub height m	Price ex works DKK	Installed price DKK	Primary Energy content GJ	Primary Energy content kWh	Electricity Output per year ¹⁾ kWh	Primary energy saved/yr kWh	Energy payback period months
Kuriant	15/4	10	18	89 500	116 500	233	64 500	26 933	77 000	10.1
Vestas	22/3	10	18	131 500			
Nordtank	22/7.5	10.8	18	130 000				38 321	109 500	10.4
Average	22			130 750	170 000	340	94 500			
Vestas	30/5	10	18	135 000				35 500 ⁴⁾	101 500	
Nordtank	30/7.5	11	20.5	140 000				39 154 ²⁾	112 000	10.7
Average	30			137 500	179 000	358	99 500			
Vestas	55/7.5	15.3	18 ³⁾	185 000				91 396 ³⁾	261 000	6.1
Nordtank	55/10	16	22	180 000				99 141	283 000	5.6
Average	55			182 500	237 000	474	131 700			5.9

Notes:

- 1) We assume a relatively poor siting in roughness class 2, using European Wind Atlas data from Beldringe, Denmark, and use the officially published power curve for the turbine.
- 2) The power curve seems to underestimate true output. These machines typically produce 50 000 kWh/year according to *Vindstyrke* statistics.
- 3) Most machines were delivered with 22 m towers, and the power curve only extends to 15.4 m/s, consequently statistics show substantially higher average production.
- 4) Estimated as an average from 3 turbines (no roughness classification given) in 1995 *Vindstyrke* statistics, normalised to an average wind year.

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