Wind Energy

Author:
Jos Beurskens (ECN), Peter Hjuler Jensen (Risø)

Reviewers:
Peter Hauge Madsen, Erik Lundtang Pedersen (Risø)
Jens Peter Molly (DEWI)
Gijs van Kuik (TUDelft)

1. Introduction, Potential and Basic Strategy

1.1. Introduction

Wind energy is the kinetic energy of moving air. The air moves from high pressure to low pressure areas in the world. Non uniform heating of the earth's surface by the sun is the driving force behind the global wind system. The power of the wind is proportional to the cube of the wind speed. See figure 1. This non-linear relationship in relation to the fact that the wind varies constantly in magnitude and direction, is one of the fundamental reasons for the complexity of the technology and its application in electricity supply systems.

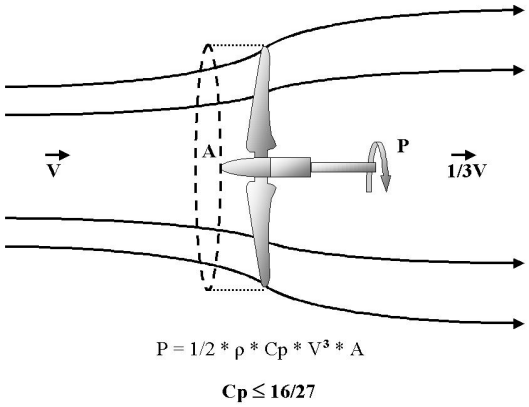


Figure 1. The power in the wind is proportional to the cube of the wind speed. The maximum fraction a wind turbine can extract from the wind is 16/27 (0.593).

The energy density of the wind is relatively low compared to densities in machines like gas and steam turbines. Average power densities in high potential areas are typically 400 to 800 W per m^2 swept rotor area. These low densities are the reason that many large machines have to be built in order to generate significant amounts of energy.

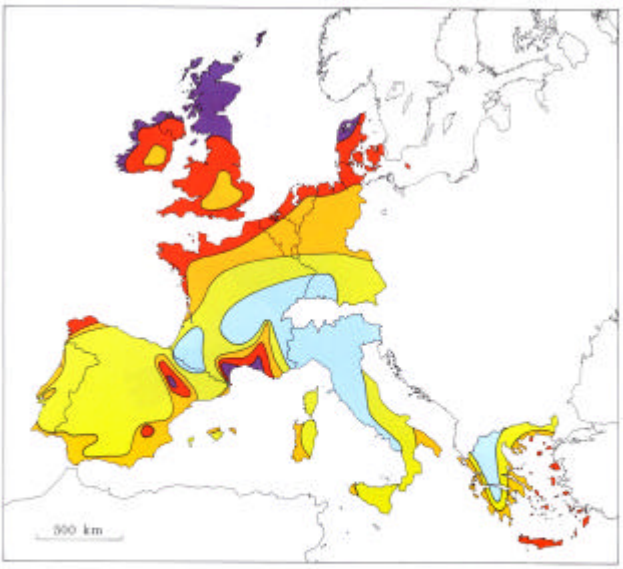
1.2. Potential: the European wind energy resources

Resource assessment

Assessing the European wind resource, one has to look both at the wind resources on land and offshore. Since the early eighties, the land resources are being investigated and mapped. A large volume of data is available in the public domain (see for example [1]) but an increasing amount of data is considered as strategic and confidential. Although offshore applications have been a point of interest since the late 70's

[3], a first more or less comprehensive glimpse of the European offshore resource was provided in 1995 by an EC study, called " Study of offshore wind energy in the EC" [2].
The local potential very much depends on the average wind speed, as the power in the wind is proportional to the cube of the (momentary) wind speed. For the design of an optimised wind turbine system, also the statistical distribution of the wind speeds has to be available for both energy output predictions and establishing desig n criteria. Thus, a thorough evaluation of the circumstances at the site is needed additionally to the overall averaged data. For offshore applications essential data are still lacking, such as simultainuous wind speed and wave height data.

The technology and software (for example the European Wind Atlas [1] and the computer code WASP [10]) for evaluating the available wind resource is being used intensively by project developers. Figure 2. The European Commission has played a key role by funding the research leading to the development of these tools. Despite the fact that in several other regions of the world evaluations of the wind resources have been carried out a lot of areas remain to be mapped. Although a lot of efforts have been invested in resource assessment and wind turbine output prediction methods, the uncertainty of the results still is too high for economic assessments by energy economists who are used to evaluating fossil fuelled plants with a high degree of dispatchebility.



Wind resources at 50 metres above ground level for five different topographic conditions

	Sheltered terrain		Open plain		At a sea coast		Open sea		Hills and ridges	
	m s⁻¹	W m⁻²	m s⁻¹	W m⁻²	m s⁻¹	W m⁻²	m s⁻¹	W m⁻²	m s⁻¹	W m⁻²
	> 6.0	> 200	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	100-200	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0-8.5	400-700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Figure 2. Example of a wind resource map from the European Wind Atlas [1].

The uncertainty in estimating the annual energy output has two causes: the annual variation of the average wind speed compared to the long term average (in coastal areas the annual wind speed may vary up to 7% plus or minus compared to the 30-year average) and the uncertainties of measurements and the use of those measurements for energy output calculations (terrain effects, inaccuracies of the wind turbine power characteristics). Currently, on the average the uncertainty in the latter part of the calculations is of the order of 10%.

The wind resources on land
Areas potentially suitable for wind energy application are dispersed throughout the European Union. Major areas that have a large wind energy resource include Great Britain, Ireland and the north-western continental parts of the EU: Denmark, northern Germany, south-western Sweden, the Netherlands, Belgium, and north-western France. Other areas include large parts of Spain, a majority of the Greek islands and some parts of Italy. In addition, there are many areas, where wind systems associated with mountain barriers give rise to high energy potentials. Some of these wind systems extend over large areas: the Mistral between the Alps and the Massif Central in south of France, the Tramontana north of the Pyrenées in France and south of the Pyrenées in the Ebro valley. In other cases such wind systems are of smaller geographical extent, but may nevertheless present a large wind resource locally. Of particular interest are mountain valleys, funnels and ridges where natural concentration effects of wind occur (e.g. mountainous parts of Germany, Austria, Portugal, Italy, Sweden and Finland).

The offshore resources
The scope of the earlier mentioned Offshore study [2] encompassed the assessment of the total offshore wind resource of Europe (12 countries), gathering of experience from the offshore industry concerning construction, erection, transportation and maintenance relevant to offshore wind farm operation and design aspects and adaptation of computer codes accounting for the differences between land-based and offshore machines (combined wind and wave loading, etc.).
The study showed Europe's technical offshore potential to be greater than Europe's total electricity consumption. See figure 3.

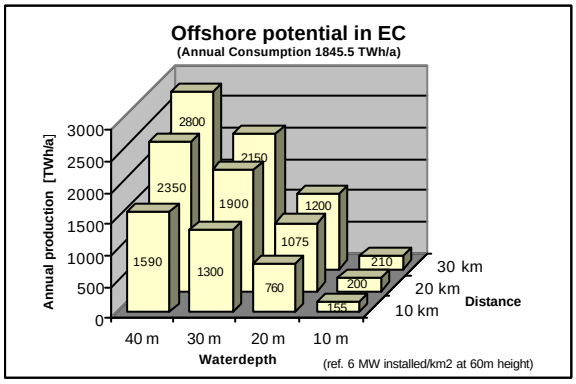


Figure 3. The European offshore potential (12 countries). Bars indicate cumulative figures.

These estimates were based on the selection of sites having a waterdepth between 0 and 40 meters, a distance to the shore not exceeding 30 km and a generating density of the wind turbines of 6 MW/km^2. The authors state that the review most likely overestimates the exploitable resource because political and other constraints relating to alternative use of the sites were not taken into account. On the other hand, there are considerable resources outside the 30-km limits, for example in the North Sea.

The total resource of Europe
The overall conclusion that can be drawn from the resource information that is available is that the total exploitable wind resource in the countries of the European Union is more than twice the total present electricity demand.

1.3 Basic Strategy
Various (international) governmental bodies and professional organisations have formulated goals to exploit the wind resource in Europe. Besides meteorological data, these goals are based on infrastructure,

physical planning, environmental and economic considerations. Apart from these issues also economic development, employment and decreasing the tension between the industrialised 'north' and the developing 'south' provide important arguments for a policy to stimulate the introduction of renewable energy sources in general and wind energy systems in particular.
The European Wind Energy Association (EWEA) along with Greenpeace concluded that even if the demand for electricity increases quickly (according to the IEA the world electricity demand will double by 2020 under business as usual), wind energy is able to provide 10% of the world demand by the year 2020. [7]. This implies an average annual growth of the installed wind power of 20 % between 1998 and 2003 (at present the average growth is about 30%), 30 % between 2004 and 2010 (resulting in 181,000 MW) and 20% again between 2010 and 2020 resulting in 1,200,000 MW, generating 3,000 TWh's, equivalent to almost 11% of the world electricity consumption by then.
In the past the European Wind Energy Association EWEA was twice forced to adjust its targets to higher figures because of the spectacular growth of sales of wind turbines among others in the European Union. Its present targets are as follows: 8,000 MW by 2000 (at the beginning of 2000 the actual figure was approximately 13,600 MW (!)), 60,000 MW by 2010 of which 5000 MW is to be installed offshore and 150,000 MW by 2020.
In order to meet these ambitious goals a number of conditions have to be fulfilled. Essentially this means a continuation of the success of those 3 countries on the European continent which now host 82% of the total installed power in Europe These countries are Denmark, Germany and Spain. (Worldwide 5 (!) countries constitute (also) 82% of the total installed power: Denmark, Germany, India, Spain and the USA.) Analysing the success factors of those countries is crucial in order to 'repeat' these developments and guarantee an accelerated market growth. Of course strategies have to be adapted to the specific circumstances in the countries concerned.
However in general the following aspects can be considered to constitute the complex determining the success factors.

- **Cost reduction** of wind energy.
- **Improving the value of the wind electricity.** In the first instance value is determined by the avoided fuel cost of fossil-fuelled plants. Equally relevant are cost components which seldom are made explicit in the electricity market, such as the environmental advantages, capacity credit (to be improved by utilising methods to forecast the output of wind farms a fewer hours in advance), demand for green electricity by customers.
- Finding **new sites**: in densely populated coastal countries: offshore; in mountainous land locked countries: funnels, hills, mountains.
- **System development**. On the one hand national grids have to be able to absorb large amounts of varying electricity output and on the other hand, wind energy plants need to meet specific requirements such as the amount of reactive power produced, harmonic distortion, predictability and controllability of the output.
- **Reduction of uncertainties** in predicting the technical and economic feasibility of projects. This means improved resource assessments, wind speed measurements, maintainability of machines, reliability, lifetime design methods.
- **Reducing environmental and negative social impacts** such as visual impact on the landscape, effects on birds and their habitats, acoustic noise emissions, etc..
- **Education and human resource development.** EWEA and Greenpeace expect a workforce for 1.7 million jobs if the 10% target for 2020 is to be met. People have to be educated and trained in both technical and non technical capabilities. Training precedes actual employment!
- **Implementing national and international environmental and energy policies.** A large number of instruments have been implemented in the past by mostly national states. Some schemes proved to be very efficient and some were not. The proper integration of financial and other legal measures, in relation to the maturity of the technology appeared to be a necessary condition. On the international

stage a number of agreements are being developed to protect the environment and in which renewable energy plays a crucial role: Joint Implementation (JI) and Clean Development Mechanism (CDM).

The first two mentioned factors of course are closely linked together. The bigger the difference between the cost of wind energy and its value the bigger the driving force behind the economic development of the wind energy technology.

The educational establishments such as universities and polytechnic schools, the R&D communities in the institutes and in industry have to provide the know how and capabilities to further specify the success factors, to develop and operationalise them.

The aspects, discussed before are to be linked to strategic goals in order to be effective. The strategic goals encompass the future wind energy generating capacities in different markets, industrial and employment goals. The table below links the success aspects to these strategic goals. The number of bullets indicate the relative importance of the aspect concerned in order to meet the strategic goal. The importance of course depends on the maturity of the technology, the stage of development and know how. The last column indicates the relative state of know how and practical experience with the various aspects. The fewer bullets appear the more R&D is required.
EWEA's wind energy targets form a sub group of the European Union's target of covering 10% of Europe's energy demand by means of renewable energy. To emphasise the importance of renewables for the developing economies, we rather arbitrary added a target for those countries. This target again is a sub group of EWEA and Greenpeace's recommendation of covering 10% of the world electricity demand by means of wind energy by the year 2020.
Later we will develop the R&D road map on the basis of the relation between success factors and types of wind energy systems which have to be commercially available in order to meet the goals, discussed above.

Strategic goals Success factors	10% renewable energy in Europe	30% new RE capacity in developing countries	Maintaining Industrial capacity & employment
Cost reduction of wind energy	●●	●●●	●●●●●
Increasing the value of wind energy	●●●	●●●	●●●
Finding new sites	●●●●	●●	●
System development	●●●●	●●●●	●●●
Reduction of uncertainties	●●	●●●●●	●●●●●
Reduction of environmental effects and negative social impacts	●●●	-	●
Education & human resource development	●●	●●	●●●●●
Development of policy and instruments	●●●●●	●●●●●	●●●●●

Table 1. The relations between strategic goals and aspects of implementation success factors for wind energy systems.

2. Present situation and achievements

2.1. Status of the technology

Depending on the application, wind turbine systems exist in a range of capacities. Usually the technology is divided into three categories, according to table 2.

	Type of application	Type of wind turbine
A	Onshore and offshore grid connected wind farms in size varying from about 10 MW to several 100 MW's.	Installed power > 1.5 MW
B	Decentralised and single operating machines connected to the grid.	0.5 MW< installed power < 1.5 MW
C	Decentralised units for both grid connected operation and for hybrid and stand-alone operation.	Installed power < 0.5 MW

Table 2. Wind turbine categories for different applications.

Figures 4 to 9 represent typical examples of systems from the different categories.

Figure 4. Example of a category A application. A 2 MW wind turbine with a rotor diameter of 72 m, designed for offshore applications. Further characteristics: active stall control by means of limited blade pich control, constant rotational speed. (NEG-Micon)

Figure 5. Category A. A wind farm consisting of 35 machines of 1.5 MW each and a rotordiameter of 66 m at Holtriem, Germany. Further characteristics: blade pitch control, variable rotational speed and direct drive generator. (ENERCON)

Figure 6. Example of a category B application. A Danish offshore wind farm at Tunø Knob, consisting of 10 machines of 500 kW each and a rotor diameter of 39 m. Further characteristics: blade pitch control and limited variable rotational speed. (ELSAM)

Figure 7. Category B. "La MUELA III" wind farm near Zaragoza, Spain comprising 26 machines of 660 kW each and a rotor diamater of 46 m.(MADE)

Figure 8. Category C. Single grid connected 400 kW wind turbine with a rotor diameter of 31m owned and operated by a farmer at Sint Maartensbrug, the Netherlands. Characteristics: stall control (fixed rotor blades) and constant rotational speed. (Jos Beurskens)

Figure 9. Example of a category C application. An experimental wind-diesel system under test at ECN, Petten, the Netherlands. Characteristics: Installed power of diesel set: 50 kW, wind turbine: 35 kW. Passive blade pitch control, variable rotational speed. (Jos Beurskens)

Category A

Category A is formed by large size grid connected wind turbines for onshore and offshore applications. The size of commercially available grid connected horizontal axis wind turbines has evolved from 22 kW in the early eighties, via 0.6 MW in the early nineties to about 2.5 MW today (associated rotor diameters are approximately 10 m, 40 m and 90 m respectively). The next generation of commercial wind turbines in the 2.5 - 5 MW range are being tested and they are scheduled to reach the market in 2002 to 2005. The larger machines mostly are designed for offshore applications.

Many different design concepts are employed. There is a strong tendency for large machines to move from stall regulated machines operating at near fixed rotational speed to concepts with variable speed and blade pitch control. Other concepts with direct driven generators or low ratio gear boxes and integrated low speed generators are occupying an increasing part of the market.

The European industry is leading worldwide in the development and manufacturing of grid connected wind turbines. In 1999 the European industry produced slightly more than 90 % of the sales worldwide. However, as the ownership of the companies and the manufacturing facilities are more dispersed, it becomes increasingly difficult to determine the 'nationality' of the technology.

Modern wind turbines have a high quality, which results in technical availability of typically 98-99 %. The high level of availability is a result of the reliability of the machines and – for most present land based machines - the easy accessibility for repairs and maintenance. However, under offshore conditions the situation is basically different. Because of poor accessibility of the site, a higher degree of reliability is one of the necessary conditions, which are to be fulfilled in order to arrive at an acceptable level of availability. See Figure 10. Besides transportation and installation loads, combined wave and wind loads and reliability are very important design drivers for offshore turbines.

Category A (and also B) wind turbines require more fundamental research as dynamic mechanical, aerodynamic and aeroelastic phenomena play a dominant role in creating stable constructions, whereas R&D on category C machines concentrates on energy system improvements.

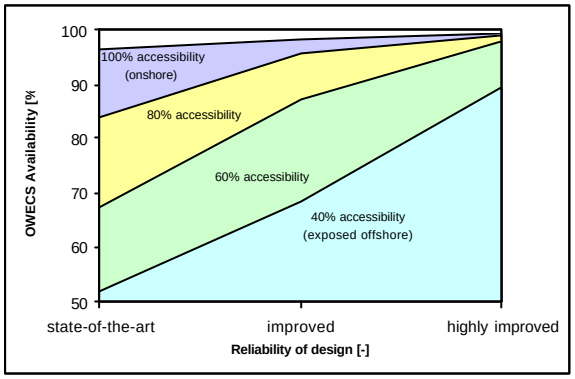


Figure 10. Availability of wind turbines in relation to reliability and accessibility of the terrain. [4]

More and more wind turbines are placed in clusters, so called wind farms, which are operated as single energy generating units. Unit size has evolved from few MW's in early eighties to a hundred of MW's at present.
At present it is estimated that a penetration (supply fraction) of wind energy on a large grid can be as much as 15-20 % without special precautions to secure grid stability. Turbines equipped with state-of-the-art power electronics may even add stability to the grid, because reactive power can be adjusted and the harmonic distortion of the electricity generated is extremely low. Also power fluctuations can be limited and the output of wind farms is partly controllable.
The fact that wind turbines are clustered into bigger units requires specific R&D on system integration. Focal points are control systems of wind farms, improvement of power quality, system and grid stability, operational management systems (maintenance based on conditioning monitoring and early failure detection), system reliability and output forecasting.
As land based large size wind farms are very visible and produce noise, these aspects among others play an important role in the planning process, especially in densely populated countries where the best locations are already being used up.

Category B.
Here is where most of the generating capacity of the first independent wind farms and later individual wind turbine owners can be found. The machines in this category almost all are installed on land. (Exceptions are the first demonstration offshore installations in Sweden and Denmark.) Generating capacities are matched to the local grid capacity (short circuit power). These machines are also being used in large wind-diesel units.
Learning curves on which predictions of future generating cost of wind turbines and the long term wind capacity targets (for instance those from the EWEA and Greenpeace) are based upon the experience with wind turbines from this category. See figure 11. Until the end of 1999 almost 44,000 machines (including all categories) have been sold world-wide. [5]
Areas of improvement are power quality, controls and system design for autonomous hybrid units. As the machines in this category (and also the machines of 100 kW to 500 kW from category C) are the oldest ones in operation, tear and wear and fatigue induced failures appear more frequent as the end of the projected lifetime comes in sight. This leads to increased maintenance cost in the overall statistics. Questions of replacing those machines by larger state-of-the-art machines or refurbishing the old ones are being addressed by project owner/operators.

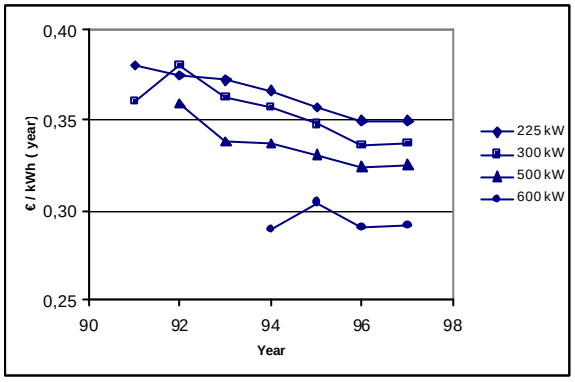


Figure 11. Cost development of medium size wind turbine [6] in terms of ex factory turbine list prices per unit of annually produced electricity (Roughness class 1; 1996 prices; 1 Euro = DKK 7.5)

Category C
Grid connected machines
The commercial development of grid connected electricity generating machines started after the oil crisis in the mid 1970's in countries like Denmark, the Netherlands and the USA with machines of typically 22 - 35 kW installed power and rotor diameters of 10m. Owners were almost exclusively private persons, farmers and small enterprises. For remote areas with weak grids in both the industrialised and developing world, machines between, say 50 kW and 500 kW still find a sizeable market that is ignored by the established industry because of the booming market for larger machines. Some niche-oriented manufacturers are focussing on this market segment.
A relatively new development is the use of small grid connected machines (smaller than 10 kW) in the built environment and farms (USA).

Autonomous systems
In the early eighties, at the beginning of the modern renewable energy development period, relatively much attention was paid to utilising wind energy systems to provide electricity to remote, isolated communities without any energy infrastructure. As the supply of wind energy varies stochastically in time, energy supply and energy demand do not match most of the time. To provide security of supply, a storage system is needed, which absorbs energy during periods that supply exceeds demand and supplies energy in times that the situation is reversed. Storage of energy in general and of electricity in particular is very expensive. So in order to overcome this cost problem solutions were sought in so called autonomous - hybrid - systems where wind turbines were working in combination with other energy conversion systems such as photovoltaic arrays/hydro/diesel and/or storage systems. These wind turbines were also used for special stand alone applications such as water pumping, battery charging, desalination, etc. (10 kW to 150 kW range).
Many experiments were carried out and over 10 research establishments had more or less comprehensive development programmes. Looking back from the present situation, one can conclude that virtual all development efforts on autonomous systems had limited success.
The need for independent island renewable energy systems has not changed since. Analysing and understanding the reasons why this happened could provide us with the conditions for a real successful revival of the development and market implementation of autonomous systems. The generally accepted notion that the market did not develop is that the actual players (technology developers, manufacturers) were not familiar with the demand side of the market for energy supply to remote places. However we also have to consider that the market concerned, is not self sufficiant and lacks even the most basic technical and logistic infrastructure for after sales services. While developing renewed development strategies, the aspects of the demand side of the market should be fully integrated, among others by involving the established manufacturers and distributors of diesel sets for remote electricity supply.

This category also constitutes *small stand-alone turbines* for battery charging, water pumping, heating,

etc. (<10 kW). Small battery charging wind turbines, (25 to 150 watts; i.e. rotor diameters from 0.5 meter to 1.5 meters), are by far the most successful in commercial terms. At present in the world probably some 1,000,000 small battery charging wind turbines are in operation.
Of all forms of applications of wind turbines, wind driven pumps still are the most numerously applied One to two million units are used world-wide for irrigation, cattle watering and domestic supply. Over 50 manufacturers are known to be active. In general the technology has not developed significantly since the first machines appeared on the market in the mid 1800's. Few improvements from R&D activities supported by national programmes were implemented successfully. Interest in these machines seems to be increasing.

General
Although the market share of the category B machines in 1999 was still the largest (in 1999 about 70% of the total number of sold machines), the market share of category A machines is growing rapidly.

2.2. Markets *[5]*
General trends
The installed wind power is distributed very unevenly over the world: only five countries make up 82 % of the total installed capacity (which was nearly 18,5000 MW at the end of 2000). See table 3. Also the annual growth of the capacity is unevenly distributed: in one year (2000) Germany installed about four times (which is 1665 MW) the cumulative wind capacity of the Netherlands, although the exploitable wind resources in both countries are of the same order magnitude.
Over the last 20 years the world-wide annual installation rate of wind turbines has increased from a few megawatts to almost 4,500 MW in 2000. The growth of the cumulative capacity varied the last 4 years between 26 % and 37 %. The average growth during the last 5 years was 31 %. Europe hosts 74 % of the world's capacity: 13,630 MW at the end of 2000. In a decade (the eighties) the generation cost of wind electricity were roughly reduced by a factor 10.

	Total by the end of 2000 (MW)	Added in 2000 (%)
Germany	6107	37
USA	2610	7
Spain	2836	57
Denmark	2341	35
India	1220	18
% of total	82	
Netherlands	473	9
UK	425	17
Italy	424	53
China	352	34
Sweden	265	20
% of total	11	
Rest of the world	18.449	54
Total	13,932	32

Table 3. Installed world wind capacity 2000 (Source: BTM Consult), [5]

Realising these facts (spectacular growth concentrated in just a few countries) could lead to the conclusion that the present world wind energy market in principle is unstable. If market conditions in one of those countries change, this could have a significant impact on the world market and the manufacturing industry. It is a fact that in individual countries, even those belonging to the top 5, the annual market volume varies considerably. These variations can very clearly be seen from the country profiles that each year are published by BTM Consult [5]. Most dramatic changes occurred in the USA where the annual

market volume dropped from 400 MW/a in 1985 to about 50 MW/a in 1988. In 1997 the volume increased from about 30 MW/a to 570 MW/a in 1998 (!) Also India showed dramatic variations: from 370 MW/a in 1995 to 80 MW/a in 1998. Even Denmark, who has shown high growth figures, shows relatively large variations. The only countries that until now appear to have a continuous growth are Germany and Spain. The UK has a periodic growth and decrease of the volume with a period time of about 3.5 years. During the last 4 years growth in the Netherlands has been low but rather constant.
There are no simple explanations to these trends. Often changing governmental policies, uncertainties in revenues and planning procedures are the basic reasons why the number of machines installed annually vary so much. Referring to the present successes in Denmark, Germany and Spain, some professional associations claim that the most effective incentive for market development is fixing a minimum feed back tariff for a sufficiently long period, e.g. 10 years. It is evident that countries like Denmark, Germany and Spain, fixed tariff systems indeed have been very successful. Of course an attractive feed back tariff system is not the only condition for a successful development. Additionally a proper national energy or environmental policy with specific renewable energy targets, R&D facilities, an appropriate legal planning framework, public acceptance and an industrial homebase are needed.
In the near future the co-existence of different systems in the open (European) market might become problematic. Introducing a tradable green certificate system for instance, next to (high level) fixed tariff systems might lead to a situation where one country generates the required renewable energy quota – and takes all the burdens – for a neighbouring country. The country, buying the certificates would not be stimulated to develop its own renewable energy sources or its own industry. A careful matching of national systems would therefore be needed for a market with equal opportunities and fair burden sharing. Nevertheless one can imagine it were not too difficult to create market conditions in a large number of countries similar to those in Denmark, Germany and Spain providing the wind regimes and infrastructural circumstances allow so. Further expansion of the market in the future would thus be very feasible.

Offshore applications
As the best (i.e. wind regime and grid connection) land locations are being used up and public acceptance starts to vanish, coastal countries start investigating and exploiting the near and offshore resources.

	First rotation	**Installed power [MW]**	**Status per 09-2001**	**Details**
S: Nogersund. Baltic Sea	1991	Bonus: 1 x 0.22 = **0.22**	Abandoned in 1998	Tripod foundation on solid rock.
DK: Vindeby.	1991	Bonus: 11 x 0.45 = **4.95**	In operation	Caissons on saindy soil. (2.5-5 m water depth) 1.5-3 km from coast.
NL: Medemblik. IJsselmeer DK: Tunø Knob Kattegat NL: Dronten. IJsselmeer	1994 1995 1996	NedWind: 4 x 0.50 = **2.00** Vestas: 10 x 0.50 = **5.00** Nordtank: 28 x 0.60 = **16.80**	In operation In operation In operation	Mono pile foundation. Corrosion life time 50 years. Fresh water. Caissons on sandy soil Monopiles a few meyers outside dike body
S: Bockstigen. Baltic Sea	1998	Wind World: 5 x 0.50 = **2.50**	In operation	Monopile foundation. (5.5-6.5 m water depth) 4.5 km from coast.
DK: Middelgrunden	05-2001	Bonus: 20 x 2.00 = **40.00**	In operation	Gravitational foundation. (3-5 m water depth) Between 1.7 and 3.5 km from coast
GB: Blyth. North Sea		Vestas: 2 x 2.00 = **4.00**	In operation	Mono pile foundation. (Water depth 6 m(+ 5 m tides))
S: Utgrunden. Baltic, Kalmarsund	12-2000	Enron: 7 x 1.43 = **10.00**	In operation	Monopiles (7.2-9.8 m water depth) 12.5 km from coast.
S: Yttre Stengrund. Baltic, Kalmarsund	07-2001	Neg Micon: 5 x 2.00 = **10.00**	In operation	Monopile foundation. 5 km from coast.

Table 4. Overview of near shore demonstration and commercial wind farms, built before 1999..

Denmark, the Netherlands, Sweden and the UK have already accumulated experience with near shore wind farms, using existing technologies from the wind turbine industry civil engineering industry. See table 4.
In Europe some 5 near shore wind farms, varying in capacity from 4 to 150 MW and totalling up to almost 450 MW are in the design stage. All new wind farms will have wind turbines of which the capacity is exceeding 1.5 MW. Capacities totalling several thousands of MW's appear in total in the long term government plans of notably Denmark, Sweden, Germany, Belgium and the Netherlands; the UK, Spain and others are likely to follow suit. At present all project designs are derivatives of machines designed for land applications, equipped with specific features for operation in water.

2.3. Industry and employment [5], [7]

In 2000 the European industry produced more than 90 % of the total worldwide sales in that year, total turnover of the wind energy sector worldwide was slightly more than 4 billion Euro, growth of turnover was 17% compared to 1999.
In 1999 the total employment, both direct and indirect, of the wind industry was close to 17.000 man-years/year, which corresponds to about 20 jobs/MW installed power. According to the EWEA/Greenpeace scenario the labour intensity will gradually decrease to a level of about 12.3 man-years/MW by the year 2020.
Of the top manufacturers in terms of sold MW's in 1999 three were Danish, four Spanish, two German, one German-USA, one German-Danish and one Japanese. The others produced 5.4% of the total volume. The four largest manufacturers exported between 75% and 93% of their output.

2.4. Economy

International organizations without any links to wind power (for example, the International Atomic Energy Agency, IAEA) estimate that in many countries wind power will soon (2005 to 2010) be competitive with fossil and nuclear power when external/social costs are included.

The economics of grid connected wind power can be evaluated from two different perspectives.
The first is that of public authorities or energy planners making assessments of different energy sources. Here the focus is on levelised cost. These calculations exclude factors determined by society or governments such as inflation and tax.
The second perspective is that of the private or utility investor, where inflation, interest rates, tax, amortisation period etc. are most relevant. Here the focus is on cashflow in each project, on pay-backtime and present value of the investments. Consequently the economics of wind energy differ significantly from country to country.
Here, reference will be made to costs based on an explicit model containing the real relevant physical and economic parameters by means of which deviating economic analyses can be made. The issue of the value of wind-produced electricity (avoiding fossil fuel and environmental cost, capacity credit - to be improved by output forecasting models, etc.) will not be addressed.
The generation cost of wind energy basically is determined by the following parameters:

- total investment cost, which consist of
- production, transportation and erection cost of wind turbines,
- project preparation costs (permits), cost of land, cost of the infrastructure, etc.,
- operation and maintenance cost,
- average wind speed at the particular site at hub height,
- availability,
- technical life time,
- amortisation period,
- real interest rate.

Ex works cost have been estimated by surveying commercially available wind turbines belonging to the top 10 of units sold. The survey shows average ex factory costs of around 350 Euro/m^2 rotor swept area. Assuming a specific installed power of 450 W/m^2 swept rotor area this translates into 780 Euro/kW of installed capacity. Note however that the generating capacity primarily is determined by its swept rotor area and the local wind speed and not by its installed power. The power installed should be properly matched to the wind speed and rotor swept area in order to achieve optimum energy output and capacity factor (defined as the energy output divided by the output as if the machine were running at rated power during 100% of the time) for the best economy. For this reason manufacturers supply wind turbine types with different values for the specific installed power. The higher this value is the more suitable the wind turbine is for higher wind speeds. Actual ex-factory prices in terms of cost per m^2 swept rotor area may vary plus or minus 20 % compared to the key figures mentioned above. Machines with the lowest cost per unit of installed power are thus not necessarily the most economic ones for a particular site. The above ex work costs are based on published materia l such as brochures. The actual price of course depends on negotiations and the number of units acquired during one transaction, for instance when purchasing machines for wind farms. At present (mid 2000) the number of machines per transaction may amount to as much as 2,000 units.

Project preparation cost depend heavily on local circumstances, such as condition of the soil, road conditions, proximity to electrical grid sub-stations, efforts to acquire land and permits and to overcome possible public resistance, etc.. In some countries, like the Netherlands the procedures to acquire permits are longer than the typical innovation time of a wind turbine type. As a consequence the technology to be applied is actually outdated, the moment permits are granted and the project construction can start. Investigations indicate that project preparation costs in Denmark for wind projects with 600 kW machines amount to the average value of 1.25 times the ex-factory cost [6]. This does not include grid reinforcement costs and long distance power transmission lines. Project preparation cost per machine can be reduced considerably by wind farm operation.

Operation and maintenance costs include service, consumables, repair, insurance, administration, possible lease of site, etc. Danish and German experiences indicate that the annual operation and maintenance cost for new category B wind turbines are approximately 0.6 to 1.0 Eurocent/kWh, of which half consists of insurance cost. For machines of over 10 years of operation these cost may go up to a level of 1.5 to 2 Eurocent/kWh.

The availability, defined as the capability to operate when the wind speed is higher than the wind turbine's cut-in wind speed and lower than its cut-out speed, is typically higher than 98 % for modern machines.

Technical design lifetime for modern machines is typically 20 years. However, this does not exclude the need to replace certain components after a shorter interval. Because of the rapid development towards large machines uncertainty about the reliability of components of category A machines increases again and maintenance cost tend to increase slightly. This is expected to be a temporary phenomenon. Consumables such as oil for gearboxes, brakes, clutches, etc. are often replaced with intervals of 1 to 3 years. Parts of the yaw system are replaced in intervals of 5 years. Depending on the operational strategy and design, components exposed to fatigue loads such as main bearings, bearings in gearbox and generator are foreseen to be replaced halfway the design lifetime. Sometimes the reason for early replacement is due to design errors, often caused by the need to reduce cost by ignoring safety margins.

Choice of *amortisation period* (or economic lifetime) depends on:
• the economic model to be used (levelised cost method or private economy perspective); and
• the type of investor and its financial strategy.

From the levelised cost perspective the amortisation period is often is taken to be equal to technical lifetime. A serious complication is that the innovation speed in the wind energy sector is so high that the technology 'ages' during the project preparation phase.

The average annual wind speed on the site is of paramount importance to the cost of energy. As a rule of thumb the annual energy output of modern wind turbines can be estimated by means of the following expression: $e = 3.2. V^3. A$ (kWh/m^2 swept rotor area), given the installed power is properly matched to the rotor swept area and the local wind speed at hub height and that the shape of the frequency distribution curve is close to those found in the coastal areas of Europe. V (m/s) is the annual average windspeed at hub height and A is the rotor swept area in m^2. [17]
At the best locations in the Netherlands, Northern Germany and Denmark annual outputs of over 1000 kWh/m^2 are often achieved (1000 kWh/m^2 corresponds to an annual wind speed slightly higher than 5 m/s at 10 metres height with average new technology). In the UK sites with a wind speed of 8, 9 and 10 m/s are common and annual outputs of over 2000 kWh/m^2 are being recorded. The average normalized (to a normal wind year) annual output of all wind turbines in Denmark in the period 1996, 1997 and 1998 was 937 kWh/m^2 [6].

The cost of wind energy can be exemplified assuming the following:

ex works cost (note the slight increase in cost for larger machines, figure 15)	350 Euro/m^2
total investment	125% of ex factory cost
annual O&M cost	1 Eurocent per kWh
availability	99 %
technical life time	20 years
amortisation period	20 years
real interest rate	5 %

The cost were calculated by means of the following expressions:

$$c = \frac{a.I_{tot}}{A.E} + m$$

where:
c : cost (€/kWh)
a : annuity factor
I_{tot} : total investment per m^2 rotor area
A : availability
E : annual energy output per m^2 rotor area (kWh/m^2)
m : operation and maintenance cost

while: $$a = \frac{i(1+i)^n}{(1+n)^n - 1}$$

where:
i : real interest
n : amortization period,

while: $E = 3.2\ V^3\ (kWh/m^2)$ [17].

where:
V : is the average annual wind speed m/s) at hub height.

The results are presented in figure 12.

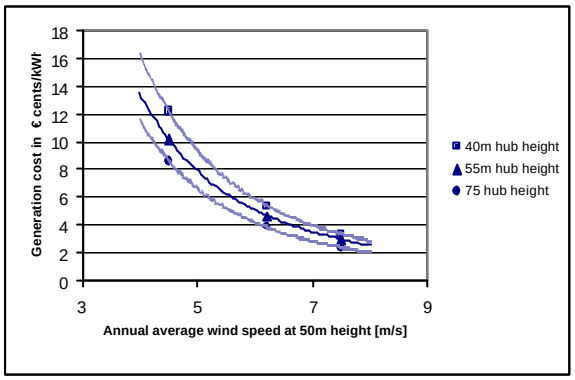


Figure 12. Generating cost of wind energy as a function of local average wind speed. The calculations have been carried out for three sizes of wind turbines. The ranges of inaccuracy are due to varying wind speeds at different hub heights. To take into account various dimensions, outputs were calculated at 40 m hub height (typically 500 kW machines), 55 m hub height (typically 1 MW machines) and 75 m (typically 2 MW machines) for a roughness class 2 terrain according to [1].
A wind speed of 7.5 m/s at 50 m height corresponds to the coastal areas of Ireland, Scotland, northern Denmark and sections in southern France; 6.2 m/s to large areas of Denmark, nothern Germany, Netherlands,the UK, Ireland, France, Spain, Greece and some sections of Spain, Portugal and Italy; 4.5 m/s to large parts of the European land mass. For reference see also figure 2.

2.4. Non technical implementation issues

Wind energy's environmental impact has been investigated thoroughly in both Europe and America. The main conclusions are:

*Atmospheric emissions***.** No direct atmospheric emissions are released during the operation of wind turbines. The emissions during production, transport and decommissioning of a wind turbine mainly depends on the type of primary energy used to produce steel, copper, aluminium, plastics etc. from which the wind turbine is constructed.

*Energy balance***.** The energy needed to produce, install, operate, maintain and decommission typical wind turbine equals to approximately the energy output during a period varying between 3 and 6 months. This is fundamentally different from fossil fuel fired plants, which continuously need energy (oil, coal, gas) to produce electricity. In this sense wind turbines, along with solar and biomass plants, are the only net energy producers.

*Social costs and liabilities after decommissioning***.** Electricity from wind turbines has very low external or social costs and no liabilities related to decommissioning of obsolete plants. Almost all parts of a modern wind turbine can be recycled.

Land use. Wind energy density is low and thus harvesting significant amounts of energy requires large areas of land. As a rule of thumb wind farms require 0.06 to 0.08 km^2/MW (12 – 16 MW/km^2). However, the land on which wind turbines are built can still be used for other purposes such as agriculture and cattle farming. Foundations, utility buildings and access roads occupy about 1% of the land.
On the typical flat onshore sites wind turbines do not cause erosion and they do not influence vegetation or fauna. In most countries wind power developers are obliged to minimise any disturbance of vegetation during the construction of wind farms and its infrastructure works on sensitive locations such as mountains.

Acoustic noise emissions. Acoustic emissions from wind turbines are composed of a mechanical and an aero-acoustic component, both of which are a function of wind speed. Reducing noise originating from mechanical components is a strait forward engineering exercise, whereas reducing aero-acoustic noise is a rather difficult trial and error process. In modern wind turbines mechanical noise seldom causes problems. Figure 13 illustrates the reduction of the acoustic source level of wind turbines in the course of time, resulting from R&D into this area.
The nuisance caused by turbine noise is one of the important limitations of siting wind turbines close to inhabited areas. The acceptable emission level strongly depends on local regulations. One example is the Dutch regulation for 'silent' areas, where a maximum emission level of 40 dB(A) near residences is allowed, at a wind speed of about 5-7 ms^{-1}. At this wind speed level the turbine noise is most distinctly audible. In Europe an acceptable minimum distance between wind turbines and living areas is 150 to 200 metres.

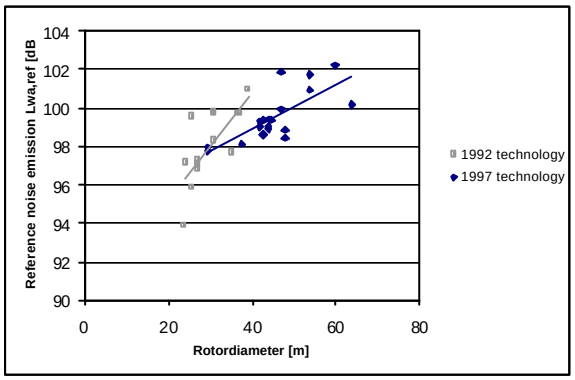


Figure 13. The reduction of the acoustic source level of wind turbines in the course of time [10].

Visual impact (landscape, shadow, reflections). Depending on the characteristics of the landscape (small scale elements or large scale industrial or empty plains) modern wind turbines with a hub height as of 40 metres might have a disturbing visual impact on the landscape, which a lot of dwellers find difficult to accept. This visual impact, although very difficult to quantify, often poses severe difficulties in the planning process in most European countries.
A more objective case of visual impact is the effect of moving "shadows" and reflection of sun light from the rotor blades. This is only a problem in situations where turbines are sited very close to workplaces or dwellings. The effect can easily be predicted and avoided through careful siting. Wind turbines in the MW range can cause shadow effects, which reach further than disturbing acoustic noise effects.

Impact on birds. From studies in Germany, the Netherlands, Denmark and the UK it appears that wind turbines do not pose any substantial threat to birds. The number of bird kills due to wind turbines is small compared to birds killed by natural causes, hunting, traffic and high voltage lines. Only isolated examples have been reported, such as the Spanish wind farm of Tarifa near the Strait of Gibraltar, which is located

near a major bird migration route. However, in principle disturbance of breeding and resting birds can be a problem on coastal sites.

*EMI (Electro-magnetic interference)***.** The propagation of electromagnetic waves from navigation and telecommunication systems may be influenced by wind turbines. The waves will be scattered and diffracted and as a result interference could occur which may lead to malfunctioning communication systems. Investigations by among others the BBC in Britain and the PTT in the Netherlands concluded, that interference can easily be avoided by proper siting (e.g. keeping a certain distance from the axis of relay connections) and/or the use of antennas with enhanced directivity or gain.
The IEA has published preparatory information on this subject [18], identifying the relevant wind turbine parameters (diameter, number and radar cross-section of blades, speed, etc.) and the relevant parameters of the potential vulnerable telecom services (spatial positions of transmitter and receiver, carrier frequency, polarisation, etc.).

*Personnel safety***.** Accidents with wind turbines involving people are extremely rare and there is no recorded case of persons hurt by parts of blades or ice loosened from a wind turbine. Insurance companies in the USA, where most of the experience with large wind farms has been accumulated, agree that the wind industry has a good safety profile compared with other energy producing industries. The International Electrical Committee (IEC) has issued an international standard on wind turbine safety [19].

Public acceptance. This issue has two aspects: the attitude of the general public towards wind energy and the attitude of people living nearby (planned) wind farms. On the one hand the general public in many countries favours renewable energy sources such as wind power. On the other hand, deploying a wind farm in a community sometimes raises resistance due to the neighbours' uncertainty and negative expectations about the wind turbine's visual impact and noise emission. This has been called the NIMBY (Not-In-My-Back-Yard) dilemma. Experiences from all over the world indicate, that the potential neighbours' participation in planning and ownership of a wind farm can secure the public's acceptance and active support of wind power.
Opinion surveys in areas of the European Union with many wind turbines or clusters (such as Denmark and UK) showed that 70 to 80 % of the population is "general supportive" or "unconcerned" with respect to wind turbines in their neighbourhood. In a referendum in a Danish municipality with a very large number of wind turbines, 77 % of the votes favoured more wind turbines, though legal procedures fed by resistance by a number of persons very often is the main reason for slow progress in implementing wind energy.

3. Goals for R&D

3.1. Introduction

In chapter 1 strategic coals were linked to success factors that are essential for reaching those goals. Here different aspects of the success factors in R&D are linked to the different categories of application (category A, B, C from paragraph 2.1) by means of actions required. The actions actually constituate R&D priorities to further stimulate the use of wind energy systems. In table 5 the structure is illustrated and the necessary R&D activities have been listed. In paragraph 3.2 more explanatory information on most of the listed activities will be given.

	Large scale wind farms on/offshore: P> 1.5 MW	Distributed systems on land: 0.5 MW<P<1.5 MW	Decentralised systems: P<0.5 MW
Cost reduction of wind energy	*Design improvement *Manufacturing technology *Transport and installation techniques *Reliability design for offshore	*Design improvement *Manufacturing technology	*Testing and evaluation prototypes
Increasing the value of wind energy	*Output forecasting methods *Controllability of large wind farms	*Output forecasting methods	
Finding new sites	*Offshore resource assessment *Resource assessment mountainous areas *Resource assessment in cold climates *Design conditions and methods adapted to extreme external conditions	*Resource assessment mountainous areas *Resource assessment in cold climates *Design conditions and methods adapted to extreme external conditions	*Resource assessment mountainous areas *Resource assessment in cold climates *Design conditions and methods adapted to extreme external conditions *Market surveys
System development	*Optimisation of power electronic converters *Control strategies (for output and power quality control and to stabilise mechanical constructions) *Grid connection	*Optimisation of power electronic converters *Control systems (for output and power quality control) for weak grids	*Energy storage systems *Energy management systems *Standardisation and modularization *Updating system design methods and verification by means of experiments
Reduction of uncertainties	*Reliability design methods *More accurate resource assessment methods and output prediction calculation methods *Methods for fine tuning of power curves to local climatical circumstances *Development of fast aerodynamic diagnosis methods	*More accurate resource assessment methods and output prediction calculation methods *Methods for fine tuning of power curves to local climatical circumstances *Development of fast aerodynamic diagnosis methods	*System reliability
Reduction of environmental effects and negative social impacts	*Development of low noise blades *Monitoring effects on birds habitats *Minimise visual impact *Develop and test participation models for the public	*Development of low noise blades *Monitoring effects on birds habitats *Minimise visual impact *Develop and test participation models for the public	*Design systems with minimum electrical storage by means of batteries
Education and HRD	*Joint international R&D programmes on universities *Develop training schemes for lower and medium level technical skills *Establish specialised proffesorates at universities *Develop educational material for primary schools	*Joint international R&D programmes on universities *Develop training schemes for lower and medium level technical skills *Establish specialised proffesorates at universities *Develop educational material for primary schools	*Joint international R&D programmes on universities *Develop training schemes for lower and medium level technical skills
Development of policy and instruments	*Obligatory national targets for wind energy *Co-ordination by EC (European Directive) *Evaluate market stimulation programmes and design more effective instruments *Create open European market	*Obligatory national targets for wind energy *Co-ordination by EC (European Directive) *Evaluate market stimulation programmes and design more effective instruments *Create open European market	*Incorporate technology introduction in national rural devt. programmes and programmes of multi national organisations (World Bank, UNDP, etc.)

Table 5. Summary of R&D activities in relation to success factors and applications of wind energy systems. Those in the technology domain (non-shaded) are being addressed explicitly.

3.2 Cost reduction of wind energy

Introduction

Compared with traditional energy sources wind energy today is competitive at very good sites, even without the compensation for the environmental advantages. For less favourite sites wind energy can compete if CO_2 credits are taken into account. However, to install 100,000 MW of wind power in the EU economically full competitive to fossil fuel and nuclear based power production requires further cost reduction of wind power.

If the strategic goal for wind power in Europe is realised, Europe will remain the world's largest market for wind turbines. Having such a strong 'home' market is extremely beneficial to the European wind energy industry as a world player in terms of maintaining and further strengthening its competitiveness. Since the appearance of the first commercial grid connected wind turbines (typically 22 kW) at the end of the 1970's, the generating cost of wind electricity has roughly been reduced by a factor 10. In the beginning, during the transition from prototypes to medium scale batchwise production, cost reduction was fast, easy and very significant. Later as the obvious improvements were all implemented in the designs, progress became slower. Between 1981 and 1995 the generating cost in Denmark was reduced from DKK 1.1/kWh to DKK 0.4/kWh [10]. Since the mid 90's cost reduction again became slower, but continuous. There is still a perspective for further cost reduction of 15% on the short term and close to 50% by the year 2020 [5].

Cost reduction of a market product is characterised by means of the progress factor. This is the relative cost level compared to the previous one, after each doubling of the cumulative production volume. As the Danish industry has been in business the longest time on a relatively high production level this industry can be considered as representative for the wind energy technology in general. From 1980 to 1995 the progress rate has been fairly constant at a level of 80 %. Of the 20% cost reduction, about 15 % are due to design improvements and more efficient manufacturing and about 5 % due to improved siting. There are no reasons to assume that this ratio will change as the market further develops. Further cost reduction however is not an automatic process. Different activities have to be undertaken depending on the elements that determine the cost structure. The cost of establishing a wind energy project is depicted in figure 14. The cost distribution of the main elements is based on a Danish analysis presented in [9].

Wind turbine Ex factory 80 %	• Design features (concept, loads, materials, component, controls) • Manufacturing (methods, economy of scale) • System efficiency • Overhead (marketing, warrenties, management)
Wind farm realisation 15 %	• Transport • Installation • Infrastructure (civil works, electrical connection, buildings) • Commisioning
Project development 5 %	• Financing • Insurance • Permits and licenses • Certification • Bidding • Land acquisition • Siting (wind speed) • PR, participation of public, lobbying

Figure 14. Cost elements of wind generated electricity. This cost distribution is based on a 0.6 MW wind turbine operating as a single unit or a small wind farm of less than 8 MW. [9] It has to taken into account that for large land based wind farms the main contribution of cost is different. The project development cost will be relatively more expensive. For near and offshore wind farms the cost of civil works will be relatively high. It has to be noted that in this figure only the cost of designing a financial structure were included. The effect of applying different financial strategies to the final energy cost of course can be much bigger than 5%.

To arrive at the cost per unit generated electricity, the operation and maintenance (O&M) cost have to be included. Especially for wind turbines located on difficult accessible terrain, such as on offshore and mountainous terrain, this cost element is very important.

Realizing a cost reduction of 50% in 20 years' time thus is a combination of addressing all factors mentioned. To set detailed priorities, which have a general value, is not possible. Priorities depend on the concept and on the manufacturing and O&M strategy of a particular manufacturer. But some general priorities can be established on the basis of the following considerations.

Technology development: larger wind turbines and improved designs
From the very beginning of the modern wind energy technology development, starting in the mid 1970's, we have noticed a gradual and consequent growth of the unit size of commercial machines. From 10 m diameter in the mid 1970s to 80 m at present. For the trend since 1992, see also table 6.

1992	200 kW
1994	300 kW
1996	500 kW
1998	600 kW
1999	700 kW
2000	900 kW

Table 6. Approximate average capacity (kW) of wind turbines installed each year in Europe.

The demand side of the market mainly drives the trend towards larger machines. The most important arguments for larger machines are: utilising economy of scale, less visual impact on the landscape per unit of installed power and the expectation that the multi MW machines are needed for exploiting the off-shore potential. The effects of the scale on the relative cost of the machines are illustrated in figure 15.

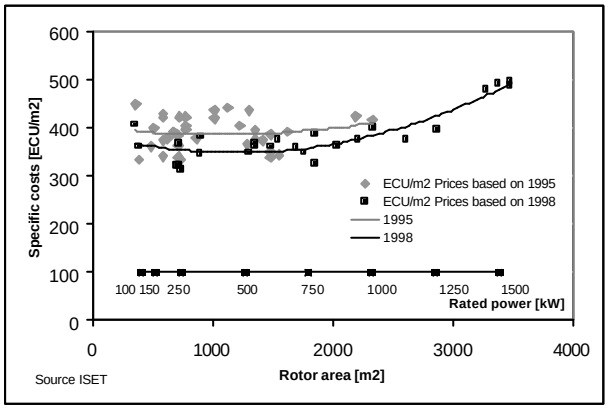


Figure 15. Relative wind turbine cost as a function of size in the course of time ISET 1999 [11].

At present the specific weights of the MW class machines is already approaching those of machines in the 0.75 to 1 MW class: 25.1 kg/m^2 swept rotor area and 23.8 kg/m^2 respectively.

Ex factory cost reductions of 15 to 20 % are being expected from the combination of the following features in advanced wind turbine concepts [12], [13]:

- Reduction of loads by means of less conservative design and by means of the use of flexible turbine components, such as flexible blades, flexible hubs, variable speed generator systems. This leads to lower weights and in the final end to lower machine cost.

- The reduction of the number of components. Some examples: the application of direct-drive generators, passive blade pitch control (in combination with variable speed drive trains), passive yaw combined with a down wind located rotor.
- The use of improved materials featuring higher strength to mass ratios and better internal damping. R&D on these aspects have been carried out since the early eighties and even earlier. The claims of this work are still valid, although there are no success stories in the commercial sense yet. Main reason is that the market pressure is so large that time is lacking for long term, high-risk developments. In the present commercial machines elements of these innovative design features can be noticed already. An increasing number of manufacturers are offering variable speed conversion systems, although the first ones were offered on the market in the late 70's already (In Europe: Lagerwey later followed by ENERCON and still later in the USA by former KENETECH). A number of manufacturers, (ENERCON (D), Lagerwey the Windmaster (NL)) are offering or developing (Jeumont (F) and ScanWind (S/N)) direct drive generators with solid state energy converters. Because of the low content of harmonic distortion, the absence of inrush currents and adjustable reactive power supply, these modern inverters make wind turbines particularly suitable for weaker grids. The market share of wind turbines equipped with direct drive generators and/or variable speed systems at the end of 1997 was slightly over 30 % and is increasing slowly. Figure 16 shows two examples of wind turbines equipped with direct drive generator systems.

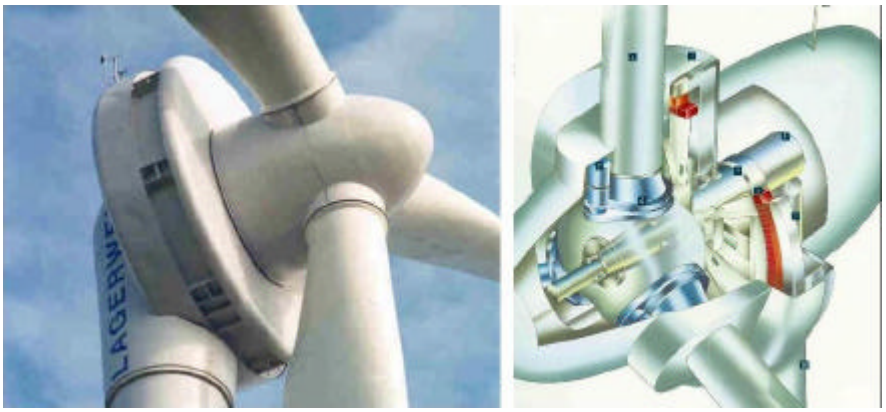


Figure 16. Examples of wind turbines equipped with direct drive generator systems (Lagerwey the Windmaster, ENERCON).

Measurements of some experimental rotor concepts with different flexible blade attachments in the Netherlands, the USA, the UK, Germany and Denmark have shown a dramatic reduction of dynamic loads on the blades. In classical designs these loads the most important design drivers of the blades, hub and tower structures.
The promising results of this and other research projects have never been fully implemented in new designs. As wind turbines become larger and thus intrinsically more flexible, these findings certainly will be implemented in new designs.

As offshore applications will be very important in the near future in North and North West Europe some special remarks have to be made concerning typical offshore design features.
Integration of wind and wave loading into the structural dynamics codes is necessary to avoid overdesign. From calculations it appears that the combined wind and wave-loading spectrum is lower than the wave loading treated separately. Applying this finding in the design will lead to lighter structures, translating the absence of noise emission constraints (tip speeds of rotors can be higher, leading to smaller transmission ratios and lighter drive trains) and lower turbulence intensities into relative cheap constructions. Jamieson

[14] even claims that these advantages could make up for the cost inherent to offshore conditions.

The final goal of all cost reducing R&D efforts is to reduce wind electricity generation cost by 15% on the short term (2005) and close to 50% by the year 2020.

3.3 Increasing the value of wind energy

As the difference between value and cost increases also the economic drive to realise wind energy plants will grow. For the society wind energy, like other renewable energy technologies, represent the following values:

- displacement of fossil fuels that cause hazardous gas emissions;
- displacement of installed power in fossil fuelled and nuclear energy plants;
- saving natural resources;
- creating sustainable employment;
- independence from politically sensitive fossil fuel resources (increased supply security).

It is not clear how these advantages are to be reflected in the economic process. However, R&D should concentrate on the development of methods to quantify and improve the value. First priorities are developing energy output forecasting models (see under 'systems'), improving methods to control power output of wind farms in order to maximize capacity credit, and the replacing of fossil fuels. This becomes particular interesting when a spot market for renewable energy develops.

The R&D goal is to have a fully quantified value system of wind electricity by the year 2005.

3.4 Finding new sites

Already now in densely populated countries with a high level of installed wind capacity, the best sites are being occupied. Combined with complicated physical plannine procedures and the increasing public resistance against new wind farms, this leads to the need for alternative sites. Nevertheless the relative average output of wind turbines, based on a large number of machines is increasing. See for example figure 17. This increase is mainly caused by a combination of the utilisation of sites with higher wind speeds and the use of higher towers, but also, although to a lesser extent, by improved system efficiency and availability. The improvement of the overall system efficiency is due to improved aerodynamic efficiency of the rotor blades, the application of high efficiency electric conversion systems and better matching of the windturbine rating to the loacal wind regime. (The latter means that the installed power per unit of swept rotor area has to be in accordance with the local wind speed. To this end, manufacturers offer wind turbines with various generator capacities and one rotor diameter, or wind turbines with various rotor dimensions going with the same generator capacity.) The overall system efficiency of present commercial wind turbines is close to what is theoretically feasible.

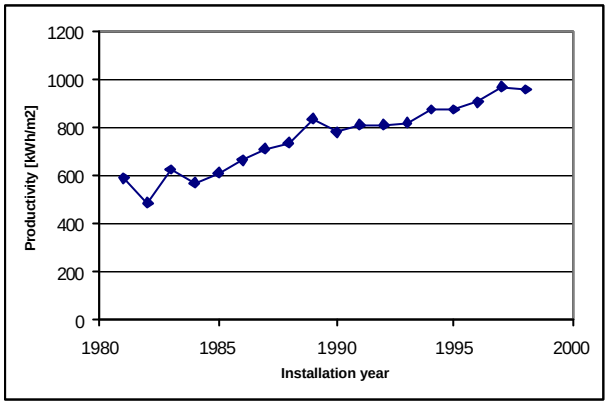


Figure 17. Development of the energy output per m^2 swept rotor area of all Danish wind turbines [6].

As the developments proceed and the best sites are being utilised, in the future we might see a gradual decrease of the output curve (figure 17), indicating the saturation of the utilisation of the wind potential on land. This effect can be delayed by replacing the older and smaller wind turbines by state of the art large units. Countries with a coastline will have the opportunity to continue the exploitation of the wind potential by using the off shore sites. See paragraph 'Markets' for initiatives in various European countries.
Besides, non-conventional inland locations might be considered. In Germany 45 % of the total installed power is realised in inland states (Länder). In many cases extended towers are being used to compensate for the reduced wind speeds at 'normal' heights.
Other extreme locations would include mountainous sites with extreme high wind speeds and elevated turbulence intensities.
In Europe Finland, Sweden and Norway among others are deploying wind turbines in extreme cold climates.
Dedicated wind turbine types will be developed for low wind speed inland locations, for high wind speed - high turbulence locations, for cold climates and offshore locations respectively.

Specific R&D goals are: complement the European Wind Atlas with measured data of the North Sea and a number of high potential mountainous sites.

3.5 System development

European utilities consider wind power more and more as a viable and reliable source of energy in the grid's supply portfolio. However there is still some reluctance, especially in countries with no experience, because of the utilities' concern about power quality, power predictability and grid integration.
Furthermore, Europe's electrical utility sector is facing a significant restructuring process (generation, transport and distribution are being separated, whilst decentralised generation now is the main responsibility of the distribution sector), leaving less attention to the introduction of wind power and other renewable energy sources.
Because the widespread use of wind power in Europe demands an active participation of European utilities, wind power's credibility from the perspective of the utilities must be increased. The most important means to this end are 1) ensuring of wind energy's power quality (harmonic distortion, reactive currents, inrush currents, voltage stability) and predictability (see under 'Value') and 2) reduction of wind powers transmission costs and grid costs. and maximise the quality of the electricity produced

The R&D goals are: developing electrical output prediction tools that predict output 24 hours in advance for wind farms with at standard deviation of 5 - 10 % by 2010 and to arrive at technical and economic optimal planning tools for integration of 100,000 MW of wind power into the European grid by 2010.

Virtually all installed electricity generating wind turbines are grid connected machines. Often the exploitable wind potential is high in areas with a poor electricity infrastructure. Modern power electronics make wind turbines more suitable to connect to weak grids, as addressed earlier.

A very important application, being electricity supply systems to remote areas without an electricity grid, never developed commercially on a significant scale. Wind-diesel systems providing electricity, to small to medium sized autonomous grids were tested and demonstrated on a limited scale.
Apparently the need for autonomous systems has not changed since the eighties. However the technology has improved considerably. Especially those components that in the past appeared to be too expensive or too unreliable, such as wind turbines, electronic components and control strategies have improved dramatically since. This leads to the conclusion that a revival of the development of autonomous systems is very well possible. The first signs are already visible. Some examples: ENERCON (Germany) started the production of a 0-series of stand alone desalination units; Atlantic Orient Company (USA) installed 11 wind diesel systems (comprising 35 wind turbines) in extreme climates (Alaska, Siberia); Lagerwey the Windmaster (Netherlands) is developing new systems; Northern Power Systems (USA) supplies a number of specialised autonomous and stand alone units including wind turbines and PV arrays.

Standardisation of sub-systems to increase the modularity of systems is a necessary condition for accelerated market development. It will not only lead to reductions of the production cost of systems, but also the design and engineering cost.

The R&D goal is to have co-ordinated system development and testing programmes in place in all major European R&D centres, in which the industry, familiar with the market for autonomous energy systems (including battery chargers and wind pumps), is fully involved. The first fully testing programme should be operational by 2005.

3.6 *Reduction of uncertainties*

Finance and insurance companies consider wind power as a reliable source of energy and have confidence in the overall performance of the wind energy industry. Within the overall necessity to utilise all possibilities to optimise cost, services provided by the financial and insurance companies will become cheaper if uncertainties in assessing both technical and economic risks can be decreased. Most significantly this applies to determining wind resources, the prediction of the wind turbine's performance, prediction of O&M cost.

Wind resources

Earlier the importance of the wind regime for the economic performance of a wind energy project has been addressed (see paragraph 'Economy' and also 'Potential: the European wind energy resources'). Non-surveyed terrains with an obvious high potential should be mapped and added to the 'European Wind Atlas' project, which is specifically concerned with detailed measurements of near and offshore areas and mountainous regions.

Wind turbine performance prediction

There is still considerable room for improvement taken into account the present level of accuracy. It is a basic problem of stochastic data and non-linear behaviour of the systems that pose considerable theoretical problems. Necessary activities include improvement of anemometry, terrain calibration, transfer methods of measured power-wind speed curves of wind turbines from one site to the other.
It often appears that the actual performance of wind turbines differs considerably from the predicted one, depending on the local climate or season, leading to under or over production of energy (over production often leads to accelerated consumption of lifetime and is not acceptable). In those cases manufacturers may be faced with financial claims from the project owners. One solution is to have methods for fine

tuning the aerodynamic performance of rotor blades and associated fast field diagnosis instruments available.
A particular aspect, mentioned earlier, specially applies to large wind turbines. The actual dynamic behaviour regularly differs from analyses carried out during the design stage. If prohibitive vibrations appear during operation, involved cost do not permit the wind turbine being replaced by another one. In those cases control systems can be used to actively damp vibrations after the turbine is put in operation. See for isntance [20].

Operation and maintenance
From figure 10 it appeared how availability (and thus energy output) depends on reliability and accessibility of the wind turbine installations. Especially wind turbines located in offshore locations and in mountainous terrain are subject to potential very high cost due to increased O&M cost and loss of availability. In this respect the accelerated development of early failure detection and condition systems are essential. These systems are to be connected to planning systems for maintenance. Data may be used as inputs for improving the reliability of the wind turbine design.

The condensed R&D goal for the various activities described here can be formulated as follows: the uncertainty of generation cost for flat terrain and offshore should be reduced to 5 - 10 % by 2010. For complex (mountainous) terrain uncertainty should be reduced to 10 - 15% by 2010.

3.7 Reduction of environmental effects
If 100,000 MW of wind power is to be installed in Europe over the next 20 years it essential to maintain and increase the public's acceptance of wind power. R&D efforts to minimise the environmental impacts and to increase the public's involvement, e.g. by developing participation models should be balanced with those needed for the technical aspects where we concentrated on.

R&D goals include the availability of European standards and codes of practice for noise emissions, siting, physical planning, minimising impact on bird's habitat, etc.

Some of these standards and codes of practice have to be based upon R&D results, such as design methods for low noise blades and monitoring of bird's behaviour near wind farms in sensitive areas.

3.8 Education and human resource development
A workforce, skilled in both technical and non-technical aspects of the technology, is an absolute necessity to meet the strategic goals. It is the responsibility of the national ministries responsible for education and science to incorporate wind energy technology in the different school programmes on different levels. These efforts need to be closely co-ordinated with similar activities concerning other renewable technologies.

The specific goal is to have at least one European, formally accepted, university degree on renewable energy, with a specialisation option on wind energy technology.

3.9 Policy and instruments
Apparently the first three activities listed under this heading in table 5 do not need an explanation. The issue of creating an open European market is less obvious.
As mentioned in the European Commission's Green Paper "For A European Union Energy Policy", the free operation of the market has to be the principal instrument of any policy so also for wind energy. Also non-EU-based actors must have access to this market.
One important instrument is to develop harmonised European standards, legal structures and institutional frameworks on the essential aspects of market operations.

In this respect the following goals are to be met:

- *European planning procedures for ranking feasible sites (on flat coastal and inland sites, in mountains and offshore) for 10,000 MW by year 2000 and 100,000 MW by 2010.*
- *A European certification and accreditation system facilitating a free market for wind power technology by 2005.*
- *A European standard for performance (test and measurement) by 2000.*
- *A European standard for risk assessment for investment in renewable energy by 2000.*
- *A transparent, harmonised cost and tariff system facilitating free market for wind power by 2005.*
- *A European code of practice for access of wind power into the grid system and the reinforcing of the grid to enable grid integration.*

4. Roads to market

Land based wind energy systems in industrialised countries

Although the share of wind energy in the annual newly built electricity generating capacity is still small (in 1999 10% in terms of MW's installed, which means approximately 3% in replaced capacity), wind energy in principle has developed into a common option in the planning of electricity generating capacity. In industrialized countries with suitable wind regimes and adequate infrastructure wind turbine systems do not need to be demonstrated on land locations.

Financing is not a major problem either as financial institutions have gained sufficient confidence in the wind energy technology. Thus (initial) investment support is not needed either.

Some countries have a high population density, conflicts often arise in the quest for land to build wind farms. Therefore, problems related to conflicting land use need to be resolved by means of *policy development, acquiring broad public* suppor and the *development of participation models* to which the liberalised electricity market provides a very good base supported by a variety of *legal measures which support national targets.*

Naturally this requires *firm national targets per renewable energy technology band*. These targets need to be established in national energy and environmental policies. For the members of the European Union, the European Commission could be a strong catalyser, which could enforce the implementation of national targets, check progress and implement a fair share of burdens between member states.

Economic conditions need to be created so that the industry can operate on a level playing field, meaning that barriers and subsidies for fossil fuel-based electricity generation should be removed, or alternatively, feedback tariffs should be fixed for a sufficiently long period to compensate for the external advantages of wind energy. Minimizing the cost of wind turbine systems is a task of the industry (and the are forced to because of competition), but maximizing the value of wind energy is the responsibility of national governments and the European Union.

The role of R&D in following the road to market is to identify barriers and trying to solve them: develop and evaluate participation models, develop and evaluate policy instruments, reduce acoustic noise emission, extend or modify the existing distribution grid gradually so it can absorb a large amount of electricity generated at a large number of locations distributed over a large area, etc.

Land based systems in developing economies

All recommendations formulated in the previous section in principle apply also to these countries. However, the impact of the general public's involvement is much less. On the other hand, the electric infrastructure in most cases is much less developed and not designed for the fast growing demand for electricity. The fact that the grid is unreliable poses specific problems to grid connected wind turbines. *Design specifications from the point of view of electrical system and control design have to be derived from these circumstances.*

Wind energy can contribute to these economies in terms of creating local manufacturing capacity and associated employment. In this respect transfer of know how is essential.

The R&D communities, both in the industrialised north and in the developing world, are to play a vital role in system design, know how transfer and building up local expertise and human resources.

Wind energy systems for remote areas
Earlier we concluded that the technology of autonomous (hybrid) systems is insufficiently developed and that therefore the market does not develop. As there is no market the industry finds the risk to invest into the development of autonomous systems and its potential markets (distribution and after-sales systems, expertise) too high. As most of the concerned markets are lacking financial means this viscous circle is very hard to open up. *First priority has to be given to market development*, before dedicated R&D efforts can be useful. As the demand side of the market and financiers is not familiar enough with the technology and thus confidence is lacking, the proper way of initialising the market (again) seems to be *large-scale demonstration programmes and investment support schemes after potential markets have been identified. In parallel technology oriented R&D programmes carried out by the industry (preferably the industry that is familiar with this typical market segment) in co-operation with R&D institutes should be (re-)initiated.*

Offshore applications
The applications fall into a gradual spectrum of offshore conditions: from near-shore wind farms in shallow water to far offshore, deep water floating farms. The difference is made up from water depth, distance to the shore, maximum wind speeds and wave heights. Apart from the impact on the design specifications for the machines, transport and installation equipment, these external conditions are the reason for a big difference in the accessibility of the wind turbine systems and thus on operation and maintenance strategies and cost.
Experiences so far (see table 4) do not suggest different implementation strategies from land-based farms for near-shore applications. All technologies applied are adopted existing technologies from the wind turbine and civil engineering sector. *Monitoring of environmental impacts is essential in order to provide information for future near and offshore projects. Near shore projects are being projected in environmentally sensitive areas.*
The situation for far offshore applications is basically different as has been pointed out in the previous chapter. Here **a number of first-of-a-kind prototype projects seem appropriate, where a limited number of newly developed wind turbine concepts in combination with the support structure, transport and installation methods and O&M strategies can be tested**. The European Commission could play a key role in initiating, co-financing and co-ordinating these rather large-scale projects. Even if the big multinational energy companies are taking own initiatives a multinational governmental body, such as the EC, is essential as many legal uncertainties, especially in the non-exclusive economic zones, are likely to be encountered during the planning process.
In both cases the role of the wind turbine industry, the offshore industry, contractors, national governments and the R&D community is essential as far as technology development, assessing environmental impacts and the development of legal structures (primarily to control possible conflicts of interest between the various users of the open sea: defence, fishery, ship traffic, oil and gas exploration and mining, sand mining, nature values, etc.) is concerned.

General
As the demand for wind energy systems developed very fast, manufacturers were not in the position to fully incorporate R&D results in their designs in order to optimise the systems. This implies that lessons from learning curves from other technologies have not yet been fully implemented. The full use of R&D results however is needed in order to be able to utilize the cost reduction potential to its full extent.
Reducing R&D budgets at the very moment wind energy technology appears to become successful in the market place is therefore very short-sighted.
On the contrary, R&D efforts should be intensified, but targeted on those problems, which are likely to hamper the large scale implementation speed of wind energy in the future.

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