Introduction to wind energy

13.9.99 G.Böhmeke

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1. Theory

The power in an air stream grows with the power of three. Double the wind speed gives eight times the power. Maximum power extraction is theoretically 0,593 (=16/27) of the wind's power, but practically you can expect 0,48 mechanically or 0,42 electrically.

The power curve is independant from the number of blades. Three-bladers are common, two-bladers are rare, single-bladers died out, zero-bladers exist only in patent applications.
Small wind pumps have 12 to 40 to obtain sufficient low speed for the pump.

The airfoil-shaped blades can be operated in two modes to ensure power limitation in high winds. If the tip speed is kept constant by using a constant speed generator, the blades will come into stall condition at high wind speeds. (Fig. 3)

The second mode is "pitch", and the blades are turned actively around their axis towards zero lift angle. The blades are suspended on bearings. The pitch concept needs variable speed of the drive train. Pitch movement is dynamic and needs appropriate control. Typical pitch speed is 5 deg/s to 15deg/s.

2. Basic technics

The wind energy converter consists usually of the rotor, drive train and tower. Vertical axis systems have died out.

The rotor is nearly in every case a thin-walled glass fibre structure as a boat hull or sailplane wing. (Fig.1). The drive train consists of a hub (globular cast iron), axle, bearings, gearbox and generator. Everything is arranged on a mainframe. The mainframe turns on its yaw system into the wind. (Fig.2) There are also direct drive plants, using a large generator much like in a water power plant.

An operation control computer controls the whole plant. Superposed safety systems cover failures. There are always two independent safety systems with crosswise supervision and self test procedures.

The power is fed into the grid with no storage in between. Different drive train concepts result in different behaviour towards the grid.

The power curve (Fig.4) begins at some 4 m/sec and ends with 20 or 25 m/sec. Rated power is at 12 to 15 m/sec. The relation between energy yield and average wind speed is almost linear, assuming a Rayleigh- distribution for wind speed vs. time (Fig.5).

3. Rules of thumb

Annual energy per square meter of rotor area is Ea=0,32*vm –1,14 [MWh/m¨2 a], where vm is the average wind speed in hub height.

Energy yield on a coastal site (6 m/sec hub height) of a 1,5 MW plant is around
3000 MWh/a or 780 kWh/m2. On an excellent site you may reach 1000 kWh/m2 a.

A complete wind power plant costs 5000FIM/kW plus 20% for foundations and grid connection. Lifetime is usually 20 years.

The nacelle of a 1500 kW unit weights some 90 tons.

Tower height is usually between 1 and 1,2 times rotor diameter.

Rated speed of a 1,5 MW plant is some 18 r/min (one turn takes three seconds).

Energy yield is roughly 23% of whole time rated power.

4. Generator systems and grid connection

First Principle	Induction generator directly grid connected, fixed blades, power control preferably by stall, pitch anyhow possible.
Power fluctuations	typically +-10% with short peaks +-20%, dominant frequency is 3 * rotor speed (threeblader), (Fig. 6)
Harmonics	none
Power factor	between 0,95 and 0,98. Compensation by switched capacitors intervals of some 10 min to 2 hours
Grid connection	soft starter (phase cut control) activated close to synchronous speed, inrush current some 1,5 * rated current
Comment	over 80% of all turbines use this so-called classical Danish system. If pitch is used for power control, the slip ratio has to be above 2%, preferably over 4% Power fluctuations become less with increasing number of turbines, rule of thumb is, with the square root. So 16 wind energy converters have only a quarter of the fluctuations of a single unit.

Second principle	synchronous generator with DC link, variable speed, speed control by pitch
Power fluctuations	during partial power according to gusts, above rated wind speed constant (Fig.7)
Harmonics	very slightly in the range of some kHz, usually not relevant
Power factor	continuously controllable usually between 0,9 inductive to 0,9 capacitive
Grid connection	synchronised, no inrush, no power peaks
Comment	used by ENERCON. Can be used to improve voltage shape by actively eliminating present harmonics

Third principle	double-fed induction generator with DC link on rotor side, stator directly grid connected, variable speed is rated speed +- rotor frequency. Speed control by pitch
Power fluctuations	during partial power according to gusts, above rated wind speed constant
Harmonics	very slightly in the range of some kHz, usually not relevant
Power factor	continuously controllable between 0,9 inductive to 0,9 capacitive
Grid connection	synchronised, no inrush, no power peaks
Comment	used by DEWIND, SUEDWIND (now part of NORDEX), PROTEC. Advantage:smaller inverter. Disadvantage: coal brushes on rotor shaft

In discussion is a 12 pulse GTO-inverter using a three-winding transformer or sixphase generator winding for coming offshore machines.

All wind will be used. The power is very rarely limited by shutting down wind plants during times of low consumption. Other power plants have to be controlled.

Wind energy can be foreseen using meteorological data and the location of the wind farms. Schleswig-Holsteins SCHLESWAG uses a computer code named PELWIN. This allows time for measures, for example the control of consumers and fossil-fuelled power plants.

Average wind energy grid penetration is around 1,2% in Germany, 10% in Denmark. Locally it is more, for example some 15% in Schleswig-Holstein, 70% in Nordfriesland. These are newest numbers from journals. The numbers in Fig.12 are partially old.

Future grid penetration is scheduled to reach some 30% in Denmark. The control of existing power plants will be consequent task.

The larger the geographical distance is between wind farms, the smaller is the probability of having no wind power due to calms.

Under research are combined wave power/ wind power plants, energy storage by electrolysis/hydrogen/fuel cells and others.

5. Growth and the reasons for

Installed capacity distribution (see fig.8)

Worldwide together	10'000 MW
whereof Europe	6'300 MW
whereof Germany	3'000 MW
Finland	25 MW

Optimistic forecast is 40'000 MW until 2010. (also fig.9)
Pessimistic forecast is 40'000 MW until 2020 or 20'000 until 2010

A rapid growth has happened, and an even stronger growth is foreseen.

Wind energy is not competitive to conventional energy sources, based on conventional economy calculations.

How come, that a non-competitive form of energy generation is strongly growing?

The basis for growth is ***not*** technology development, but the political means of supporting wind energy. With increasing sales due to political support, the wind power companies had the money and the perspective to carry out product development. This lowered the cost of wind energy slightly. The situation in the eight most important countries is as follows (Fig.10).

5.1 Germany

The German subsidy system is simple. The utilities have to pay 90% of the average consumer price to the wind farm operator. Decreasing electricity prices also decrease the wind electricity price. Formerly 17.3 PF it is now 16.5 PF=50p/kWh. There is no investment subsidy.

The law is not valid for offshore. Offshore projects will have to be negotiated individually. Schleswig-Holsteins utility SCHLESWAG spoke about some 36 - 42 p/kWh, which would be enough to operate offshore wind farms successfully.

Germany has about 3000 MW installed wind power, so over two times more than Denmark.
The sites are exploited to the acceptable limit and offshore is a future must. In 1998 794 MW have been installed. This year the aim of 4000 MW will be reached.

The wind electricity contributes to some 1,2 % in the grid.

5.2 USA

Presently the subsidy is 1.5 US-cents per kWh (=8.7 p/kWh). Together with customer demands for green electricity, the last year was quite successful, leading to some 190 MW new turbines. A part of this market is replacement of old worn-down turbines on excellent sites in California. Within 1999 the newly installed power will be around 665 MW. Interesting is, that some organisations instead of individual persons are buying green electricity.

As soon as the subsidy law (Production tax credit) expires, there may be a sudden stop of all wind projects. The US-subsidies are usually limited to a certain time period, expire and are renewed some time later. According to Vestas' salesmen the US market is an on/off market.

The official goal of the US government is 5% of wind power by 2020, requiring 80'000 MW. This aim is very ambitious and can hardly be reached. It shows anyhow, that there are strong political support and long-term plans.

5.3 Denmark

Denmark has some 1500 MW installed wind power, which contributes to over 10% of the country's electricity. The plans are for 4000 MW in 2020. The market is closed to foreigners. The worlds largest two companies are Danish. In Denmark 300 MW have been installed during 1998.
The subsidy system is complicated as depending on age and size of the turbines, but based on a subsidy per kWh.

5.4 India

India experienced a wind boom from about 1990 to 1994. Enercon and Micon founded joint-ventures. Tacke tried but did not succeed. The market came to a sudden stop due to political reasons in 1994. It is slowly reviving now. India has some 1000 MW installed.

In India (as in Spain) the manufacture of components is politically very important. The unit size is below 600 kW, as the Indian infrastructure is not suited for large trucks or cranes.

The Indian cooperation partners of Enercon manufacture the special ring generators and the blades themselves, which is a surprising manufacturing depth for such projects.

The turbines installed 1998 came to 28 MW of installed power.

5.5 Spain

The Spanish subsidy system offers a choice between a fixed price of 40p/kWh or an electricity price based on the average market level plus an environmental bonus. The result is roughly the same.

Spain has built 256MW last year (other source 195) and is the country with probably the strongest growth.
The projects have been realized by Gamesa Eolica/Vestas, NEG-MICON, BAZAN-BONUS, Desarrollos Eolicos, Made, Ecotecnia.

In Spain it is necessary to manufacture nearly all components within the country and create jobs. Else the projects have no chance. Enercon has a problem doing so, as the components are very special.

The Spanish manufacturers aim at export markets, and their low manufacturing cost level eases international sales against Danish competition. First market range is Latin America.

5.6 The Netherlands

The subsidised price is 47,3 p/kWh, but the official aims have not been reached. The additional power within 1998 was only 42 MW despite the good wind resource. One of the reasons is the building permission in the fairly densely populated area.

An other reason is the tendency to support own manufacture against Danish competition, but the products were not competitive on the market. WINDMASTER went bankrupt and was sold to LAGERWEY, LAGERWEY themselves only survived some years ago by additional funding. NEDWIND was bought by NEG-MICON. These turbulencies also influenced the market.

5.7 UK

The UK have among the windiest sites in whole Europe, but so far the exploitation is hindered by the rather complicated funding system, which makes it difficult to carry out small individual projects. The funding happens through the NFFO (non-fossil fuel obligation) system. The wind park project has to state its cost of generated electricity. The funding is given to the projects with lowest generating cost. The bids are carried out regularly, but are linked to certain deadlines. This slows down the projecting of wind farms significantly. The electricity price within the last bid was about 30 p/kWh.

The 1998 sales figures were 14 MW.

It should be mentioned, that the calculated energy price for wind farms in windy places of Scotland equalled 27 p/kWh, which is the lowest figure stated in Europe.

The only manufacturer in UK, the Wind Energy Group, was bought by NEG-MICON and the production closed down. The wood-epoxi blade manufacture, however, was very successfully continued.

5.8 China

200 MW of installed power is small compared to the country's size. China just received a World Bank credit for wind power, which will result in building 190 MW within the next 2 years. The 1998 figure was 48 MW.

Finland

In Finland there are no subsidies by kWh, but 30% on the investment. We carried out economy calculations. The same wind power plant under same wind speed conditions will pay back after 7 years in Germany, but after 15 years in Finland. If we want the same payback time of 7 years in Finland, the investment subsidy would have to be 65%. Without any subsidies the payback time is 26 years, so above lifetime.

Compared to other countries, the subsidy is low. As the Swedish subsidy system is being changed from investment subsidy to a subvention per kWh, we might expect this tendency also in Finland. This would probably improve economy.

The way of financing wind projects is by customer demand. If sufficient consumers are willing to pay a higher price for "green" electricity, the utilities will finance and operate wind farms. The new Pori wind farm (8 MW) is based on this system.

The official statements of KTM are to subsidise 500 MW until 2010. An exploitation of this potential would mean to erect in average one wind energy converter every 10 days, so we can hardly expect this aim to be reached.

The geographic situation in Finland is quite different to Germany or Denmark. The lack of open coastal terrain allows the use of only a very narrow coastal strip for siting. This area is fairly densely spaced with summer cottages, and we can expect significant public unrest. The need to go offshore will arise far more quickly than in Germany. The use of shallow waters for artificial islands is very promising, see Lumituuli.

A second and quite different possibility is wind power on top of the hills in Lapland. The potential is in the order of 273 MW installed power, but the public opposition will probably be even stronger. A realistic estimation is one or two additional MW per year.

6. Manufacturers

The present-days leading manufacturers can be seen in the appendix, fig.11.

Largest manufacturer is NEG-Micon. NEG and MICON united two years ago. Then they bought Taywood-Aerolam, WEG, Windworld and Nedwind. There is a certain concentration process in Denmark.

Presently there is not yet much concentration in Germany, as the good market feeds all, anyhow all companies work at the limit of bankruptcy.

From about 30 former wind power plant manufacturers only 13 are still existing, 6 of these are only in standby condition, some 7 really produce turbines. We can see a kind of gold rush, (Goldgräberstimmung, kullankaivohenki) every time a subsidy law is released. Some time later many give up in despair.

The reason is the missing cover margin. The economy of a scheduled wind farm dictates the price level, at which the project can be realised. The price level of the necessary quality components dictates the material cost. The remaining margin after having deducted the own expenses for assembly is at the limit, at which a company can exist.

7. Economy generally and in Finland

Sales price of a wind turbine is for example

Rated Power 600 kW	1 Mio DM = 3 Mio FIM or 5000 FIM/kW
Rated Power1,5 MW	2,5 Mio DM = 7,5 Mio FIM or also 5000 FIM /kW

Add roughly 20% for foundations and grid connection.

Energy yield on a coastal site (6 m/sec hub height) of a 1,5 MW plant is around
3000 MWh/a or 780 kWh/m2.

Breakeven time is around 7 years in Germany, assuming 0,5 FIM/kWh. If the machine continues operation until the end of lifetime without major defects, it is like winning in the Lotto! Many individual persons see a windpower investment as a kind of retirement pension.

The typical German investor wants to have a short payback time and a long warranty. The time in between is risky for him.

With a 30% investment subsidy and 20p/kWh a wind power installation in Finland will have a payback time of typically 14 to 16 years. This is so close to the scheduled lifetime of 20 years, that the investment is risky. The insurance will pay for damage, but not for series damage or design faults, so there are many possibilities to increase the payback time to over lifetime. (Fig.14). Only the best sites in Finland are suitable, wind power applications in the inner country can not payback. (Besides possibly some small battery chargers in remote locations).

If we want the same payback time as in Germany, the subsidy would have to be 65%, which is unrealistic. In fact we may expect the subsidies to be cancelled totally in future.

The situation improves by designing with some 5% of additional cost for 30 years of lifetime with very small maintenance effort. The cost of generated electricity is acceptable, but the long time period introduces uncertainties. The calculated values are "soft". Nobody knows the electricity price level and the political situation in 30 years.

As the liberalised electricity market in Scandinavia does not allow an "Einspeisegesetz", the only basis for wind farm development in Finland is the demand for clean energy by the final consumers.

There is very few scope for improving economy through technology development. Manufacturer concentration and production in large series will lower the manufacturing prices somehow.

Only in the USA there is a tendency towards downwind twobladers for onshore applications.
This “American way” is not practicable in Europe or Scandinavia, as too dangerous or noisy.

Keyword is *Offshore*, also solving the problem of rare sites. Offshore plants are presently calculated to be more cost-effective as the higher wind speed will compensate for the foundation and connection costs.

The most economic offshore machine is larger than presently available onshore units. The development of large offshore machines takes place in Denmark by increasing and modifying existing plants from 1,5 MW to 2 MW. In Germany they favour a special compact 5 MW drive train. The available blades limit the development.

Generating costs of 22 to 26 p/kWh are already reached. The reduction potential is in the order of still some 10%. It is not possible to reach lower values due to basic physical laws.
Realised and planned offshore projects confirm these figures. (Fig.16)

One of the long-term keys to future success of wind power will be increasing cost of fossil fuel, and possibly a harm tax on conventional energies. The calculated cost of nuclear energy is constantly increasing in Germany, as the tear down of old plants and the final storage seems to be more costly than formerly assumed. The opinions on what is the generation cost seem to differ significally, see fig.15.

If wind farm financing takes place with low interest rates due to company-internal bank-credits, there is a further increase of economics, at least on the paper. Wind power is sensitive to the interest rate, as the operating costs are fairly small and the investment large. (Fig.17).

8. Tendencies and outlook

The largest coming technology step will be a fast and cheap manufacturing process for the blades. Injection moulding, automatic tape laying, injection of thermoplastics, etc are under investigation and in discussion. AERPAC already uses RIM (Resin Injection Moulding) generally. Coal fibre will replace glass.

One of the coming keywords will be blade removal in special pyrolysis plants.

The twoblader will come up again for offshore, , as in very large sizes it has significant technical advantage. The machine size will grow to 5 MW at 120 m diameter.

A natural limit is around 150m diameter due to gravitational loading of the blades. If still larger units are necessary, the vertical-axis machines will come up again (no gravitational fatigue).

The decreasing price of semiconductors will lead to increased use of inverter systems.

Permanent magnet price decrease will replace induction generators with permanently excited inverter drives, increasing overall efficiency.

9. Appendix

1. Typical blade section
2. Typical drive train
3. Stall effect
4. Power curve based on stall
5. Energy yield versus average wind speed
6. Typical power fluctuations of a "hard" drive train, induction generator
7. "soft" drive train, power is smooth above rated wind speed
8. Wind power in Europe
9. Wind power worldwide
10. The 10 first countries in wind energy
11. The 10 largest manufacturers of complete wind turbines
12. Wind power contribution to overall electricity consumption
13. Viewpoints of wind farm developer and wind energy converter manufacturer
14. Payback times of different wind power installations versus average wind speed
15. Different calculated electricity price levels in Europe
16. Calculated energy costs for some offshore wind farms
17. Factors influencing wind energy cost