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WIND-POWER FEASIBILITY
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FOREWORD

Wind energy is abundant and has a vast potential. Wind energy is currently one of the world's fastest growing energy sources, with the possibility to make a relevant contribution to a future based on sustainable, pollution-free electricity.

In response to such considerations, the WFEO Energy Standing Committee set up a Task Group to develop this Report on WIND-POWER FEASIBILITY - 2005. This Report gathers information on the state-of-the-art of the wind-power technology and its current technical and economic feasibility based on engineering criteria and technological maturity.

Members of the Task Group were appointed by WFEO Member Organizations.

This Report is being presented as a publication in the Energy Standing Committee Series on Feasibility of Current Energy Options. The Series is intended to give the viewpoint of the engineer on questions related to technical and economic feasibility of energy issues of significance to society. It aims at providing the engineer and decision-making officers with updated information regarding the state-of-the-art of different technologies that are being used or under consideration for the supply of energy.

WFEO hopes this report will assist the engineering community, policy and decision makers, and the public to be aware of the conditions that make wind-power utilization a feasible option for assuring sustainable development and mitigation of climate change effects.

Dato Ir. Lee Yee Cheong
President, World Federation of Engineering Organizations
September 2005

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WIND-POWER FEASIBILITY

1. INTRODUCTION

Wind energy is abundant and has a vast potential. In recent years, it has shown a good environmental advantage and, in a number of situations, it has gradually approached cost competitiveness.

Recent concerns for the environment, global warming, and remaining stock of fossil fuels have driven increased participation in wind energy by many countries, and states and municipalities therein. Since it is a clean energy that avoids greenhouse gas (GHG) emissions, wind energy has been part of the energy supply mix. Even if its competitiveness has not always been apparent, consumers accepted to pay more for such clean energy.

Although in absolute terms wind energy still represents a small amount of global energy supply, it should be realized that it is one of the world's fastest growing energy sources. Around the world today, wind-power already meets the electricity needs of around 14 million households, encompassing more than 35 million people.

The wind-power technology is a commercial mature technology in the sense that currently there are more than ten manufacturers offering high quality machines, that generate quality frequency for network electricity, and that is designed to operate continuously, unattended and with low maintenance, for 15 - 20 years. These machines are highly reliable, with an operating availability reaching about 98% [1].

There are over 55,000 wind turbines installed today. Globally, the industry employs around 70,000 people, is worth more than US $5 billion and is growing at a rate of almost 30% per year [2] [3].

Generally, the wind is harnessed in a cluster of wind turbines, called wind farm or wind park, with a size ranging from few megawatts up to 300 MW - the largest so far, in western United States.

Wind-power technologies are suited to small off-grid applications, good for rural and remote areas, where energy is often crucial in human development. In fact, the supply of energy from intermittently occurring and magnitude-variant wind current is not a constant, and this must be recognized in new developments.

2. GENERAL CONSIDERATIONS

2.1 THE WIND RESOURCE POTENTIAL

Wind energy, in common with other renewable energy sources, is broadly available but diffuse. Winds develop when solar radiation reaches the Earth's highly varied surface unevenly, creating temperature, density, and pressure differences. Tropical regions have a net gain of heat due to solar radiation, while Polar Regions are subject to a net loss. This means that the Earth's atmosphere has to circulate to transport heat from the tropics towards the poles. The Earth's rotation further contributes to semi-permanent, planetary-scale circulation patterns in the atmosphere. Topographical features and local temperature gradients also alter wind energy distribution.

The wind resource is available all around the world. Its distribution in each region of the world is described in Table 2.1 [4].

Table 2.1 - Estimated Annual Wind Energy Resources

Region	Land surface with wind class 3-7*		Wind energy resources w/o land restriction		Wind energy resources with <4% of land used	
	%	10^3 km^2	10^3 TWh	EJ	10^3 TWh	EJ
N. America	41	7,876	126	1,512	5.0	60
L. America & Caribbean	18	3,310	53	636	2.1	25
W. Europe	42	1,968	31	372	1.3	16
E. Europe & former USSR	29	6,783	109	1,308	4.3	52
M. East & N. Africa	32	2,566	41	492	1.6	19
Sub-Saharan Africa	30	2,209	35	420	1.4	17
Pacific Asia	20	4,188	67	804	2.7	32
China	11	1,056	17	204	0.7	8
Central & S. Asia	6	243	4	48	0.2	2
Total	---	30,199	483	5,796	19.3	231

* *Note: Wind energy with average power density of more than 250-300 watts per m^2 at 50 m (resources class 3 & higher in the U.S. classification of wind resources). The energy equivalent in Exajoules (EJ) is calculated based on the electricity generation potential of the referenced sources by dividing the electricity generation potential by a factor of 0.3 (a representative value for the efficiency of wind turbines, including transmission losses), resulting in a primary energy estimate. Totals are rounded.*

Source: WEC, 1994

Currently, offshore installations only constitute a very small part of the wind turbine market, but offshore wind is set to develop in a significant way and the potential offshore market is the main driver for large turbine technology development.

The only publicly, consistent, energy estimates for offshore Europe's wind resource are a European Commission study [5], that estimated the wind resource in offshore waters at up to 3,000 TWh/year.

2.2 HARNESSING THE WIND

Once the wind resource is established at a specific site, the engineering challenge is to harness the energy, convert it into electricity, and dispatch it to local consumers or nearby electrical grid system. In contrast to windmills common in the nineteenth century, a modern power generating wind turbine is designed to generate high quality, network frequency electricity, and operate continuously, unattended and with low maintenance, for more than 20 years.

A wind-power turbine transforms wind kinetic energy into electric power according to the formula [6]:

$$P = 0.5\ \rho\ A_r\ v^3\ C_p\ \eta\ \text{(Watts)}$$

where

- ρ = air density in kg/m^3 (~1.225 kg/m^3 at sea level and 15°C)
- A_r = surface developed by the rotary blades in m^2 ($\pi D^2/4$, D = rotor diameter in m)
- v = wind velocity (m/s)
- C_p = rotor aerodynamic power coefficient (~0.45)
- η = efficiency of the mechanical/electrical devices for electricity generation and transmission (~0.93-0.98).

The wind resource is the fuel for a wind-power station, and just small changes in speed and direction have large impact on the commercial value of a wind farm. Every time the average wind speed doubles, the power produced increases by a factor of eight, so even small changes in average speed can produce large changes in performance. In general, unless the annual average wind speed for a site exceeds 17 km/h, such location is not a candidate for a wind farm. Other factors including proximity to an energy consumer or electrical grid transmission line are also crucial.

Because of the sensitivity to wind speed, determining the potential of wind energy at a specific site is not straightforward. More accurate meteorological measurements and wind energy maps and handbooks are being produced, enabling wind project developers to better assess the long-term economic performance of projects.

Detailed and reliable information about how strongly, from which direction and how regularly the wind blows, is therefore vital for any prospective development. At a national and regional level, many countries have produced wind atlases which record the wind speed to be expected in particular areas.

Technological advancement in wind turbine and generator performance is still a significant topic of research globally.

2.3 ADVANTAGES AND DISADVANTAGES OF WIND ENERGY [7] [8] [9]

2.3.1 Advantages

Environmental aspects

Environmental aspects come into play in the three phases of a wind turbine project: building and manufacturing, normal operation during the turbine lifetime, and decommissioning. The environment advantage of a wind turbine is that it causes virtually no emissions of either greenhouse gases (GHGs) or other pollutants such as SO_2 or NO_x, during operation, and very little during the rest of the manufacturing and end-of-life removal cycle. Similarly, aside from fossil fuels used in the manufacture of wind farm equipment and its lubrication, no fossil fuels are consumed or combusted and virtually no waste streams are created.

Building and manufacturing. No exotic materials or manufacturing processes are required in producing a wind turbine or building the civil works of the wind farm.

Normal operation. Aero-acoustic research has provided design tools and blade configurations to make blades considerably more silent, reducing the distance needed between wind turbines and residential and commercial areas, and people.

The energy balance of a wind turbine is very favorable. A 1997 study of a typical turbine by the Danish Wind Industry Association shows that a modern wind turbine recovers all the energy inputs involved in its manufacture and operating life within three to four months – i.e. over its lifetime, an average turbine will provide 63-78 times more energy than used to construct, operate and eventually dismantle the turbine.

Decommissioning. Because all components are conventional, the recycling methods for decommissioning the wind turbine are also conventional. Most blades are made from glass or carbon fiber reinforced plastics, processed by incineration. To replace glass and carbon and close the cycle of material use, wood composites are being applied and bio-fibers developed.

Technological and geo-political aspects

Global benefits of wind-power are:

- Reduction of climate change effects and other environmental pollution
- Diversification of energy supply, eliminating imported fuels
- Provision of energy security and prevention of conflict over natural resources
- Reduction of poverty through improved energy access
- Provision of a hedge against price volatility of fossil fuels
- Free, abundant and theoretically boundless fuel source
- Rapid installation of modular generation equipment.

From an energy security perspective, a healthy and growing contribution of wind energy is suitable to the security and diversity of any energy portfolio, and reduces dependence on fossil fuels. For global areas where fossil fuel and other energy sources are scarce, expensive, or tied to foreign suppliers, wind sources may offer significant advantages toward a secure energy provisioning.

2.3.2 Disadvantages

Environmental aspects

Negative environmental aspects connected to the use of wind turbines are: acoustic noise emission, visual impact on the landscape, impact on bird and bat life, and moving shadows caused by the rotor. In practice the noise and visual impact cause the most problems increasing public resistance against the installation of new turbines in densely populated areas.

Acoustic noise emission prevents designers from increasing the tip speed of rotor blades, which would increase the rotational speed of the drive train shaft and thus reduce the cost of gearboxes or generators.

In Spain, in some regions of the Mediterranean coast, wind farms have changed patterns of seasonal migration habits of some African bird species causing ecological disruption. The impact on bird and bat life is attenuated if the turbines are properly located. A research project in the Netherlands showed that the bird casualties from collisions with rotating rotor blades, on a wind farm of 1,000 megawatts, are a very small fraction of casualties from hunting, high voltage lines, and vehicle traffic.

Visual impact has created court actions in cases real estate values would be impaired by the installation of offshore wind parks in front of highly valued property; this was the case of several projects along the Atlantic Ocean coastline in Massachusetts, USA.

As with many other energy options, the construction of transmission lines from remote off-shore projects has provoked opposition from local residents, like in the Scottish Highlands.

Technological and security aspects

In the case of wind, the output is not only intermittent but also unpredictable beyond a few days' notice. Managing the intermittency of wind energy is a particular challenge that requires specific treatment for integrating wind-power into electricity systems [10] [11]. Aspects related to reliability of supply, alternative flexible resources, operational reserves, availability for load demand and grid reinforcement add non-negligible costs to wind-power integration.

Wind-power intermittency is reflected in the plant capacity factor that, according to recent performances around the world, has been in the range of 17 to 38% for on-shore plants, and of 40 to 45% for off-shore ones [10].

Wind turbine electromagnetic interference with radio, television, telecommunication and radar signals are relevant technological negative aspects. Radar interference for landing approach into some airports, and security on the UK coastline was considered an important drawback by airport authorities and defense officers.

3. STATUS OF WIND TECHNOLOGY

3.1 STAGE OF THE TECHNOLOGY [12]

Commercial wind turbines started in earnest in the 1980s, and in the last twenty years turbine power has increased by a factor of 1000. In the same period wind-power generation life-cycle costs have declined by some 80 percent.

From units of 20-60 kW in the early 1980s, with rotor diameters of around 20 m, generators of single wind turbines have increased to 5,000 kW, at the time of writing, with rotor diameters of over 100 m, as shown in Figure 3.1

Some prototypes designs for offshore turbines have even larger generator outputs and rotor diameters. The dramatic increase in size and technological know-how, coupled with economy of scale from fast growing production volumes have greatly reduced the cost of wind-power to the point where some high yield onshore wind farms are approaching a range of competitiveness with conventional power generation technologies.

Market demands drive the trend towards larger machines: economies of scale, less visual impacts on the landscape per unit of installed power, and expectations that offshore potential will soon be developed.

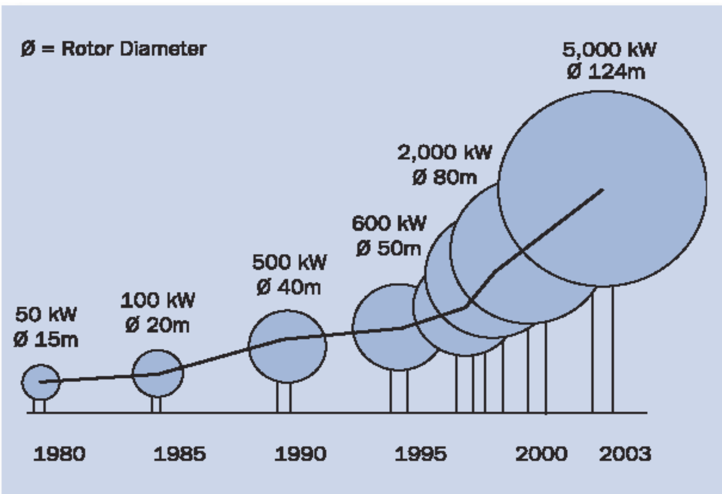

Figure 3.1 – Increase of Wind Turbine Rotor Diameter

Table 3.1 shows the status of wind turbine current technology as related to the unit power generated [6]

Table 3.1 – Wind Turbine Current Technology

Power (kW)	Rotor Diameter (m)	Tower Height (m)
500-600	40-45	45-65
600-1000	46-57	55-70
1500-2500	65-80	65-80
3000-4500	80-112	80 -124

Note, however, that the optimum size of a turbine -in cost, impact, and public acceptance- differs for onshore (nearby as well as remote) and offshore applications.

The output of stall regulated wind turbines is hardly controllable, apart from switching the machine on and off. Output varies with the wind speed until reaching the rated wind speed value. As the application of the aerodynamic stall phenomena to structural compliant machines gets more difficult with bigger turbines, blade-pitch control systems are being applied. For structural dynamics and reliability, a blade-pitch system should be combined with a variable speed electric conversion system. Such systems typically incorporate electronic AC-DC-AC converters. Modern electronic components have enabled designers to control output -within the operational envelope of the wind speed- and produce good power quality. These developments make wind turbines more suitable for integration with the electricity infrastructure and ultimately for higher penetration. These advantages are of particular interest for weak grids, often in rural and remote areas that have large wind resources.

For lower costs and greater reliability and maintainability, designers seek technology with fewer components -such as directly driven, slow-running generators, with passive yaw and passive blade pitch control. Already in 1998, 34 percent of the installed power in Germany was built with this type of technology.

The high cost of complete offshore installations implies the use of large wind turbines, of the order of 3 - 6 megawatts. Offshore design features include special installation concepts, including electricity conversion and transport systems, corrosion protection, deep water foundations, and integration with external conditions (both wind and wave loading). Outages onshore can often be corrected quickly so that only a small amount of energy is lost. But, offshore, the window for carrying out repairs or replacing components is often limited requiring redundancies and more resistant materials.

As it will be seen in Section 5 – Wind-Power Grid Integration, because wind energy is intermittent, wind turbines mainly deliver energy, but with little capacity value: frequently, such energy is expressed in terms of the capacity factor times the rated turbine output at peak wind (as noted below, this capacity factor is often of the order of 20 percent or less of the installed wind-power). This percentage falls when the penetration of wind turbines increases, requiring even more back-up power for a reliable energy supply. Wind-generated electricity can be transformed from intermittent to base-load power if it is combined with other means of storage, for instance batteries, compressed air energy storage or hydro-pump storage. In this way a high capacity factor can be achieved with an economic penalty, potentially about $0.01 per kilowatt-hour.

Meteorological research on predicting the output of wind farms a few hours in advance has produced computer programs that optimize the operational and fuel costs of regional electricity production parks (Denmark, Germany).

The capacity factor (annual energy output/output based on full-time operation at rated power) depends on local winds and wind turbine design. By optimizing the turbine characteristics to the local wind regime, the capacity factor can be optimized to values on the 20–25 percent range.

Mechanical noise has been practically eliminated and aerodynamic noise vastly reduced. Aerodynamic noise often up to 50 decibels A-scale (dBA) is typically at or close to background noise from other sources and imperceptible to the human ear. Wind turbines and generators have proven to be highly reliable, with operating availability of about 98%.

3.2 WIND INDUSTRY STATUS [12] [13]

The industry has changed significantly in the last seven years. Seven years ago, a wind farm of 20 MW would be considered large – today the largest single wind farms have nameplate capacities of over 500 MW. The growing scale of wind-power projects and a larger market have bought new players into the market, including industrial conglomerates, as well as conventional power companies.

The progress of wind-power around the world has been rather large in recent years, with Europe leading the global market. By the end of 2004, approximately 48,000 MW of wind turbine capacity were operating in 50 countries around the world. Of these, more than 34,600 MW (72.7 %) were installed in the Europe Union. The average annual market growth in Europe over the last decade has been in the region of 30 %. The U.S. Department of Energy has announced a goal of obtaining 6% of U.S. electricity from wind by year 2020 -a goal that is consistent with the current rate of growth of wind energy nationwide.

Offshore is a new emerging market segment. Some 600 MW of offshore wind-power capacity has been installed in the seas of the Netherlands, Denmark, Sweden, Ireland and the U.K. According to the Douglas Westwood World Offshore Wind Database, a further 9,000 MW is scheduled for construction in northern Europe by the end of 2006.

Figure 3.2 shows the growth of worldwide total installed wind-power capacity.

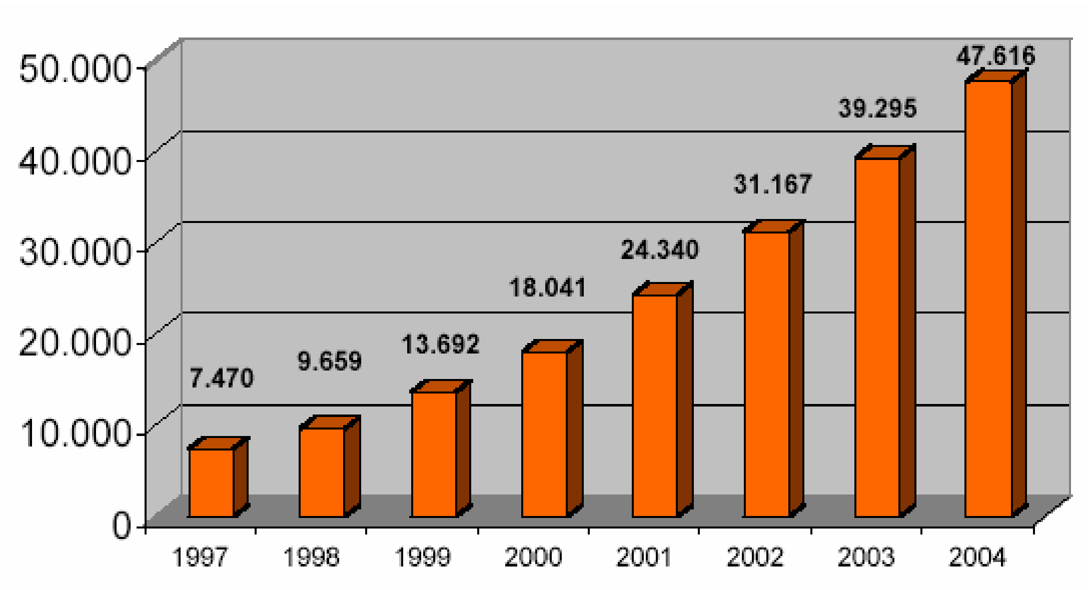

Figure 3.2
Growth of world total wind energy installed capacity (MW) [14]

Figure 3.3 shows the wind-power capacity distribution by regions.

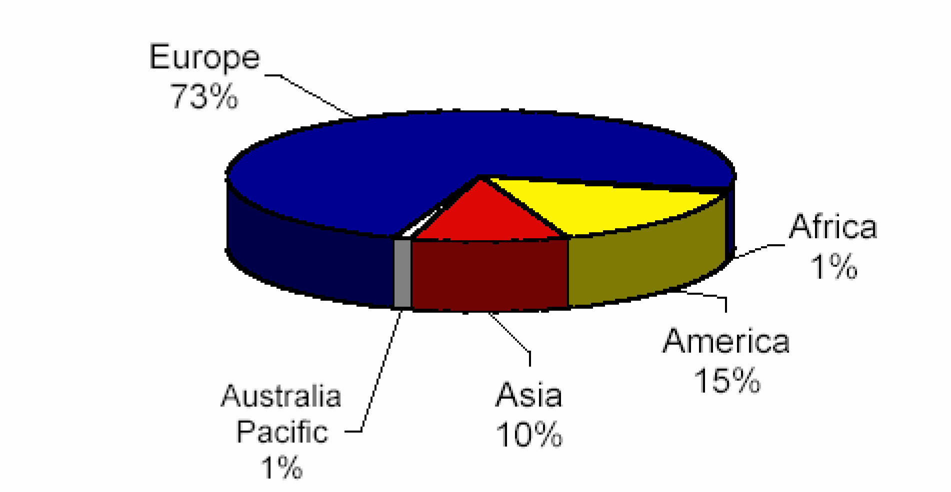

Figure 3.3
World wind energy installed capacity (MW) by continent
as of 31 December 2004 [14]

Installed wind-power capacity in the ten wind-power top countries is listed in Table 3.2.

Table 3.2 - Top ten countries total installed wind-power capacity as of 31 December 2004 [15]

COUNTRY	MW	% World Total
Germany	**16,629**	**35.1**
Spain	**8,263**	**17.5**
United States	**6,740**	**14.2**
Denmark	**3,117**	**6.6**
India	**3,000**	**6.3**
Italy	**1,125**	**2.4**
Netherlands	**1,078**	**2.3**
United Kingdom	**888**	**1.9**
Japan	**874**	**1.8**
China	**764**	**1.6**
Top Ten Total	**42,478**	**89.8**

Source: GWEC

In the year 2005, the European Union countries' installed capacity is expected to generate electrical energy with a capacity factor around 23%.

4. <u>WIND PARK IMPLEMENTATION</u> [12] [16] [17]

Previous sections have discussed turbine state-of-the-art and the wind resource. This section presents a brief summary of the design of a wind farm as a whole.

4.1 PRELIMINARY LAYOUT DESIGN

The design of a wind farm is a compromise between electrical grid access, road access, easy permitting and commercial viability.

Once a site has been identified and the decision has been taken to invest in its development, the wind farm design procedure commences. This is inevitably an iterative process. The first task is to define the constraints on the development:

- Maximum installed capacity (due to grid connection or power purchase agreement terms)
- Site boundary
- Restrictions from roads, dwellings, overhead lines, ownership boundaries, etc.
- Environmental constraints
- Location of noise sensitive dwellings and assessment criteria
- Location of visually sensitive viewpoints and assessment criteria
- Exposure to wind source, and turbine minimum spacing as defined by the turbine supplier
- Constraints associated with communications signals such as radar signals and microwave link corridors.

Once constraints are known, a preliminary layout is defined. The selection of a specific turbine model is often best left to the more detailed design phase when the commercial terms of the various suppliers are known. The wind resource at the site is the key parameter in determining its economic viability. To assess the capacity of the project it is necessary to install anemometry equipment at the site. The preliminary layout allows the wind measurements to be made in appropriate locations and better define constraints to be ultimately considered.

4.2 DETAILED LAYOUT DESIGN

A key element of the layout design is the minimum turbine spacing used. In order to ensure that the turbines are not being used outside their design conditions, the minimum acceptable turbine spacing should be obtained from the turbine supplier and adhered to. The appropriate spacing for turbines is strongly dependent on the nature of the terrain and the wind rose at a site. If turbines are spaced closer than five rotor diameters (5D) in a frequent wind direction, it is likely that unacceptable high wake losses will result. For areas with predominantly unidirectional wind roses, such as the San Gorgonio Pass in California, or bi-directional wind roses such as in Galicia, Spain, greater distances between turbines in the prevailing wind direction and tighter spacing perpendicular to the prevailing wind direction will be more productive. Tight spacing requires approval by the turbine supplier if warranty arrangements are to be kept in force. As a first estimate, an average value for land use is ~10 MW/km^2.

The detailed design of the wind farm is facilitated by the use of commercially available wind farm design tools (WFDTs). Once an appropriate analysis of the wind regime at the site has been undertaken, a model is set up which can be used to design the layout, predict the energy production of the wind farm, and address economic and planning related issues.

For large wind farms, a computational optimization using a WFDT may identify a layout for which substantial gains in predicted energy production are achieved. Even a 1% gain in energy production from improved micro-sitting (maximizing the energy production of the wind farm whilst minimizing the infrastructure and operating costs) is worthwhile. The computational optimization process will usually involve many thousands of iterations and can include noise and visual constraints. WFDTs conveniently allow many permutations of wind farm size, turbine type, hub height and layout to be considered quickly and efficiently. Financial models may be linked to the tool so that returns from different options can be directly calculated, further streamlining the development decision-making process.

In many countries the visual influence of a wind farm on landscape is an important issue. The use of computational design tools allows the zone of visual influence (ZVI), or visibility footprint, to be calculated to identify what areas will be visible from the wind farm and to predict the noise and shadow flicker from a proposed development. These are often key aspects of the project environmental impact assessment.

4.3 INFRASTRUCTURE

It is important to devote adequate attention to the infrastructure needed to support turbine/generator operation and to transmit the energy produced to local consumers or commercial electric grid.

For a typical onshore wind farm, the cost of the turbines is approximately 75% of the total cost of the farm. This infrastructure is often called the “balance of plant”. There are three essential elements of the balance of plant: the foundations; the electrical works; and the supervisory, control and data acquisition (SCADA) system which links all the turbines to a central computer and acts as the wind farm “nerve centre”. A typical cost breakdown for medium sized wind turbine (850 kW – 1500 kW) is shown in Figure 4.1.

4.3.1 Foundations

The foundations must be adequate to support the turbine under extreme loads, including wind, ice, and seismic factors. Normally, the design load condition for the foundations is the extreme, once-in-50- year wind speed. In Europe, this wind speed is characterized by a three-second gust which would probably lie between 45 and 70 m/s. At the lower end of this range, the maximum operational loads are likely to be higher than the loads generated by the extreme gust and would therefore govern the foundation design. The turbine supplier normally provides a complete specification of the foundation loads, including any vortex shedding resulting from desired turbine spacing, as part of a tender package.

The following formula gives approximately the weight of a turbine (including rotor, generator and I&C):

$$W = D^2 / 57.8$$

where, W is the weight in Ton and D is the rotor diameter in m [6].

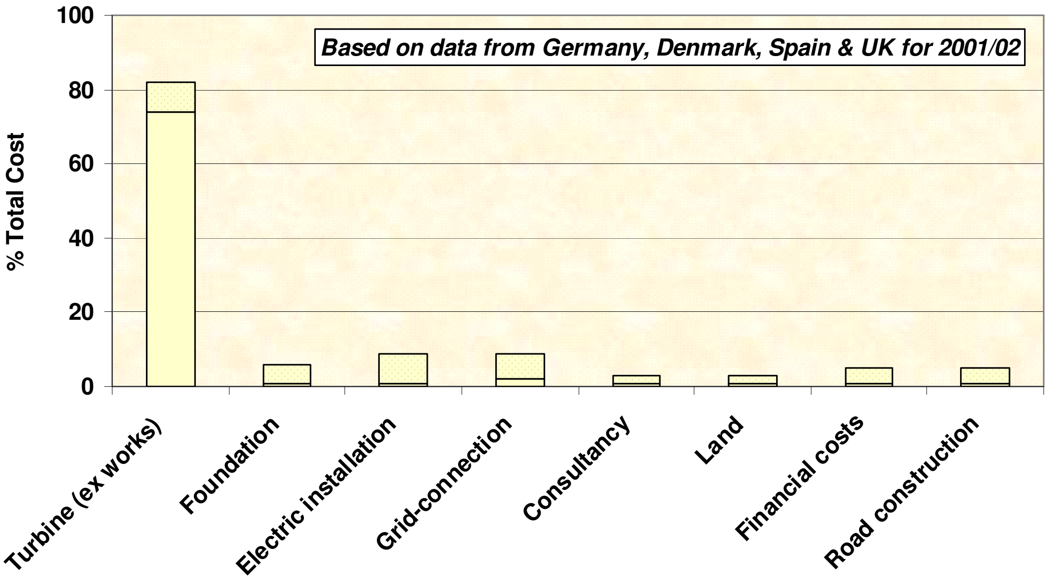

Figure 4.1 – Typical cost breakdown for a medium sized wind turbine farm

A typical foundation would be around 13 m across a hexagonal form and one to two meters deep, made of reinforced concrete. The construction time for such a foundation is normally less than a week.

4.3.2 Electrical works

The turbine generator output field voltage is often 690 V although some larger modern turbines generate at 10-12 kV. For the vast majority of onshore wind farms, the voltage output of the turbine generator is connected via cable or rigid bus to a pad mount transformer which steps the voltage up to a level used by the local distribution system or external grid -usually between 10 and 138 kV. The transformer is either mounted on a plinth beside the turbine foundation or, for bigger turbines, is contained within the base of the tower. The individual transformers are connected by underground cables to an internal circuit or grid which takes the power to a substation. A typical electrical layout is shown in Figure 4.2.

The substation sometimes distributes power to local consumers (e.g., manufacturing plant) but usually contains another transformer which steps the voltage up from the internal grid/circuit level to the distribution or transmission level of the external power grid. It can be anywhere in the range from 10 kV upwards; a typical external grid level would be 20 to 138 kV or possibly higher. The custody transfer metering for the wind farm will usually be located at the high voltage circuits existing in the substation.

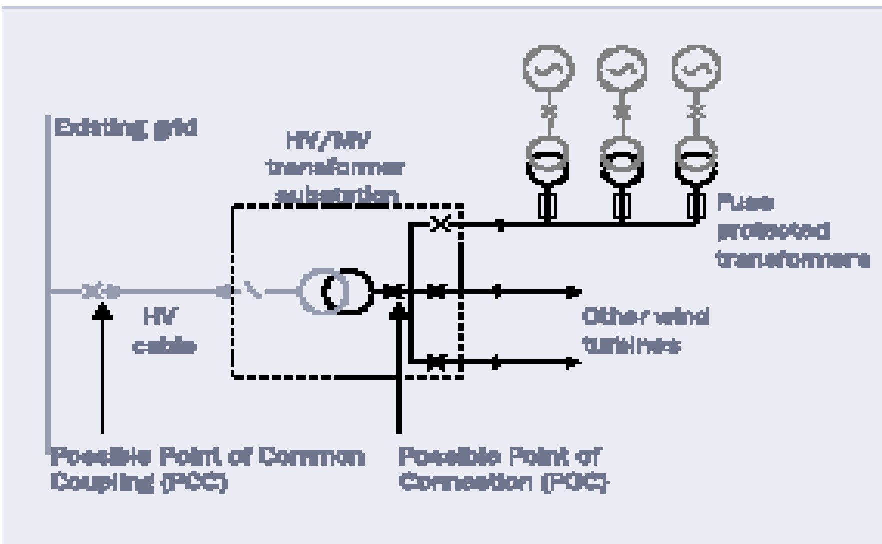

Figure 4.2 – A typical electrical layout

Design requirements for the internal grid need to comply with two conditions: the losses must be kept to a minimum (usually less than 2.5% of annual energy), and the design must allow the turbines to connect safely to the external power grid and satisfy both local grid requirements, usually in the form of a "grid code", and turbine specifications [18].

4.3.3 SCADA and instruments

In addition to the equipment needed for a functioning wind farm, it is advisable to erect permanent anemometry, if the project size can warrant the investment. This equipment allows the performance of the wind farm to be carefully monitored to find out whether there is more or less than expected wind resource. Large wind farms usually contain a permanent meteorological mast which is installed at the same time as the turbines.

A vital element of the wind farm is the SCADA system which connects the individual turbines, the substation and meteorological stations to a central computer. This computer and the associated communication system allow the operator to supervise the behavior of all wind turbines and the wind farm as a whole and, where applicable, to communicate with the external grid operator. Activities and operating data are recorded at least every 10 minutes, allowing the operator to take corrective actions, if required, and energy output, availability and error signals are logged to serve as the basis for performance assessments and improvements, possible warranty claims, and revenue collection if the energy is sold under a power purchase agreement with an external party. SCADA systems typically utilize fiber optic communication wire, remote terminal units, metering, computers (man-machine interface), and other hardware, and typically communicate directly with the wind farm's control system as well. Alarms, such as from protective relaying on electrical equipment, may also annunciate into the SCADA system.

4.4 CONSTRUCTION

A wind farm may be made up of few turbines or a large number of turbines - possibly several hundred. The design approach and the construction method will, however, be almost identical whatever the size.

Due to its modular characteristics and its relatively reduced capacity, a 10 MW wind farm can easily be built within a couple of months. The construction of a wind farm is more akin to the purchase of a fleet of trucks than it is to the construction of a power generating station. This allows minimizing interests during construction and price changes during project implementation, since the turbines can be purchased at a fixed cost agreed upon in advance and a delivery schedule will be established. In a similar way, the electrical infrastructure can be ordered well in advance -again at a fixed price. Although there may be some variable costs associated with the civil works, this cost variation will be small if compared to the cost of the project as a whole.

4.5 COMMISSIONING AND OPERATION

Commissioning of an individual wind turbine takes little more than two days. The long-term availability of a commercial wind turbine is usually in excess of 97%. It will take a period of some six months for the wind farm to reach full commercial operation; during that period availability will increase from around 90% immediately after commissioning to the long-term level of 97% or more.

Commissioning tests will usually involve standard quality control and performance tests of the electrical infrastructure, generator, metering and the turbine proper, and inspection of routine civil engineering quality assurance records.

It is normal practice for the supplier of the wind farm major equipment to provide a warranty for between two and five years. This will often cover lost revenue, including downtime to correct faults and a test of the power curve of the turbine/generator. During the first year of turbine operation some "teething" problems are usually experienced. For new turbine or generator models this effect has traditionally been more marked.

After commissioning, the wind farm will be turned over to the operation and maintenance (O&M) crew. A typical crew will consist of two people for every 20 to 30 wind turbines installed. For smaller wind farms there may not be a dedicated O&M crew but arrangements will be made for regular visits from a regional team. Typical routine maintenance time for a modern wind turbine is 40 hours per year. Non-routine maintenance may have a similar duration.

The building permits obtained in order to allow the construction of the wind farm may have some ongoing environmental reporting requirements, for example the monitoring of noise, avian activity or other flora or fauna interest. Similarity, there may be, depending on local bye-laws, regulatory duties to perform in connection with the local utility. Therefore, in addition to the normal O&M activity, there is often a management role to perform in parallel. Many wind farms are the subject of project finance and hence reporting to lenders will also be required.

The noted SCADA system allows an owner/operator to staff wind farm operations and complete data collection from a point remote from the farm itself. Unlike with other forms of power generation, there are few operating conditions requiring the attendance of personnel, and most unusual events (e.g., electrical trip from external grid source, turbine overspeed, generator fault) result in simple turbine/generator shutdown.

5. <u>WIND-POWER GRID INTEGRATION</u> [19]

The variable nature of the power output from intermittent generation sources brings with it a number of issues that require special consideration to be fully understood and managed. Intermittent generation sources are not new concepts as they have been a component of several electricity systems for some time. An informed understanding of their impact in the context of an electricity market will enable intermittent generation to be developed to its potential and at the same time integrated successfully into the external power grid.

The main issues of integrating intermittent generation technologies into the power system appear in the following areas:

- Accuracy of central forecasting processes for power generation,
- Frequency control ancillary services,
- Voltage control, and
- Network management.

Forecasting

Increased penetration of non-scheduled and intermittent generation will create additional uncertainty in reserve forecasting processes. When the contribution of non-scheduled generation has a large highly-variable nature, the way to supply demand will be increasingly difficult to predict, as generation reserve forecasts will require shorter-span updating.

This could translate into higher reserve level requirements to cover uncertainties in the availability of intermittent generation. Thus, the output of intermittent generation may result in a specific source of uncertainty for scheduled demand inputs right up to the time of dispatch. Some of this uncertainty may be overcome through use of external storage devices and systems (batteries, compressed air storage, hydro-pump storage). Generation forecasting also has many site dependencies, as they relate to capacity factor and local grid power demand.

Frequency Control Ancillary Services

Unforeseen variations in generation (supply) and customer loads (demand) cause power system frequency deviations within the external grid. In certain situations, the effect of frequency variation in other interconnected plants could make their output to vary up or down by up to 50% of nameplate rating. Some manufacturers prefer that their generating units trip during large frequency disturbances to minimize any risk of plant damage. In order to maintain frequency within a strict range, frequency control ancillary services are utilized, namely, by using another generation plant to counteract most of this variation in generation in real time. If the variable output from intermittent generating units is not compensated with a complementary change of output of another generation source, then a corresponding deviation of frequency on the power system will be set off.

Intermittent generation to the external grid will increase the uncontrolled variation of generation levels and will amplify the need for, and usage and cost of such ancillary services. In many countries, causers of frequency deviations pay directly for the ensuing control frequency services. In some countries, Market Generators pay about 30% of regulating service costs, and Market Customers pay the remainder.

The amount of service needed for a single wind farm may be of the order of 30% of nameplate rating. Whereas, for large amounts of diverse wind generation at various locations, only 5% to 10% of the total wind generation nameplate rating may be needed. If appropriate forecasting is found to be feasible, it may result in intermittent generators being able to reduce their exposure as causers of grid frequency deviations. For grids wherein the contribution of wind energy is very small, wind energy suppliers are in general not the cause of frequency deviations.

Voltage Control

Voltage is regulated by reactive power inputs and outputs to the external grid. Contingency events, including loss of a large generating unit, failure of a transmission line or disconnection of an industrial load require voltage regulation. The ability of generating units to remain on-line during disturbances is an important aspect of this issue. Just as frequency is regulated by controlling active power, voltage is regulated by controlling reactive power.

Voltage is regulated in external grids principally by the following means: (a) transformer tapping; (b) capacitor bank (and reactor) switching; (c) synchronous and static compensators, and (d) generating-unit excitation and regulator systems. Methods (a) and (b) are switched in fixed amounts to change the turns ratios of transformers connected to the grid and to provide fixed amounts of reactive power respectively. Due to their switching nature, they are not normally switched frequently to regulate short term variations in voltage. Methods (c) and (d) act continuously and can be adjusted to any level over their range of operation to automatically and rapidly regulate grid voltage within the range of tolerance.

Some equipment is switched in and out, or generators are altered, at certain times of day in anticipation of the usual load variation on the grid. Such adjustments are not made, or are inadequate for the frequent changes in voltage due to intermittent generation. At distribution levels, the usual methods of voltage control are transformer taps and capacitor bank switching at the substations. However, this equipment is designed to switch only a few times per day with the slow variation of system demand, and more frequent switching would increase maintenance costs and decrease component or plant life.

These methods of voltage control are also relatively slow acting and may impose short-term voltage variations downstream on customers' facilities and appliances. The variability of intermittent generation causes variability of voltage, particularly if connected to distribution networks or weak radial transmission networks that may not have specifically been designed to cater for significant and possibly rapid loading variations.

For highly variable intermittent generation such as wind generation, a higher cost of connection may be imposed to provide additional or upgraded voltage control facilities to the associated external grid. To avoid these additional costs and minimize customer impacts, it may be necessary for intermittent generation to provide a share of the local reactive power requirements in a continuously acting form, such as via synchronous and static compensators, generating unit excitation systems, or other forms of electronic control or support.

An important issue is that power system security principles assume that any credible contingency event, such as loss of a generating unit or transmission element does not lead to consequential events, which could lead to cascading tripping and, in the extreme, system instability, separation into islands and even system collapse. In this regard, the need for intermittent generation to withstand voltage disturbances is the same as for any other form of generation.

Network Management

Interconnector flows vary from the dispatch outcome when the balance between generation and load in different external grid regions varies from that assumed in forecasts for dispatch. Significant variations from interconnector flows controlled by dispatch targets may result in the flows on interconnectors exceeding operational limits.

A material increase in the amount of intermittent generation to the external grid may result in greater variability of the power flow on interconnectors and other network elements scheduled to operate at their limit and such events would increase the potential of interconnector power flows to exceed flow limits. Without an appropriate measure to keep flows within operational limits, a critical fault during this time may result in damage to the grid, connected generators and auxiliaries, power system instability and/or tripping of grid customer load.

Increased levels of intermittent generation such as wind turbine/generator addition will potentially reduce the ability of current approaches to control network flows. Therefore, the management of power flows on the grid transmission system will need to be upgraded to ensure they remain within operational limits based on transmission network capability.

Power system inertia may become an issue with an increase of intermittent generation in smaller sections of the power grid system or areas that may separate into islands. Intermittent generation technologies that use power electronic converters or asynchronous machine technologies tend to have little or no inertia, and provide no dynamic voltage support to the local network in the presence of network faults. Network power transfer capability due to transient stability considerations could potentially be reduced below accepted levels. Study of this phenomenon is typically accomplished by the owner or operator of the external grid to which the wind generation is proposed to be added.

6. ECONOMICS OF WIND ENERGY [17] [20]

The main parameters governing wind-power economics include the following:

- Capital investment costs, including auxiliary costs for foundation, grid-connection, physical property, interest paid on construction funds, and others.
- Operation and Maintenance (O&M) costs.
- Electricity production and power sales as a function of average wind speed and capacity factor.
- Turbine/generator lifetime.
- Discount rate.

6.1 CAPITAL COSTS

Wind farm capital costs are largely determined by two factors: the complexity of the site and likely extreme loads. The site may be considered complex if the ground conditions are difficult -hard rocks or boggy, for example- or if access is a problem. A very windy site with high extreme loads will result in a more expensive civil infrastructure as well as more complex turbine specification. After sitting engineering is complete and major equipment selected, the balance of project engineering and construction is not too complex. This is particularly true for land-based applications.

Capital costs of wind energy projects are dominated by the cost of the wind turbine itself (ex works). Figure 4.1 shows the cost structure for a medium sized turbine (850 kW to 1,500 kW) sited on land and based on data from the UK, Spain, Germany and Denmark. The turbine share of total cost is typically a little less than 80%, but, as shown in Figure 4.1, variations ranging from 74% to 82% do exist.

Other dominant cost components are, typically, grid-connection, electrical infrastructure (substation and transformer) installation and foundations. Other auxiliary costs, such as land or easement acquisition, road construction, or environmental permitting could represent a substantial proportion of total costs. There is considerable variation in the total level of these auxiliary costs, ranging from approximately 24% of total turbine costs in Germany and the UK, to less than 20% in Spain and Denmark. The costs depend not only on the site of installation, but also on the size of the turbine.

The total cost per installed kW of wind-power capacity differs significantly between countries. In 2003, the installed cost for a large wind farm was between €850 and €1,100 per kilowatt installed (at 1€ = 1.25US$, between 1,062 and 1,375 US$/kW).

Wind energy is very capital-intensive at project inception, with revenue not realized until after turbine/generator commissioning. The interest paid on capital investment is likely to be a significant component of project capital cost (see Section 6.3).

6.2 OPERATION AND MAINTENANCE COSTS OF WIND-POWER

O&M costs constitute a sizeable share of the total annual costs of a wind turbine. For a new machine, O&M costs might easily have an average share over the lifetime of the turbine of approximately 20%-25% of total levelized cost per kWh produced. Thus, O&M costs are increasingly attracting the attention of manufacturers seeking to develop new designs requiring fewer regular service visits and less out-time.

O&M costs are related to a limited number of cost components:

- Insurance
- Regular inspection and maintenance

- Repair and upgrades
- Spare parts
- Administration and O&M labor.

For insurance and regular inspection and maintenance, it is possible to obtain standard contracts covering a considerable portion of the turbines total lifespan. On the other hand, costs for repair and related spare parts are much more difficult to predict. Although all cost components tend to increase, costs for repair and spare parts are particularly influenced by turbine age, starting low and increasing over time.

Based on experiences from Germany, Spain, the UK and Denmark, O&M costs are, in general, estimated to be at a level of approximately 1.5 to 1.9 US$cent/kWh of produced wind-power seen over the total lifetime.

Data from Spain indicate that a little less than 60% of this amount goes strictly to O&M and installation, with this proportion split into approximately half for spare parts and the rest equally distributed between labor costs and fungibles. The remaining 40% is almost equally split between insurance, rental of land and overheads.

In Germany, a questionnaire by Dewi (2002) also looked into the development and distribution of O&M costs for German installations. For the first two years of its life, a wind turbine is normally covered by the manufacturer's warranty. After six years, total O&M costs constituted a little less than 5% of total investment costs, which is equivalent to approximately 0.75 - 0.87 US$cent/kWh.

6.3 COST OF ENERGY GENERATED BY WIND-POWER

The total cost per produced kWh (unit cost) is traditionally calculated by discounting and levelizing investment and O&M costs over the lifetime of the wind turbine, divided by the annual electricity production. The unit cost of generation is thus calculated as an average cost over the lifetime. In reality, actual costs will be lower than the calculated average at the beginning of the life, due to low O&M costs, and will increase over the turbine lifetime.

Turbines sited at good wind locations with high capacity factors are likely to be profitable, while those at poor locations may run at a loss. Due to the importance of the power production, this parameter will be treated on a sensitivity basis. Other assumptions include the following:

- The calculations relate to a new land-based medium sized wind turbine of 850 - 1,500 kW, which could be erected today.
- Investment costs reflect the range given in section 6.1, i.e. a cost per kW of 900 to 1,100 €/kW (1 € = 1.25 US$). These costs are based on data from Spain, UK, Germany and Denmark.
- O&M costs are assumed to be 1.2 c€/kWh as an average over the lifetime of the wind turbine.
- The lifetime of the wind turbine is 20 years, in accordance with most technical design criteria.

- The discount rate is assumed to range within an interval of 5% to 10% a year. In the basic calculations, an annual discount rate of 7.5% is used, and a sensitivity analysis of the importance of the interest range is performed.
- Economic analyses are carried out as simple national economic ones. No taxes, depreciation, risk premium, etc. are taken into account. Everything is calculated at fixed 2001 prices.

The calculated costs per kWh wind-power as a function of the wind regime at the chosen sites are shown in Figure 6.1 below.

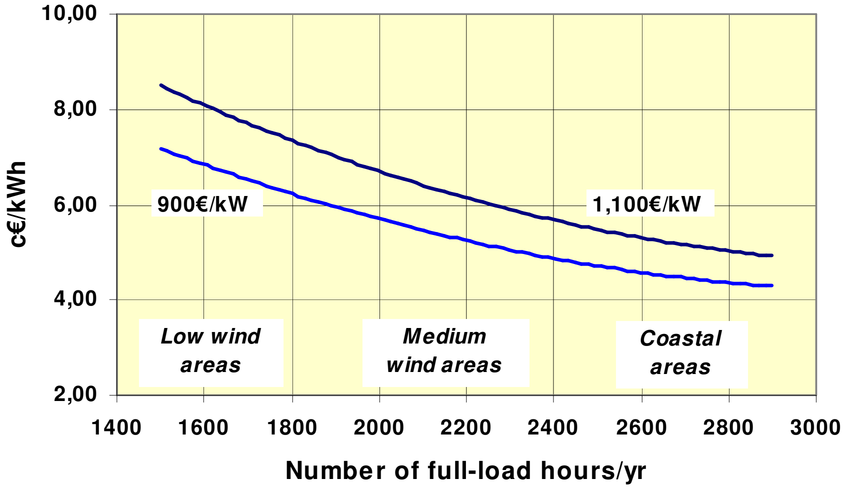

Figure 6.1
Calculated Costs per kWh Wind-power as a Function of the Wind Regime at the Chosen Site (Number of full load hours)

As shown, the cost ranges from approximately 6-8 c€/kWh (1 € = 1.25 US$) at sites with low average wind speeds to approximately 4-5 c€/kWh at sites with good average wind speeds.

In Figure 6.2, the costs per kWh wind-power are shown as a function of the wind regime and the discount rate varying between 5% and 10% a year.

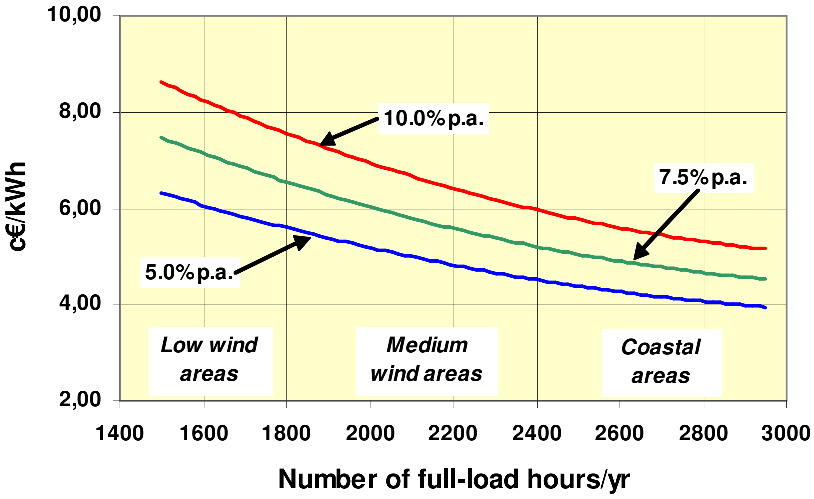

Figure 6.2
The Costs of Wind Power as a Function of Wind Speed (Number of full load hours) and Discount Rate (p.a.)

The cost per kW installed was considered to be in the mid-range of costs shown in Fig. 6.1. It can be seen that generating costs range between approximately 5 and 6.5 c€/kWh at medium wind positions, indicating that a doubling of the interest rate induces an increase in generating costs of about 30%.

Approximately 75% of total power production costs for a wind turbine are related to capital costs, i.e. costs for the turbine itself, foundation, electrical equipment and grid-connection. Thus, wind turbines belong to the so-called capital-intensive technologies compared with conventional fossil fuel-fired technologies such as a natural gas power plant, where as much as 40% - 60% of total costs are related to fuel and O&M costs. For this reason, the cost of capital (discount or interest rate) is an important factor for assessing the economic feasibility of wind-power.

6.4 COST OF WIND-POWER ELECTRICAL SYSTEM INTEGRATION [10]

Electricity supply and demand on a specific electrical grid must be balanced at every moment and flexibility on the management of supply is essential. Back-up generation, spinning reserves, and stored energy are typically used as flexible resources. During times when wind-power is not available, expensive peaking plants will have to be dispatched. Some of this reserve capacity has to be kept spinning even when the wind is blowing. One of the main utilities using wind-power in Germany estimates that spinning reserve capacity of some 50-60% of installed wind-power capacity must always be maintained [11].

The ability to plan wind-power generation is dependant on the capability to forecast wind availability. There are two aspects to be considered:

- actual meteorological wind prediction, and
- forecast of wind-power production based on the previous aspect.

The need for greater flexibility may be reduced by increasing the number of planning cycles needed in preparation of operation. The transmission system operator in the Western part of Denmark makes wind-power forecasts with a 13-37 hour-time horizon with an average error of 30-35%, implying that for every 100 MWh of wind-power, alternative resources must adjust their availability with some 30-35 MWh on average. In such a system, the quality of forecasts increases significantly when using a 36-hour period.

In addition to balancing supply and demand, the need for flexibility may arise on a short notice due to changes in grid demand or in wind-power supply during operation. To mitigate any deviations between forecasted wind-power and actual wind-power, additional reserves must be available. The needed amount of operational reserves will depend on the share of wind-power in the system compared to other on-line generators and the characteristics of the electricity system (e.g., demand pattern). If the need for operational reserves is assessed and contracted on a daily or hourly basis, as is becoming more prevalent, the needed amounts may have to be frequently adjusted by the grid operator, and possibly the generators, to the wind-power forecast.

During periods with no wind the power supply to meet demand must come from other sources. The need for resources as backup for wind-power may be denoted as the capacity cost of wind-power. The capacity cost of a given technology is not only depending on its reliability but also on the correlation of its availability and the demand load. The correlation between wind-power and load will depend on the characteristics of the weather and the electricity system on a specific location, but in general wind energy has usually a fairly low correlation with the load. The approach of assessing the capacity cost is to analyze the minimum level of wind-power production that can be expected during periods of peak load. This minimum level will correspond to the amount of alternative production capacity replaced by wind-power.

Another cost-related aspect of the intermittency of wind-power is the need of more developed control and operation systems of the external grid to which it is connected. With the expansion of the use of wind-power, some effects on electricity grids have been identified:

- at a certain share of wind-power and with large wind farms far away from the actual load, there will be a need for reinforcement of transmission and distribution grids,
- traditionally, large plants have been connected to the grid in a hierarchical structure for dispatching, with large shares of wind-power in a lower level of hierarchy close to the load, the control systems must be changed accordingly.

An overall assessment of costs of integrating wind-power into the power system is shown in Table 6.1. These costs are based on studies made by different European organizations in Germany (2004), West Denmark (2003), UK (2002) and several EU countries (2004).

Table 6.1 - Experienced & modeled costs of integrating wind-power [10]

<table>
<tr><th>Cost Studies</th><th>Germany</th><th>W. Denmark</th><th>U.K.[a]</th><th>EU countries[a]</th></tr>
<tr><th>Integration aspects</th><th colspan="4">c€/kWh of wind-power</th></tr>
<tr><td>Balancing</td><td>0.70</td><td>0.26</td><td rowspan="2">0.33</td><td>0.15-0.20</td></tr>
<tr><td>Operational reserves</td><td></td><td></td><td></td></tr>
<tr><td>Capacity costs</td><td></td><td></td><td>0.67</td><td>0.30-0.40</td></tr>
<tr><td>Transmission & distribution</td><td></td><td></td><td>0.40</td><td>0.25-0.30</td></tr>
</table>

([a]) at 20% wind-power share of consumption

7. **POLICY AND REGULATORY FRAMEWORK** [21] [22] [23] [24] [25]

Until external costs are fully integrated into conventional energy economics, some form of market incentive or subsidy is required to encourage the development of renewable sources, like wind-power. Whilst conventional power production technologies such as coal and hydropower continue to benefit from state aid, the cost to society of introducing new cleaner or renewable technologies into the market will continue to be comparatively higher.

An effective way of “internalizing” external costs is through harmonized energy taxes which reflect the actual environmental impact of each technology. In the absence of such a method of leveling the playing field, a more equitable electricity market can be encouraged by market incentives for electricity generated from renewable energy sources.

There are two main types of incentive currently in operation -fixed price systems and fixed quantity systems– as well as a range of other measures used to encourage investment in renewable technologies. These include capital grants towards the initial cost of projects, tax concessions for investors, and “green energy” marketing schemes through which consumers voluntarily pay an extra amount on their electricity bill in order to be supplied with power from a renewable generator.

Since the early days of wind-power development there has been a shift away from the use of capital investment grants on the basis that they encourage construction of the plant but not necessarily its efficient operation. This was the case with some of the initial wind turbines erected in India, for instance. However, there can still be a useful place for investment subsidies coupled with other market incentives; in the UK, for example, capital grants have been offered to the first round of offshore wind farms (to reflect specific additional costs) alongside their eligibility for the Renewables Obligation, a fixed quantity support system.

Fixed price systems and renewables quotas are both ways of creating a protected market, separate from the open electricity market where electricity from new renewable energy sources would have difficulty in competing with existing, already depreciated, hydro, nuclear or fossil based power plants.

There are also ways of offsetting (fully or partially) the competitive disadvantage arising from markets’ neglect of the environmental effects of conventional energy production.

The main purpose of the wide range of available economic measures to support wind energy and other renewable energy technologies is to provide incentives for technological improvements and cost reductions. The aim is to ensure the future availability of cheap, clean technologies as a competitive alternative to conventional power sources. In this case, it is less important whether markets are controlled through prices or through quantities.

The main difference between quota-based systems and price-based systems is that the former introduces competition between the electricity producers -the wind turbine operators. Competition between turbine manufacturers, which is crucial in order to bring down production costs, is present regardless of whether government dictates prices or quantities.

Fixed price systems

Operators of a renewable generation project are paid a fixed price for every unit of output, with the extra cost borne by taxpayers or all electricity consumers. In Germany, for example, the additional cost of the “feed-in tariff” introduced under the Renewable Energy Law is approximately US$ 1.23 per month on the average household electricity bill.

Fixed price systems have been highly effective at attracting wind energy investment in Denmark, Spain and Germany, which are among the top ten countries on total installed wind-power capacity as of 31 December 2004. Other countries with such systems in place are Austria, France, Greece, Luxembourg, the Netherlands and Portugal. However, Greece and France have had a slower than expected development because of difficulties with grid connection agreements and the planning process.

Fixed quantity systems

Also known as "renewables quota" systems, fixed quantity systems involve a decision on behalf of national governments on the level of renewable electricity to be achieved over a certain period, while market forces are left to establish the price. Under tendering versions of this system, as in Ireland, competitive bidding occurs for a limited number of power purchase contracts.

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