



## Progress and recent trends in wind energy

Ahmet Duran Şahin\*

*Energy Group, Department of Meteorology, İstanbul Technical University, Maslak, 34469 İstanbul, Turkey*

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### Abstract

Towards the end of 20th and beginning of the 21st centuries, interest has risen in new and renewable energy (RE) sources especially wind energy for electricity generation. The scientists and researchers attempted to accelerate solutions for wind energy generation design parameters. Our life is directly related to energy and its consumption, and the issues of energy research are extremely important and highly sensitive.

In a short time, wind energy is welcomed by society, industry and politics as a clean, practical, economical and environmentally friendly alternative. After the 1973 oil crisis, the RE sources started to appear in the agenda and hence the wind energy gained significant interest. As a result of extensive studies on this topic, wind energy has recently been applied in various industries, and it started to compete with other energy resources. In this paper, wind energy is reviewed and opened for further discussion. Wind energy history, wind-power meteorology, the energy–climate relations, wind-turbine technology, wind economy, wind–hybrid applications and the current status of installed wind energy capacity all over the world reviewed critically with further enhancements and new research trend direction suggestions.

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**Keywords:** Incentive; Pitch control; Stall control; Power meteorology; Wind energy; Wind modeling; Wind turbine; Wind–hybrid system

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\* Tel.: +90-212-285-3127; fax: +90-212-285-3129.

E-mail address: [sahind@itu.edu.tr](mailto:sahind@itu.edu.tr) (A.D. Şahin).

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## 1. Introduction

Energy is available in two different alternatives, non-renewable (coal, fuel, natural gas) and renewable (solar, wind, hydro, wave) sources. Especially, after the industrial revolution, in the 19th century, first coal and then fuel oil are used as primary energy sources for the needs of modern communities.

As known fossil fuels have limited potential and at current rates of exploitation they are expected to deplete within the next centuries. This is one of the reasons why clean, sustainable and environmentally friendly alternative energy resources are currently sought. The accumulation of carbon dioxide in the lower layers of the atmosphere gives way to climate change, floods, intensive rainfalls

and droughts. In order to reduce these dangerous effects, it is the responsibility of each country to improve the quality of the energy resources, and if possible, to replace fossil fuels (coal and oil) with renewable alternatives wind, solar and other energy sources.

Faced with energy crises in 1973 western countries began to search for their own clean and renewable energy (RE) sources (wind, solar, biomass, etc.) which are effective but they must inevitably compete against the conventional energy sources. In this competition, energy sources with huge and renewable raw materials have the advantage in the long run. Atmospheric environment is polluted due to thermoelectric power plants, and petroleum materials since the industrial revolution. The pollution crises are the catalysts for the search and development of RE sources.

The environmental impact of fossil fuels, in the form of air pollution, acid rain and greenhouse effects in addition to their limited availability gave added importance to the use of conventional and renewable alternative energy sources, such as solar, wind and solar-hydrogen energies. Recently, renewable and clean energy generation technological developments facilities became available on the energy market. Among the renewable alternatives, wind energy has an important potential role, and wind-power farms are becoming widely used all over the world.

Wind energy can be utilized for a variety of functions ranging from windmills to pumping water and sailing boats. With increasing significance of environmental problems, clean energy generation becomes essential in every aspect of energy consumption. Wind energy is very clean but not persistent for long periods of time. In potential wind energy generation studies fossil fuels must be supplemented by wind energy. There are many scientific studies in wind energy domain, which have treated the problem with various approaches [1–3]. General trends towards wind and other RE resources increased after the energy crises of the 20th century [6].

During the last decade, wind energy is developed and extended to industrial use in some European countries including Germany, Denmark and Spain. Their success in wind energy generation has encouraged other countries to consider wind energy also in their electricity generation systems. Its clean, economic, practical and renewable interaction with the environment soon draw attention from political, business circles and individuals. The concept of RE is utilized since 5000 BC, and wind energy is one of the oldest of these energy sources. Today, humanity is attempting to rediscover its lost or forgotten energy sources [4,5]. Opinion surveys from Europe indicate that most people support wind energy uses.

Over 2000 year, water and windmills powered the world's first industries with new technology and materials. Modern wind turbines are used to generate the clean electricity needed for lighting, heating, refrigeration and other uses. Wind energy is a rather young industry, but one which already makes good economic sense. It is a proven success and its use is increasing and the downward trend in its costs is expected to continue. Already over 20,000 turbines are producing worldwide electricity. Most are operating in 'wind farms' as groups of wind turbines generating electricity on a significant scale. Single wind turbines are also being used for generating electricity, charging batteries, driving pumps and producing heat.

In the search for RE power, the most important decisions are concerned with exploitation of local, clean and sustainable energy resources. The determination of wind energy potential depends very much on the meteorological measurements of the wind direction, velocity, and solar irradiation. Unfortunately, in many parts of the world, it is difficult to obtain such data.

The physics behavior of wind shows great temporal and spatial variability. In meteorology, wind is air in motion, whose driving force is the uneven heating and cooling of the earth's surface. The horizontal movement of air parallel to the earth's surface is a measure of the wind in both direction and magnitude, which change most frequently. As a result, wind prediction is very difficult due to random change both in wind direction and speed. This changeability adds another measure importance to wind power.

Wind power has unique characteristics for energy technology. The most significant impact on the environment is the visibility of wind turbines. Those who support the movement towards clean, sustainable energy production should take into consideration aesthetically pleasing symbols of a better future, especially when compared with the effects of acid rain, global climate change, radioactivity, land and water contamination in addition to other environmental problems associated with conventional energy sources.

## 2. Historical background

The power of the wind has been utilized for at least 3000 years. Wind energy first used for boat navigation on the Nile river 5000 BC. During the same period, windmills pumped water in China. The first written information on wind turbines is based on a simple structural horizontal axis wind turbine during the region of Alexander the Great. It is known that the Persians used vertical axis wind turbines during 700 BC. Windmills are introduced to the western world at the beginning of the 12th century from Islamic world [7]. During this century, Abou-l Iz who lived in Diyarbakır, Turkey, developed the first modern vertical wind turbine [8,9]. Until the early 20th century wind power is used to provide mechanical power to pump water or to grind cereals.

The earliest windmills had vertical axis. These windmills are simple drag devices and they are used to grind grain in the Afghan highlands since the 7th century BC. The first details about horizontal axis windmills are found in historical documents from Persia, Tibet and China from about 1000 AD. This windmill type has a horizontal shaft and blades (or sails) revolving in vertical plane. From Persia and the Middle-East, the horizontal axis windmill spread across the Mediterranean to central Europe. The first horizontal axis windmill appeared in UK around 1150 AD, in France 1180, in Flanders 1190, in Germany 1222 and in Denmark 1259 AD. This rapid spread is most likely influenced by the Crusaders who carried the knowledge of windmills from Persian to Europe.

In Europe, windmill performance is continuously improved between the 12th and 19th centuries. By the end of the 19th century, the typical European windmill used a rotor of 25 m in diameter and the stocks reached to 30 m.

Windmills are not only used for grinding grain, but also for pumping water to drain lakes and marshes. By 1800, about 20,000 modern European windmills are in operation in France alone. In the Netherlands, 90% of the power used in industry is based on wind energy. Industrialization led to a gradual decline in windmills, but even in 1904, wind energy provided 11% of the Dutch industrial energy requirements and Germany had more than 18,000 units raised.

By the time, European windmills began to disappear settlers introduced them to North America. Small windmills, pumping water for livestock became very popularly known as American windmills, which are completely self-regulated, hence they could be left unattended. The self-regulating mechanism pointed the rotor windward during strong wind speeds. European style windmills usually had to be turned out of the wind or the sailing blades had to be rolled up during extreme wind speeds, to avoid damage to the windmill. The popularity of windmills in the US reached its peak between 1920 and 1930 when about 600,000 units were in operation. The historical development of wind-turbine technology is documented in many publications [10–26].

In 1891, the Dane, Poul LaCour built the first wind-turbine generated electricity. Danish engineers improved the technology during the World Wars I and II and used the technology to overcome energy shortages. The wind turbines built by the Danish company F.L. Smith in 1941–1942 can be considered the fore runners of modern wind turbine generators. The Smith turbines are the first examples that use modern airfoils based on the knowledge of aerodynamics. In the mean time, the American, Palmer Putnam built a giant wind turbine with a diameter of 53 m for the Morgan Smith Co. Both the size and design philosophy of this machine are significantly different. The Danish design is based on an upwind rotor with a stall regulation, operating at slow speeds. Putnam's design was based on a downwind rotor with a variable pitch regulation. Putnam's turbine, however, was very successful [10].

In Denmark, after World War II, Johannes Juul further developed the Danish design philosophy. His turbine, in Gedser, Denmark, generated about 2.2 million kWh between 1956 and 1967. At the same time, the German, Hütter developed a new approach which is known as Hütter's turbine and became known for its high efficiency [10,26,27]. Despite the early success of Juul and Hütter's wind turbines, the interest in large-scale wind power generation declined after World War II. Only small-scale wind turbines received interest for power systems in remote areas, or for battery charging. With the oil crises in the beginning of the 1970s, interest in wind-power generation resumed. As a result, financial support for research and development of wind energy became available. Germany, US, Spain and Denmark developed large-scale wind turbine prototypes in the MW range. It is universally acknowledged that today's wind turbines capacities are advanced from those of 15–20 years ago. Since then, there have been some

Table 1

Development of wind turbine size between 1985 and 2002 [26,28]

Year	Capacity (kW)	Rotor diameter (m)
1985	50	15
1989	300	30
1992	500	37
1994	600	46
1998	1500	70
2001	2000	72
2002	2500	80

advances in understanding the aerodynamics and other fundamental technological areas, such as aerofoil design, tower interaction and noise production. Most progress, however, has occurred in the areas of production quality, mass production and in improving reliability. In addition to these, profitability has been the main design driver during this development period. At the end of 1989, a 300 kW wind turbine with a 30-m diameter was a state of the art. Only 12 years later, 2500 kW turbines are constructed in many wind farms. Four and five MW wind turbines are expected to become available at the end of 2002 or in the beginning of 2003 (Table 1).

### 3. Global climate change and greenhouse effect

The history of the planet shows that climate changes occur from time to time in different parts of the world. There are some differences between present day climate change and other times. Historical climate changes resulted from natural phenomena and they affected some parts of the world. Today climate change occurs due to human activities. Historical periods of earth climate are given in Table 2 [29].

Global climate change is now believed to be the most serious environmental threat facing the human race. Scientists have predicted that the average temperature around the world will increase from 1 to 3.5 °C by 2100. This is a rate of warming greater than at any time over the last 10,000 years, expected to lead to rising sea levels, flooding of low-lying coasts and islands. More frequent storms and unpredictable weather situations are also expected.

The mean global air temperature has increased between 0.3 and 0.6 °C since the middle of the 19th century until the present. Fig. 1 includes global air temperature fluctuation between 1860 and 1996. The highest temperature values are observed geographically at mean and high latitudes of the northern hemisphere during nights. Seasonally, the highest values are observed during winter and spring months in the northern hemisphere. Continental values are two or three times higher than global temperature values [30].

Table 2  
Historical periods of earth climate [29]

Date (year)	Region	Climate
BC 9000–6000	Southern Arizona	Hot and dry
BC 7800–6800	Europe	Cold and humid, ice mass occurred 7000 BC, left Switzerland in 6840 BC
BC 6800–5600	North America and Europe	Cold and dry, mammals died out
BC 5600–2500	Both hemispheres	Hot and moist
BC 2500–500	Northern hemisphere	Generally hot and dry
BC 500–MS 0	Europe	Cold and moist
AD 330	America	Drought in south
AD 600	Alaska	Moving glaciers
AD 590–645	Near East and UK	Extreme drought after cold winters
AD 673	Near East	Black sea freezes
AD 673–800	Mexico	Beginning of the moist period
AD 800–801	Near East	Black sea freezes
AD 829	Africa	Freezing in Nile river
AD 900–1200	Iceland	Calm conditions at glaciers
AD 1000	Africa	Freezing in Nile river
AD 1000–1100	Utah	Snow height is greater by 300 m than today
AD 1200	Alaska	Moving glaciers
AD 1000–1215	America	High moisture in west
AD 1220–1290	America	Drought in west
AD 1226–1290	America	Extreme drought in southeast
AD 1300–1330	America	High moisture in west
AD 1500–1900	Europe	Generally cold and dry
AD 1880–1940	Both hemisphere	Warming winter temperatures (about 11 °C); 5.2 m decrease in lake ice levels. 40% decrease Arctic glaciers; 25% decrease in Alp glaciers

### 3.1. Main greenhouse gases

The greenhouse effect can be defined briefly as an atmospheric temperature increase, due to gas emitted by human activities. Emissions of the main anthropogenic greenhouse gas, CO<sub>2</sub>, are influenced by:

- size of the human population,
- amount of energy used per person, and
- level of emissions resulting from energy use.

There are two related gas categories, which influence the greenhouse effect. These are,

1. CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, CFC-11 and CFC-12, which do not allow heat transfer to space, but reflect heated waves to earth, and
2. NO<sub>2</sub>, CO and OH radicals, which interact with greenhouse gases. As a result of this interaction the concentration of greenhouse gases increase.

Concentrations of CO<sub>2</sub> and CH<sub>4</sub> values did not change until the 18th century but then increased yearly [31–38].

Historical variations of greenhouse gases are given in Table 3. It is clearly seen that CO<sub>2</sub> has great effect upon the greenhouse phenomenon. If concentration of these gasses doubles, the temperature increase would be changed

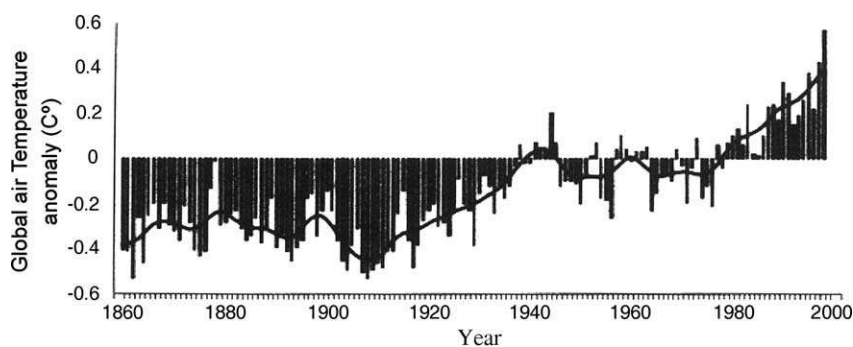


Fig. 1. Average global air temperatures between 1860 and 1996. Changes in global air temperatures depend up mean values between 1960 and 1996. Source: IPCC 1996a [31,32].

Table 3

Concentration change of some atmospheric greenhouse gases (ppm: one million per particula, ppmv: volumely per million, ppbv: volumely per billion, pptv: volumely per trillion) [34]

	CO <sub>2</sub>	CH <sub>4</sub>	CFC-11	CFC-12	N <sub>2</sub> O
Atmospheric concentration	ppmv	ppmv	pptv	pptv	ppbv
1750–1800 years	280	0.8	0	0	288
1990	353	1.72	280	484	310
1990 yearly variability	1.8 (0.5%)	0.015 (0.9%)	9.5 (4%)	17 (4%)	0.8 (0.25)
Atmospheric lifetime	50–200	10	65	130	150
Temperature increase values if concentration doubles (°C)	3.0 ± 1.5	0.3–0.4	0.1	0.1	0.3

between  $3.0 \pm 1.5$  °C. This situation means that human kind will be faced with the biggest disaster ever seen.

### 3.2. Energy production and greenhouse gases

As mentioned earlier, half of the greenhouse gases due to CO<sub>2</sub>. The production of CO<sub>2</sub> is dependent on human attitudes, especially, towards energy production. Sources of global warming effects are related to energy production nearly 50% (CO<sub>2</sub> 41%, CH<sub>4</sub> 6%, N<sub>2</sub>O 3%) and other parts of greenhouse gases are not released with energy production (C<sub>2</sub>O 9%, CH + 13%, O<sub>3</sub> 8%, CFC 17%). O<sub>3</sub> and CFC values contribute to global warming, but they have not relation with energy production. CO<sub>2</sub> productions for each energy source are given in Table 4. It is seen that highest CO<sub>2</sub> values are produced by non-conventional energy sources as wind and nuclear energy sources have minimum levels. Nuclear energy produces dangerous radioactive gases and wastes [31].

### 3.3. Developing international policy to protect the climate

A good starting point for tracing the development of international environmental policy is the Stockholm conference of 1972, which resulted in the formation of the UN Environment Program (UNEP). Climatic change was of concern in the first world climate conference, held in Geneva in 1979. Another landmark was the publication of 'Our Common Future', by the Brundtland Commission in 1987, which called for the protection of the atmosphere and the reduction of greenhouse gas emissions. The 1985 Vienna Convention, and the 1987 Montreal Protocol on substances that deplete the ozone layer are major examples of international agreements to protect the atmosphere. Climate change is placed firmly on the world's agenda by the Toronto conference of 1988. The conference statement called for the reduction of CO<sub>2</sub> emissions by 20% of the 1988 levels by 2005. In the same year, the Intergovernmental Panel on Climate Change (IPCC) was established in UNEP and the World Meteorological Organization. The IPCC is an intergovernmental scientific and technical body consisting of a small secretariat, a bureau and a global network of about 2500 scientists and experts.

The UN Conference on the Environment and Development (UNCED) was held in June 1992, in Rio de Janeiro, 20 years after the Stockholm conference. It covered a range of subjects and there were a number of developments, including the Framework Convention on Climate Change (FCCC), which came into existence in March 1994. The latest assessment was published in 1996. One of the most effective protocols was developed in Kyoto in December 1997, a very important milestone to establish an international framework for climate change policy in the 21st century. A policy is expected to be adopted regarding quantified emissions limitations and reduction these objectives are some of the key elements of the protocol [40–42]. The Kyoto Protocol has been discussed from several perspectives, a scientific [43], and economic perspective [44,45] discussions of the necessary and sufficient conditions for reducing CO<sub>2</sub> emission intensity and achieving the Kyoto Protocol [46–49].

### 3.4. Technical policy to protect the climate

In addition to developing international policy to protect the climate, technically RE sources are considered and wind energy has the greatest capacity to increase RE sources. At the end of 2003, around 23,357 MW of wind energy capacity had been installed in Europe. These turbines save between 38 and 43 million tons of carbon, nitrogen oxide and sulphur dioxide, main gases responsible for acid rain. This would realize a saving of nearly 50 million tons of

Table 4

CO<sub>2</sub> emissions production for all energy sources [39]

Energy source	Maximum value (g/kWh)	Minimum value (g/kWh)
Coal	1290	860
Fuel oil	890	689
Natural gas	1234	460
Hydraulic	410	16
Nuclear	30	9
Wind	75	11
Solar-PV	279	30
Biomass	116	37



carbon dioxide per year. Wind energy reduces emissions from polluting gases because every unit of electricity produced by wind power replaces a unit of electricity generated by other means. These are usually coal-fired plants, which tend to be taken ‘off-line’ when supply exceeds demand. Coal-fired power stations typically emit around 800–1200 g of CO<sub>2</sub> for every unit (kWh) of electricity they produce. Therefore, each unit of electricity produced by wind energy avoids an equivalent amount of emissions [50].

Combined with other renewable technologies and efficient energy use, wind power is crucial in reducing global climate change, acid rain and other environmental problems, because it produces no carbon dioxide (a gas that contributes to global warming), sulphur dioxide or nitrogen oxides (gases that contribute to acid rain), and hazardous or radioactive wastes.

It is well known that wind energy is one of the cleanest and most environmentally friendly energy sources, and unlike fossil fuels, the wind will never be depleted. All forms of energy production have an environmental impact, but the impacts of wind energy are low, local, and manageable. The production of blades, the nacelle, the tower, etc. the exploration of the material and the transport of equipment need to energy consumption. In addition to energy consumption, scrap metals remain when these devices have outlived their usefulness. These environmental impacts are negligible when compared with conventional energy sources. The significance of wind energy originates from its friendly behavior to the environment. Due to its clean, wind power is sought wherever possible for conversion to electricity with the hope that air pollution from fossil fuels will be reduced [51,52].

#### 4. Wind power meteorology

Most new and RE sources are based on meteorological variables, such as wind, solar power, hydraulics and wave. If meteorological characteristics of these RE sources are not well known, there will be important gaps in energy investments. Power meteorology concept is discussed by different authors [50,51].

As a meteorological variable, wind describes fuel of wind energy. In energy production, wind takes the same role as water, and wind variables should be analyzed. Wind-speed deviation and changeability depend on time and area. This situation requires a new tendency for wind-speed modeling and search for the atmospheric boundary layer (ABL) modeling as a special consideration in wind-power research. There are many papers concerning these subjects. For instance, Petersen et al. [52] considered wind-power meteorology in their paper, where they sought the relationship between meteorology and wind power. Their paper states that wind-power meteorology is an applied

science, based on boundary layer meteorology, with a relationship to climatology and geography. Furthermore, wind-power meteorology includes three terms as wind-turbine micro-siting, the assumptions of wind as a power source, and the short-term wind prediction. Wind-power meteorology is not a standard meteorological term; and it must be considered as a combination of meteorology, applied climatology and fluid physics. The results of wind-power meteorology are geographical specific. During the preparation of the Denmark Wind Atlas detailed research was performed on wind energy, as a meteorological source [53,54]. The most effective meteorological variables as temperature, pressure and moisture play important roles in wind occurrence. Generally, in wind engineering, moisture changeability is negligible and air is assumed to be in a dry condition. This situation can cause important errors in calculations and energy plans [55,56].

##### 4.1. Wind and its physics

Winds are described due to their source directions. Origins of western, southwestern winds and valley breezes are, respectively, west, southwest and the valley itself. Wind velocity changes depend on latitude, longitude, attitude and time. Fig. 2 represents east–west mean values, global winds for January and July, respectively. West–east winds occur at upper troposphere, generally with westerly origin. Jet winds have maximum values at nearly 10 km heights in both figures. Near equator and pole surfaces winds are weak. Western winds are located at 30–60° latitudes at surfaces of middle hemispheres. In summer months, speed of eastern winds increase with height. Near surface winds occur by pressure gradients and these gradients cause to temperature gradients, which lead to strong winds [57]. General circulation and main wind patterns near earth’s surface are shown in Fig. 3.

Wind is one of the meteorological variables and can be described as a motion of air masses in synoptic scale with potential and kinetic energies. They occur as a result of potential energy transformation to kinetic energy by pressure forces [53,58]. In wind engineering applications, horizontal winds are important because they cover greater areas.

Dynamic behavior of atmosphere generates spatio-temporal variables as pressure, temperature, density and moisture, etc. These variables can be described by equations based on continuity principles, first law of thermodynamic, Newton’s law and the state law of gases. Air continuity, thermodynamic and momentum conservation equation components at three directions are atmospheric dynamic equations. Atmospheric movements such as geostrophic, gradient, surface, height and surface winds around low air pressure and atmospheric waves can be explained on the basis of special equations.

Each mathematical equation represents atmospheric spatial variables. These models depend on initial

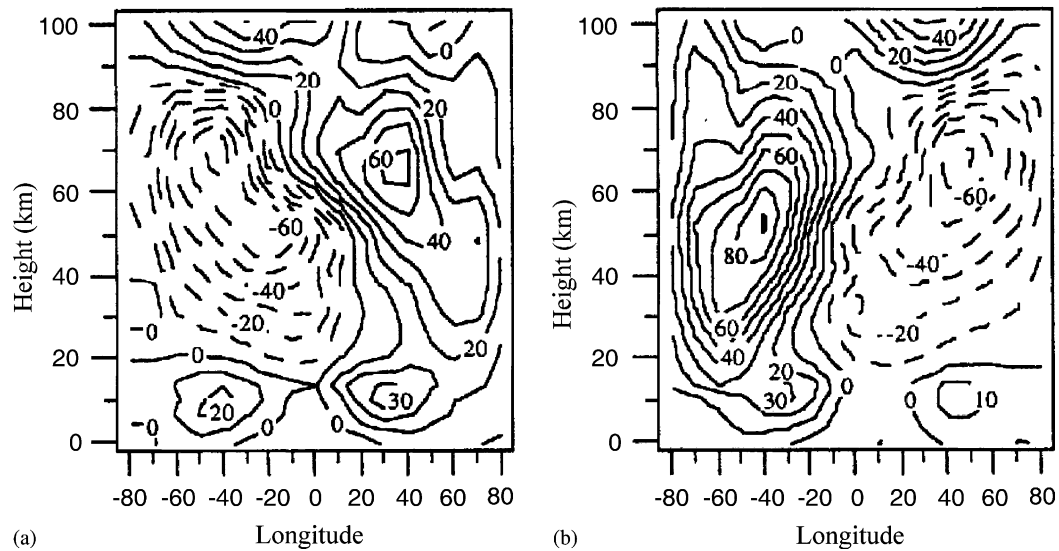


Fig. 2. Regional east–west scale mean wind speed (m/s). (a) January, (b) July [57].

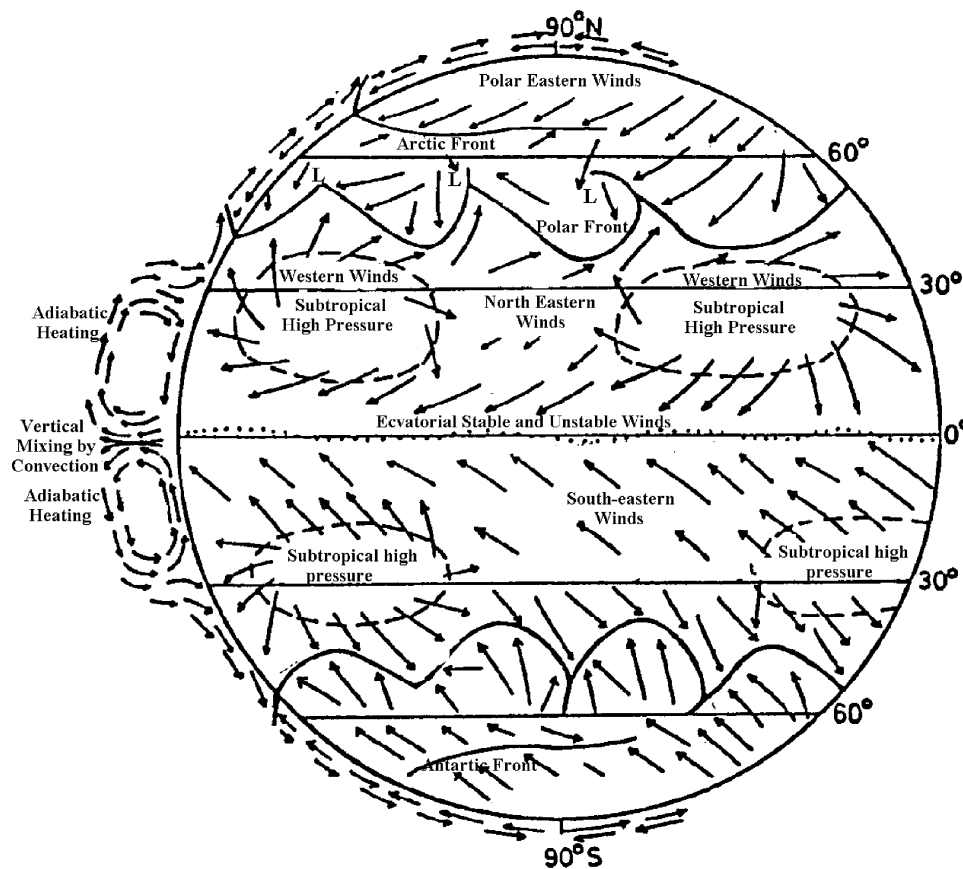


Fig. 3. General circulation.



and boundary conditions and they can be solved by ratios of time variables and finite element with variation intervals. In atmosphere, motion changes between 1 mm and 1000 km. At ideal conditions, mathematical models are based on 1 mm and 1 s time intervals. This situation should be observed so as to make models at different time scales [52].

Synoptic system is another main factor for windy areas. Generally, land–sea interaction areas are windy with stable conditions for wind speed and direction. High differences between heating and cooling during the day lead to the second-degree windy areas in valleys. Astronomical seasonal time is important for heating and cooling depending on sun position and area location. Although these features provide advantages in wind engineering applications, but discontinuities cause to disadvantages in wind energy studies. In practice, topographical stable areas can be found easier than temporally stable areas. In other words, discontinuity is the main problem in wind energy studies.

#### 4.2. Geostrophic winds

At some conditions, wind can be related with basic and measurable variables. Geostrophic wind has two main features, as no friction and blows parallel to isobars. Winds in nature are good approximations to geostrophic winds especially in the upper troposphere. This is because winds are considered truly geostrophic only when the isobars are straight and there are no other forces acting on it, and these conditions are not found too often in nature.

#### 4.3. Gradient winds

This kind of wind does not have straight flow and can represent real wind due to consideration of centrifugal force. All the winds that occur at low and high-pressure systems with consideration of centrifugal force give a real approach to wind physics [5,59].

Non-theoretical winds depend on the topographical conditions and features, which are sea–land and valley breezes together with adiabatic–catibatic winds with thermal origin.

#### 4.4. Turbulence and gusts

In 1883, Osborne Reynolds published the result of experiments on fluid flow and showed that it may be laminar or turbulent. For wind, laminar flow means air that flows along streamlines without whirling motion mixing of the air in different stream layers. However, in turbulent flow, there is a whirling motion and air mixture. In the case of fluid flow in a pipe, dimensionless Reynolds number shows the transition from laminar to turbulent. This number is defined as  $\mu r/\nu$  where  $\mu$  = average velocity of the fluid,  $r$  = radius of pipe, and  $\nu$  = kinematic viscosity of the fluid [60]. As the Reynolds number increases the stress decreases down to

a critical Reynolds number of about 2100 which marks the transition from laminar to turbulent flow.

Winds in the open area are almost always turbulent, although when they flow over hills of good aerofoil shape, there may be compression of streamlines, which damp out the turbulence and, for some wind-power calculations, because of laminar flow. The variations in the wind flow consist of gusts accompanied by small changes in its direction, which are commonly ascribed to eddies embedded in the general steady flow. In so far as these eddies are visualized, they are supposed to consist of more or less circular disturbances with the wind. If the flow in an eddy coincides with the wind direction the velocity increases leading to a gust [61].

In wind engineering applications, turbulent variations of the wind speed are typically expressed by standard deviation of velocity fluctuations measured over 10–60 min. The variation in this ratio is caused by a large natural variability. This concept could not be explained by Gaussian processes. Turbulence occurs at ABL as a result of interaction between surface and atmosphere.

#### 4.5. Atmospheric boundary layer

The troposphere extends from the ground up to an average altitude of 11 km, with modifications in the lowest couple kilometers by the underlying surface. The boundary layer is directly influenced by the earth's surface, and responds to surface forcing with a timescale of about an hour or less. These forcings include frictional drag, evaporation and transpiration, heat transfer, pollutant emission and terrain induced flow modifications. The boundary layer thickness is quite variable in time and space, ranging from hundreds of meters to a few kilometers [62].

ABL, where heat fluxes are constant with height, changes during a day depending on the areal roughness effects. Turbulence intensity also changes temporally and spatially. Heat flux is the main factor for ABL occurrence with daily changes as in Fig. 4. It consists of three major parts as a very turbulent mixed layer, a less-turbulent residual layer containing former mixed-layer air, and a nocturnal stable boundary layer (SBL) of sporadic turbulence [62].

Furthermore, there are three parts of ABL as connective mixed, stable boundary, and residual layers. During sun rise earth surface is heated, and high-energy heat fluxes move to certain heights during the day. At night, SBL conditions are valid with temperature decrease over height. There are interactions between night SBL conditions and unstable heating conditions at the beginning of the day. Stable night conditions are dominant and depending on the sunrise environmental conditions they are also effective. Interaction degree of these conditions result in ABL instability, which is higher than turbulence intensity.

The mixed layer has cloudy and subcloudy conditions. At SBL conditions, wind speed changes with height

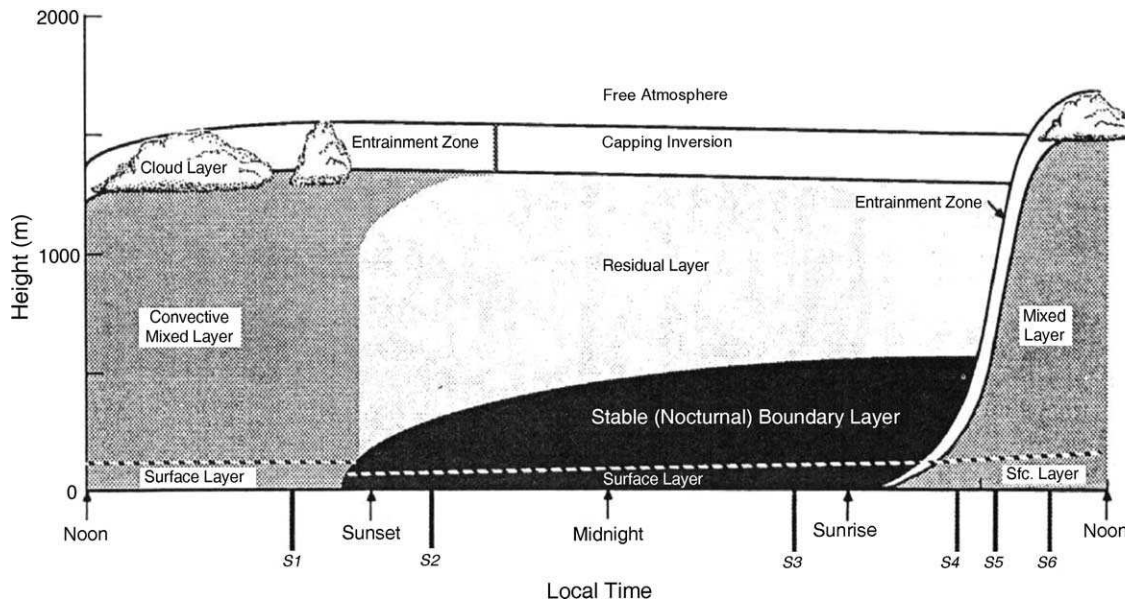


Fig. 4. The boundary layer in high-pressure region over land.

(see Fig. 5). This change accords with an exponential trend at SBL (approximately 500 m) with height, which gives another perspective to wind energy searches. Increasing hub height of wind turbine leads to more wind energy generation.

Generally, three conditions of ABL are neutral, stable and unstable conditions. In the neutral ABL, the temperature of the surface is equal to the temperature of the air. Within the stable ABL, the vertical wind follows a logarithmic profile. Above the stable ABL, the Coriolis force becomes important and the wind turns clockwise in the northern hemisphere and anticlockwise in the southern hemisphere.

In the unstable ABL, the surface temperature is greater than that of the air. This leads to a temperature inversion capping of the ABL where the turbulence is damped by a strong and stable stratification. The unstable ABL condition occurs during the day when the solar heating is important. On the other hand, in the stable ABL, the surface temperature is lower than air temperature, hence, the air heats the surface and the wind is weak near the surface generally with a maximum (low-level jet) at the top of the temperature inversion zone. The stable ABL occurs usually during the night.

In horizontally homogeneous terrain, the turbulence intensity is a function of height, roughness length and stability. General properties of air motion in ABL cause increase in wind speed with height, wind-speed fluctuations within ABL, turbulence distortion to wide frequency area, and relationships between turbulence at different heights.

Wind boundary layer is evaluated by Erasmus [63,64] at complex topographical conditions through objective analysis methods where topographical effects are conserved and this conservation does not impair wind flows.

In mathematical algorithm, surface roughness, valley slopes, changes in wind direction and mass conservation factors are taken into account. For instance, mesoscale wind valleys, like in the Tibetan plateaux are searched [65]. Valley wind takes more important role for daily mass flow distribution at plateaux. Smith and Macpherson [66] used wind measurements at wide sea surface for wind velocity estimation standard deviation and its direction. Linear scatter is valid at low-level wind speeds with 1-min autocorrelation relation between vertical wind-speed deviation and with horizontal wind speed. Carr et al. [67] proposed and compared two wind profile height–time relation methods. Wind turbulence patterns are searched over complex topograph in detail [68].

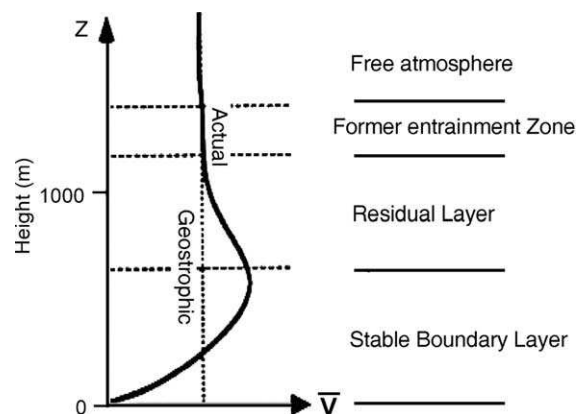


Fig. 5. Wind speed,  $\bar{V}$ , profiles for an idealized stable boundary layer in a high-pressure region [62].

#### 4.6. Wind profiles

The wind speed usually varies approximately logarithmically with height in the surface layer (see Fig. 5). In statistically neutral situations, a logarithmic relationship appears as straight-line wind profile. For non-neutral situations, the wind profile deviates slightly from logarithmic pattern. In SBLs, the wind profile is concave downward while unstable boundary layers are concave upwards.

The mean wind profile, averaged over periods of 10–60 min, is often described for engineering purposes by a power law approximation as,

$$\frac{U(z_1)}{U(z_2)} = \left( \frac{z_1}{z_2} \right)^p \quad (1)$$

where  $U(z_1)$  and  $U(z_2)$  are the wind speeds at heights  $z_1$  and  $z_2$ , respectively, and  $p$  is the power law exponent with a typical value of 0.14 [52].

#### 4.7. Wind modeling

Wind turbines give great expectations for electricity generation possibilities. Convenient site selection for efficiency is important and necessary. Wind energy and speed change with time and are not continual at the same area during the whole year. Additionally, solar irradiation, topography, pressure, temperature and moisture effect wind speed physically. Source of raw material availability and efficiency is the most important problem. If efficiency searches are not taken into account carefully, built energy plants would be imagination only. Especially, this sensitivity is important due to outside in other words natural phenomena. Characteristics of RE sources are more important because of natural phenomena and difficulty to control them.

In planning, design, operation and maintenance of wind farms, the spatial velocity variations are significant. Although, wind energy studies at a single site are plenty, but spatial assessment evaluation methods are scanty. Wind velocity maps provide a common basis for regional assessments and interpretations without regional prediction.

Wind speed is a regionalized variable measured at a set of irregular sites. The practical engineering question is whether the measurements have spatial dependence? What are the techniques for its identification? and finally, how this information is used in wind energy potential evaluations? Any atmospheric phenomenon has spatial variabilities that are recorded at a set of irregular sites. Any regional study searches simple but effective means of capturing the regional dependence structure. Such an efficient procedure is proposed by Matheron [69] in ore reserve simulation studies. The semivariogram (SV) method provides basis for the optimum interpolation approach through the Kriging procedure [70]. An ordinary SV shows the change of regional variability in terms of half-squared differences

between two sites as a function of distance between them. In general, the greater the distance, the more is the independence. At small distances, two records are expected to be close to each other. The changes of half-squared differences with distance are expected to have a non-decreasing shape. Unfortunately, this theoretical requirement is observed always in experimental SV. Şen [71] explained the reasons of such discrepancies, and suggested the cumulative semivariogram (CSV) where rather than the half-squared differences, their summations are considered in depicting the regional dependence. Both SV and CSV are considered irrespective to any direction, and consequently, the SV are referred to as the omnidirectional diagrams. Hence, they do not represent any point or direction, but globally, the whole phenomenon on an average manner over the entire region. Another type of SV for point predictions is referred to as point cumulative semivariogram (PCSV). It is proposed for identifying the local spatial behavior of any variable around a point, which is considered as the key site. Comparisons and groupings of PCSVs at different points provide quantitative and qualitative information for the heterogeneity and isotropy in wind speed field.

The PCSV can be converted to spatial dependence functions (SDFs) for practical wind speed predictions. First, the PCSV is transformed into a dimensionless form and then subtracted from one. The resulting values are between zero and one. Their change with distance shows a non-increasing trend, which is a representative of SDF. The greater the distance, the smaller is the dimensionless value. The SDFs have similar shapes to the sample correlation functions in time series analysis.

Şen and Şahin [72,73] searched wind speed of Marmara Region in Turkey by PCSV model for finding SDF. Spatio-temporal dynamics of wind energy formulation are also searched [74]. Şahin [5] developed a new alternative approach to PCSV for describing and finding both radius and area of influence. This new spatio-temporal approach is applied to wind data for identifying spatio-temporal correlation coefficient for each station.

Spatial interpolations from one point to another are evaluated by mapping or objective analysis methods. In meteorology and earth sciences, SV, CSV and PCSV methods are applied for spatial analysis [69–71,75]. Another important point is unmeasured or missing data problems, which can be solved by these techniques.

There are various methods for data interpolation from measurement stations to any desired point [76]. These are:

- (i) *Surface fitting methods.* The first objective analysis method in meteorology was the surface fitting type devised by Panofsky [77]. In this method, the analysis value is represented as a continuous mathematical function, which fits irregularly spaced observations. Among these methods are the polynomial interpolation [77], orthogonal polynomials [78,79], splines [80], and finally, spectral approaches [81].

- (ii) *Empirical linear interpolations.* Any variable at a particular location is estimated as a weighted sum of observations. Among such interpolation techniques are the iterative successive correction method [82], and Barnes analysis [83].
- (iii) *Statistical objective analysis.* These are estimation methods where spatial correlation structure determines the weights applicable to each observation site. The major approaches in this category are the optimal interpolation [84], the covariance models for atmospheric variable [85], adaptive filtering [86–88], and recently, the CSV method [71].
- (iv) *Variational techniques.* These have more mathematical abstraction basis than other methods and two of them are the incorporation of dynamic constraints [89], and the data fitting at different times [90].

Geostatistical methods are superior to other methods [91]. In contrast, an application of multivariate geostatistics is presented to problems of estimating areal average precipitation [92]. They are based on the classical semivariogram and Kriging techniques application. However, Şen and Habib [93] PCSV method of spatial precipitation assessments in mountainous areas is applicable also for the spatial wind pattern modeling.

Generally, complications in missing data problems are solved with the assistance of time series modeling and orthogonal functions [94–96]. Atmospheric variables typically exhibit dependence on preceding values [97]. Hence, temporal autocorrelation is one of the dependence measures along the successive values in a given time series at specified lag intervals. Hourly and daily wind areal predictions constitute a great occupation in meteorology. Microareas of wind prediction can be done for 48 h.

On the other hand, artificial neural networks (ANNs) are widely used in a variety of practical tasks including process monitoring, fault diagnosis, adaptive human interference to natural events and artificial intelligence such as atmospheric processes and computers. Because of their universal mapping characteristics and learning ability they are important in system control applications. An ANN process is considered as a black-box model with a set of input and output factors which are interrelated through a systematic neural network.

The first appearance as a cell model of ANN concept is presented Mc Cullough and Pitts [98]. ANNs are exemplified as a set of logical statements. Later, in 1949 researches focused the attention on the human learning ability and its modeling [99]. Öztopal et al. used neural network for wind-speed prediction and interpolation [100].

Brett and Tuller [101] found autocorrelation from 1 h to 2 months for seven stations in Canadian coastal areas as an exponential model with cosine terms fitted to empirical autocorrelation functions.

Labraga [102] searched wind velocity and energy potential by optimum direction selection, but also evaluated

extreme winds over 5100 km<sup>2</sup> area in Argentine. Hourly mean wind velocities are found as 40, 60 and 80 km/h for different areas and times. Wind storms occur at low-level pressure systems that are laid down from Atlantic to Pacific oceans.

Bryukhan and Diab [103] searched for wind velocities considering different pressure levels which are 1000, 850, 700, 500, 300, 200 and 100 hpa at global scale in some parts of southern hemisphere between 0 and 50° south latitude and 0–45° east longitude. Extreme wind values occur at 300 hpa pressure level and winter wind velocities are 25–30% higher than summer months. Additionally, strongest continental winds occur at central parts of South Africa.

Long time wind observations of surface and high levels around Glen canyon dam are also searched [104]. Caldwell and Stuart [105] studied mesoscale wind patterns in California. Spatio-temporal variations are estimated by complex empirical orthogonal functions. Andreas et al. [106] realized errors in the spatio-temporal interpolation methods. Wind patterns are modeled also by stochastic methods [107]. Zhong and Takle [108] investigated sea-land breeze effects at complex topography by synoptic scale approaches. Finite element methods are used for description of wind patterns [109].

Şahin and ve Şen [110] modeled winds speed of western part in Turkey by scatter diagram graphical methods. Şahin et al. [111] formed background of wind energy potential in the Marmara Region of Turkey. Micrositting of wind turbines at Akhisar is also studied [112]. Öztopal et al. [113] formed monthly wind maps at different heights. PCSV is applied along eight different directions in each station and SDFs are depicted [114]. Topographic classifications are investigated by Şen [115] leading to different clusters.

#### 4.8. European wind atlas and its methodology

Spatial variations of wind and other meteorological parameters can be expressed in the form of maps. European wind atlas is the most complete mapping methodology in wind-power meteorology searches [54].

This is an atlas containing calculation methods of roughness change class effects and the speed-up models for flow passes over a hill by the so-called hill model. It is also necessary to construct a model for the sheltering obstacles effect in the terrain, such as houses and shelter belts through the so-called shelter model. Five distinctive landscapes are recognized based on the topography and wind climatology. Double vertical and horizontal extrapolation methods are used for measurements of the wind speed at 10 m height. Hence, it is possible to estimate the roughness length distribution around the station, and find the friction velocity from the logarithmic profile with geostrophic drag law for calculating the geostrophic wind. Time series of geostrophic wind is calculated from the pressure data near-perfect Weibull distribution as shown in Fig. 6. Surface wind speed time series distribution functions are calculated by



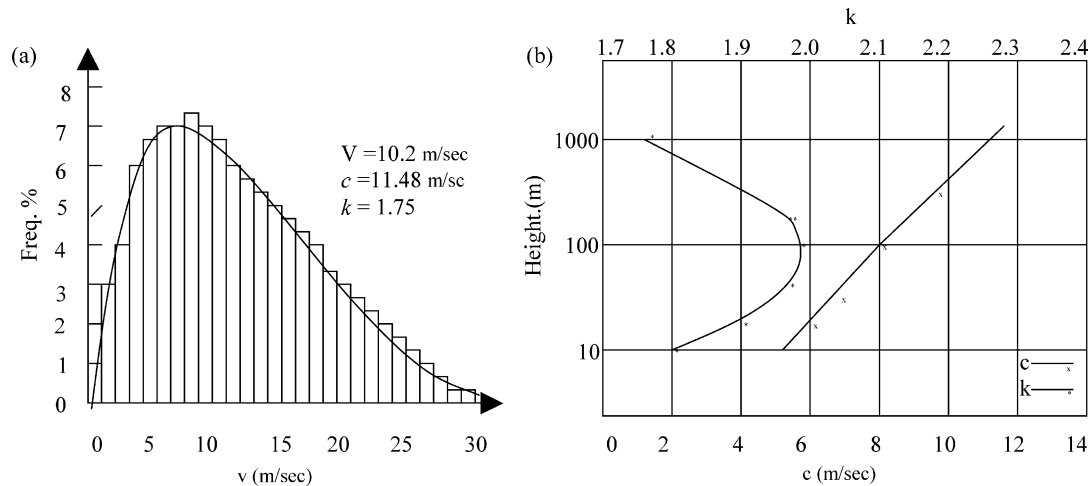


Fig. 6. (a) The distribution of the geostrophic wind over Denmark. (b) Weibull  $c$  and  $k$  parameters as functions of height over roughness class. The values are shown at 1000 m corresponding to the geostrophic wind [52].

fitting the Weibull distribution with the scale,  $c$ , and the shape,  $k$ , parameters plotted at five heights, four roughness classes and eight direction sectors (see Fig. 6b).

These are used to estimate the statistics at specific locations up to 200 m above average ground level according to the procedure shown in Fig. 7.

Owing to the complexity of the European landscape large number of stations are used for the analysis. It is necessary to replace the roughness change and the hill models by more general models, which are able to handle topographical map information in digital form. The result is a flow-over-hill model with an expanding polar grid centered at the point of interest, enabling a detailed description of the terrain around a specific location. The roughness change model is initially expanded to multiple roughness changes, and subsequently, developed into a more general model capable of handling roughness areas extracted directly from topographical maps [116].

Wind Atlas Analysis and Application Program (WASP) is used primary for siting of wind turbines singly or in farms. Many of the procedures in the method are strictly applicable only under idealized and limited range of conditions. The most severe problems are encountered in mountainous terrain, where large-scale effects render the model increasingly deficient, because of the importance of dynamics, which are not accounted in the model. The only way forward is to use more complete physical mesoscale models. They are built on a full set of equations and are, therefore, formally capable of modeling all flow types in complex situations. Their disadvantage lies in the difficulties encountered in prescribing the initial and boundary conditions accurately. They typically model an area with the order of  $100 \times 100 \text{ km}^2$  based on a resolution of 5–10 km [117,118].

At least in Europe, the Wind Atlas Analysis and Application Program—WASP, which is developed by

the Danish Risø National Laboratory, is the most commonly used computer tool in this field. In flat terrain, such as in Denmark and northern Germany, WASP delivers reliable results. In complex and very rugged terrains, however, WASP could lead to results outside an acceptable range [119–121].

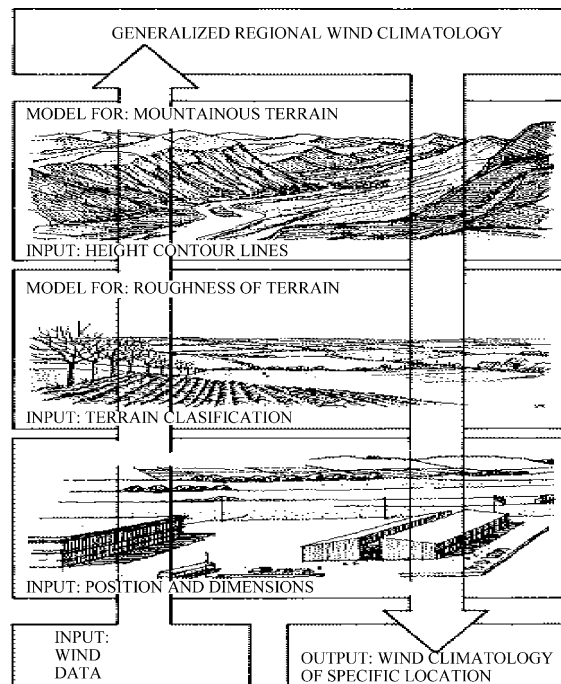


Fig. 7. The wind atlas methodology used for European Wind Atlas. Regional wind climatologies are deduced from meteorological models from the raw data. Accordingly, the wind climate at any specific site may be calculated from the regional climatology [52,116].

In the last few years, wind energy interests moved towards complex terrains, with improvement of the methodology [122–124]. Evaluation studies of the improved WA<sup>S</sup>P and other new computer simulation models are currently carried out [26].

#### 4.9. Wind statistics

Wind energy investigations mostly rely upon arithmetic average of the wind speed [125,126]. However, many authors based the wind energy estimates on elaborated wind-speed statistics, including the standard deviation, skewness and kurtosis coefficient. Some researches advocate the use of two-parameter Weibull distribution in wind velocity applications [2,127]. Their suggestions are taken as granted in many parts of the world for wind energy calculations. In some researches not the genuine wind speed data but their cubes are assumed to have two-parameter Weibull distribution [128]. Three-parameter Weibull distribution fits the wind speed data in a refined manner than the two-parameter version [129]. Generally, Weibull distribution function is used for representation of wind speed relative frequencies. Weibull distributions have two parameters and probability density function (wind speed frequency curve) can be represented mathematically as;

$$p(V)dV = \frac{k}{c} \left(\frac{V}{c}\right)^{k-1} \exp\left[-\left(\frac{V}{c}\right)^k\right] dV \quad (2)$$

where  $c$ , as the scale parameter has the same wind speed unit and  $k$  is the dimensionless shape parameter. These parameters are estimated by different mathematical approaches. Provided that the mean value of wind speed,  $\bar{V}$  and the standard deviation,  $\sigma$  are known, then  $k$  and  $c$  parameter can be evaluated from the following equations as,

$$\bar{V} = c\Gamma(1 + 1/k) \quad (3)$$

and

$$(\sigma/\bar{V})^2 = [\Gamma(1 + 2/k)/\Gamma^2(1 + 1/k)] - 1 \quad (4)$$

respectively,  $\Gamma(\cdot)$ , represents a general Gamma function and  $\sigma/\bar{V}$  is the coefficient of variation. At this situation  $k$  and  $c$ , can be evaluated explicitly as

$$k = (\sigma/\bar{V})^{-1.086} \quad (5)$$

and inversion of Eq. (3) gives

$$c = \bar{V}/\Gamma(1 + 1/k) \quad (6)$$

Values of Gamma function can be easily evaluated by Stirling formula. In this approach,

$$\Gamma(n+1) = n! = n^n e^{-n} \sqrt{2\pi n} \left(1 + \frac{1}{12n} + \frac{1}{288n^2} + \dots\right) \quad (7)$$

where the first term is a good approach to  $\Gamma(n+1)$  value.

Since, variations and deviations of wind speeds are high, simulation of wind speed is very difficult but it can be achieved by Weibull distribution function. It shows different distribution function properties according to the change in  $k$  values. For  $k = 2$ , Rayleigh distribution function is valid, but in the case of  $k = 1$ , exponential distribution function is effective. On the other hand, when  $k = 3.6$  Weibull distribution function appears as an approximate Gauss distribution. The Weibull distribution can be fitted to wind data time series by using the maximum likelihood method as suggested by Stevens and Smulders [130,131]. A lot of research is carried out by different authors in different countries [132–136].

#### 4.10. Extreme winds

In wind engineering applications extreme winds are important, especially, at turbine design cut-in and cut-off wind level considerations by many researches [137–139]. There are two methods for extreme wind descriptions, such as individual storms taken separately at regions and when observations are not long enough, Gumbel–Lieblien Blue method is preferred [140]. In practically most wind engineers use Gumbel method. The theory behind this subject and practical applications are explained in detail by Gumbel [141]. Furthermore, Gumbel extreme value statistics and annual extreme wind speed values are examined by this suggested method [142].

Generally, strong wind speeds are described as risk values but low wind speeds also have important risk potentials too in energy production. Generally, these values are called as cut-in and cut-out wind speeds, respectively. Wind turbines produce electricity between 3 and 25 m/s, and high productions are evaluated after 10–15 m/s values. Each turbine has cut-in and cut-out values depending on design rule and magnitude (Fig. 8). Wind turbine power curve is a graph that indicates the amount of the electrical power output versus different wind speeds.

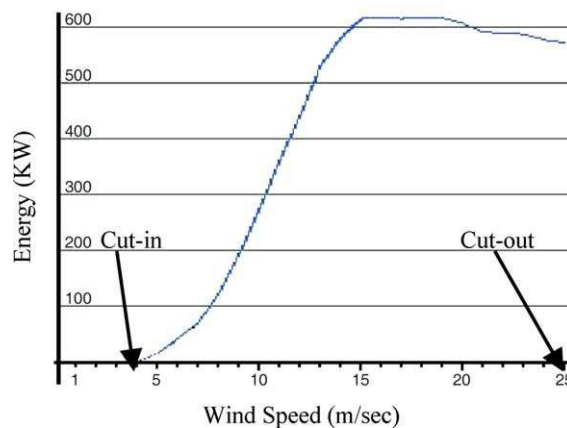


Fig. 8. Power curve with cut-in and cut-out wind speeds.



In engineering applications and scientific researches risk analysis is an important topic, which is based on extreme wind velocities. In practice, lower extremes are significant for low energy generation possibilities and for power-cut risks depending on the turbine type. On the other hand, upper extremes endanger wind turbine stability. Additionally, maximum wind velocity variations are fundamental in engineering structural designs. From the meteorological point of view, they are directly related to storms and thunder storms.

Wind occurs due to different cooling and heating phenomena within the lower atmosphere and over the earth surfaces. Meteorological systems move from one place to another by generating different wind velocities. Most of these winds occur under different pressure meteorological systems and they are influenced by topographic conditions to a certain extent. Such conditions give rise to occasional extreme wind velocities, which should be predicted prior to any wind farm planning, siting, design, operation and maintenance. If extreme values are known, then it is possible to arrive at a risk decision rather easily. Wind velocity risks are significant for building, bridge and settlement location construction. In wind energy researches and especially in turbine design cut-in and cut-out velocities, risk levels must be searched. On the other hand, Şen [126] took into account statistical investigation of wind energy reliability and its application. Şahin and Şen [143] evaluated extreme wind speeds by the first order Markov-chain model. Additionally, areal wind characteristic for western Turkey are also considered [73,144].

Wind speed category probability estimations from available time series help to predict for extreme speeds and recurrence intervals. Such predictions are necessary for natural hazard destruction, wind-speed sensitive structure constructions and engineering sensitivity analysis such as in nuclear power station site assessments. The transition probability estimations are necessary for the recurrence interval predictions and as the Weibull, Rayleigh, lognormal or Gamma frequency distribution functions for predicting the magnitude of the wind speed. Classical wind speed calculations are based on a set of the assumptions according to successive wind speed records statistically independently [141]. Such a demand cannot be satisfied especially with short time interval records such as minutes, hours or even days. Extreme value approach requires long records of wind speed measurements, and unfortunately, available wind records are comparatively short and not sufficient to make reliable studies [145].

Dependence in any time series can be modeled by the first of all first order Markov chain as variety of weather conditions are modeled by Gringorten [146]. On the other hand, Mimikou [147] has employed a Markov-chain model to generate daily extreme precipitation values. Long time weather data generations are also possible by Markov chains as shown by Racsco et al. [148]. Various authors have demonstrated that a Markov model can synthesize wind

speed time series data [149–152]. In any simulation study, the purpose is to check whether the observed and simulated averages, standard deviations and distribution functions including extreme values are close to measurements.

All Markov-chain models are based on the transitional probability matrices of various time steps ahead. Most often, a one-step Markov chain is employed in practice, because it includes all the possible transitions between one-step ahead categories. The most strong lag-one serial correlation is depicted for future simulation studies. Markov-chain transitional probabilities can be calculated initially by dividing the wind speed into many stages. For this purpose, the full of historical wind speeds of possible ranges are determined and then divided into many non-overlapping adjacent subranges.

Hourly extreme wind speed values of Britain Island are searched and first order Markov-chain model is used for simulation [153]. Markov-chain model is repeated 1000 times by using Monte-Carlo method.

#### 4.11. Wind energy formulation

In the wind energy,  $E$  is equivalent to flux of the moving air mass,  $m$ , kinetic energy with a speed,  $v$  as

$$E = \frac{1}{2}mv^2 \quad (8)$$

Since, the measurement of  $m$  is almost impossible in aero-dynamics one can express it in terms of volume,  $V$ . It is preferable to convert the volume to specific mass  $\rho = m/V$ . Hence, the substitution of  $m$  into Eq. (8) gives,

$$E = \frac{1}{2}\rho Vv^2 \quad (9)$$

The volume can be expressed as  $V = AL$  in which  $A$  is vertical control cross-section and  $L$  is the horizontal distance. Physically,  $L = vt$  and its substitution into Eq. (9) lead to,

$$E = \frac{1}{2}\rho A t v^3 \quad (10)$$

Practically, it is preferable to consider the wind energy per vertical unit area per time as unit wind energy  $E_u$ ,

$$E_u = \frac{1}{2}\rho v^3 \quad (11)$$

The air density is assumed as a constant equal to  $1.263 \text{ kg/m}^3$  at the sea level. This expression is valid for instantaneous measurements of the air density and wind speed at a given site. However, its generalization over an area requires parameterization through a regional analysis, such as semivariogram and Kriging methods. On the other hand, possible random variations consideration in the air density and wind speed may give rise to a general parametric expression of the wind energy in the form of

a power function as

$$E = aV^b \quad (12)$$

where  $a$  and  $b$  are referred to as the scale and power parameters, respectively. These parameters are reflections of regional variabilities in the actual wind energy assessments. Homogeneous and theoretical air shed characteristics lead to  $a$  and  $b$  which are expected to assume  $a = 0.62$  and  $b = 3$ . These values result from the classical calculations (Eq. (11)).

Wind speed can also be expressed in terms of the average speed  $\bar{V}$  and fluctuation term,  $\varepsilon$ , as  $V = \bar{V} + \varepsilon$  the substitution of which into Eq. (11) leads after some algebra to

$$E = \frac{1}{2} \rho (\bar{V}^3 + 3\bar{V}\sigma_\varepsilon^2) \quad (13)$$

where  $\sigma_\varepsilon$  is the standard deviation of wind velocity. A further improvement in the wind energy calculations can be achieved by considering the dependence of the air density on the pressure and temperature changes [56].

Betz [154] applied the simple momentum theory to the windmill established by Froude [155] for the ship propeller. The following brief outline covers the essentials and fundamental points. The retardation of the wind passing through a windmill occurs in two stages, before and after its passage through the windmill rotor. Provided that the mass,  $M$  is air passing through the rotor in unit time, the rate of momentum change is  $M(V_1 - V_2)$  which is equal to the resulting thrust. Here,  $V_1$  and  $V_2$  represent upwind and downwind speeds at a considerable distance from the rotor. The power absorbed ( $P_a$ ) can be expressed as,

$$P_a = M(V_1 - V_2)\bar{V} \quad (14)$$

On the other hand, the rate of kinetic energy change in wind can be expressed as

$$E_k = \frac{1}{2} M(V_1^2 - V_2^2) \quad (15)$$

Since physically these two expressions should be equal, one can write

$$M(V_1 - V_2)\bar{V} = \frac{1}{2} M(V_1^2 - V_2^2) \quad (16)$$

Hence, the retardation of the wind,  $V_1 - \bar{V}$ , before the rotor is equal to the retardation  $\bar{V} - V_2$  behind it with assumptions that the direction of wind velocity through the rotor is axial and that the velocity is uniform over the area,  $A$ . The argument holds good, however, even without these assumptions. Finally, the power extracted by the rotor is,

$$P = \rho A \bar{V}(V_1 - V_2)\bar{V} \quad (17)$$

Furthermore,

$$P = \rho A \bar{V}^2(V_1 - V_2) = \rho A \left( \frac{V_1 + V_2}{2} \right)^2 (V_1 - V_2) \quad (18)$$

or

$$P = \rho \frac{AV_1^3}{4} [(1 + \alpha)(1 - \alpha^2)] \quad (19)$$

where

$$\alpha = \frac{V_2}{V_1} \quad (20)$$

Differentiation shows that the power  $P$  is maximum when  $\alpha = 1/3$ , which means when the final wind velocity  $V_2$  is equal to one third of the upwind velocity  $V_1$ . Hence, the maximum power, which can be extracted is  $\rho AV_1^3 \times \frac{8}{27}$ , as compared with  $\rho AV_1^3/2$  in the wind originally, i.e. an ideal windmill could extract  $\frac{1}{2} \times \frac{8}{27}$  (or 0.593) of the power in the wind [61]. Many textbooks do not mention that Betz did not consider the impact of unavoidable swirl losses. For turbines with a high tip speed ratio (TSR) ( $X > 3$ ), and an optimum blade geometry, these losses are very low. The TSR  $X$ , of a rotor is defined as:

$$X = \frac{V_{\text{tip}}}{V_{\text{wind}}} = \frac{\omega R}{V_0} \quad (21)$$

Low TSR turbines, e.g. the American farm windmill with  $X \approx 1$ , the swirl losses reduce the maximum power coefficient,  $C_{P,\text{max}}$ , to approximately 0.42 [26]

#### 4.12. Wind measurement

The power in the wind is proportional to the third power of the wind speed. Therefore, if the wind blows at twice the speed, its energy content will increase 8-fold. In practice, a turbine at a site where the wind speed averages 8 m/s will produce around 80% more electricity than the wind speed of 6 m/s.

Wind data for site evaluation must be as accurate as possible, and for this wind speed measurements on site are necessary. Most wind energy textbooks, discuss the relevant issues in detail [10,11,13]. It is often not possible to measure the wind speed and direction at the hub height. Computer simulation tools are developed to evaluate the wind conditions at hub height over a certain area from a point wind measurement with the local influences and obstacles [156–158].

National Center for Atmospheric Research (NCAR) in USA and Improved Moments Algorithm (NIMA) calculate the first and second moments (radial velocity and spectral width) of wind-profiler [159]. Doppler spectra provide an evaluation of confidence in these calculations. First moments and their confidences are used by the NCAR Winds and Confidence Algorithm (NWCA) to estimate the horizontal wind. NIMA–NWCA algorithm is used for several years in a real-time application for three wind profilers in Juneau, Alaska. They presented results of an effort to evaluate the first moments produced by NIMA and horizontal winds produced by NIMA–NWCA through comparisons with guesses from ‘human experts’ and also

present a comparison of NIMA–NWCA winds within situ aircraft measurements. NIMA uses fuzzy logic to separate the atmospheric component of Doppler spectra from ground clutter and other sources of interference. The fuzzy logic rules are similar to human features in identifying atmospheric and contamination signals in Doppler spectra. Furthermore, NIMA attempts to mimic the human expert confidence of assignment the moments. A Human Moment Analysis (HMA) tool is developed to assist experts in moment quantification. A tuning methodology NIMA rules is based on human specifications. NIMA performs well on difficult datasets. The correlation between winds derived from NIMA–NWCA and HMA first-moment estimates exceed 0.96 when the data with low NWCA confidence are excluded. The correlation coefficient between NIMA winds and in situ measurements by aircraft is 0.93 for aircraft winds that are believed to be accurate.

## 5. Turbine technology

Wind turbines range in capacity from several kilowatts to Megawatts. The crucial parameter is the diameter of the turbine and the longer the blades, the larger the areas swept by the rotor and leading to energy outputs. The average size of new machines is 1500 kW, although there are 2.5 MW machines in the market. The trend is towards larger machines.

Significant progresses are made in wind turbine technology over the last decade. This progress can be described as a continuous chain of incremental improvements based on experience. Small turbines are upscaled gradually and, commercially available wind turbines are grown in size from 55 kW in the early 1980s to 500–2500 kW in the beginning of 2000s. The rotor diameter increased from 15 to 70–82 m and the hub height from 22 to 60–80 m. Moreover, the weight per swept area is reduced and the weight of a 24 m tower decreased from 32 kg/m<sup>2</sup> in the early 1980s (55 kW wind turbine) to 5.026 kg/m<sup>2</sup> in 2000s (500 kW wind turbine). The rotor weight decreased from 1.8 kg/m<sup>2</sup> (55 kW wind turbine) to 0.5 kg/m<sup>2</sup> in the same period (500 kW wind turbine). The wind turbine technology development also led to improved performance.

Wind turbine rotor efficiency increased from 35–40% in the early 1980s to 48% in the mid-1990s. Moreover, the technical availability increased up to 98% [47,160–163].

Upscaled wind turbine development with improved performance and higher towers has led to increased wind capture and electricity production (kWh/m<sup>2</sup>). Moreover, better wind resources estimation techniques enable improved wind turbine siting and increased wind capture. In the future, larger turbines are expected to serve the new offshore market. Machines in a range from 3000 kW up to 5000 kW are currently under development. In 2002, the German company Enercon has scheduled to erect the first prototype of its 4500 kW turbine with a rotor diameter of 112 m. Average sizes of wind turbines installed each year are given in Table 5 [47].

### 5.1. Horizontal and vertical wind turbine

Wind-energy conversion systems (WECSs) depend on aerodynamic drag and aerodynamic lift. The early Persian vertical axis wind wheels utilized the drag principle. Drag devices have a low power coefficient with  $C_{P,max}$  around 0.16 [11,13].

Modern wind turbines are predominantly based on the aerodynamic lift. Lift devices use airfoils (blades) that interact with the incoming wind. The resulting force from the airfoils body intercepts the airflow and consists of a force component that is perpendicular to the drag. By definition, the lift force is a multiple of the drag force and it is perpendicular to the direction of the airflow that is intercepted by the rotor blade the leverage of the rotor, it causes the necessary driving torque [10,11,13,164,165].

Wind turbines with aerodynamic lift are further divided according to the orientation of the spin axis as horizontal-axis and vertical-axis turbine types. Vertical-axis turbines, known as Darrieus after the French engineer who invented it in the 1920s, use vertical, and slightly curved symmetrical airfoils. The Darrieus wind turbine offers an advantage over the horizontal axis wind turbine, because of the structural simplicity due to the independence with respect to the wind direction. This feature makes the control system unnecessary to direct the rotor. The Darrieus wind turbine aerodynamics is rather complex because of the operation

Table 5  
Average size of wind turbines installed each year (kW) [47]

Year	China	Denmark	Germany	India	Spain	Sweden	UK	USA
1995	326	493	473	208	297	448	534	327
1996	400	531	530	301	420	459	562	511
1997	472	560	623	279	422	550	514	707
1998	636	687	783	283	504	590	615	723
1999	610	750	919	283	589	775	617	720
2000	600	931	1101	401	648	802	795	686
2001	681	850	1281	401	721	1000	941	908

under unstalled and stalled conditions, and also in the presence of the dynamic stalls, which are particularly significant in the operation at low tip-speed ratios. As known that TSR can be basically described as tip speed of blades over actual wind speed. During a single rotor rotation, the blade receives a cyclic fluid force due to the variation of incidence angle that is particularly significant under operation at low TSRs. Although the appearance of the dynamic stall acts positively on the power generation of the wind turbine [166], the presence of stall vortices produces problems, such as the aeroelastic vibrations and noises from the blades and the fatigue of the blade material by the unsteady forces [167–169]. Vertical-axis turbines are developed and commercially produced from 1970s until the end of the 1980s. The largest vertical-axis wind turbine the ECOLE C is installed in Canada with 4200 kW. Since 1980s, the research and development of vertical-axis wind turbines are almost stopped worldwide [10,11,13,165].

Presently, the horizontal-axis or propeller-type, approach dominates the wind turbine applications. This consists of a tower and a nacelle that is mounted on the top of a tower. The nacelle contains the generator, gearbox and the rotor. Different mechanisms exist to point the nacelle towards the wind direction or to move the nacelle out of the wind in case of strong wind speeds. On small turbines, the rotor and the nacelle are oriented into the wind with a tail vane. On large turbines, the nacelle with rotor is electrically yawed into or out of the wind, in response to a signal from a wind vane.

Horizontal-axis wind turbines typically use different blade numbers, depending on the purpose of the wind turbine. Two- or three-bladed turbines are usually used for electricity generation, whereas 20 or more blades are used for water pumping.

The number of rotor blades is indirectly linked to the TSR (see Fig. 9). Wind turbines with a high number of blades have a low TSR, but a high starting torque which can be utilized for automatically starting water pumping when the wind speed increases. A typical example for such an application is the American farm windmill. Wind turbines with only two or three blades have a high TSR with a low starting torque. These turbines might be started, if the wind speed reaches the operation range. A high TSR allows the use of a smaller, and therefore, lighter gearbox to achieve the required high speed at the driving shaft of the power generator [10,11,13,26,65,170].  $C_p$  is a non-linear function of factors such as blade radius, pitch angle, TSR, etc. Typically,  $C_p$  bears the shape as shown in Fig. 9.

At constant wind speed deviation of rotor speed (due to load change) leads to the variation of power efficiency. For instance, consider a wind turbine operating at some 'optimal point'. If the rotor speed increases,  $C_p$  deviates from the 'optimal value'. If the rotor speed is kept constant, any change in wind speed leads to the change of TSR ( $V_{tip}$ ), causing the change of power generation efficiency.

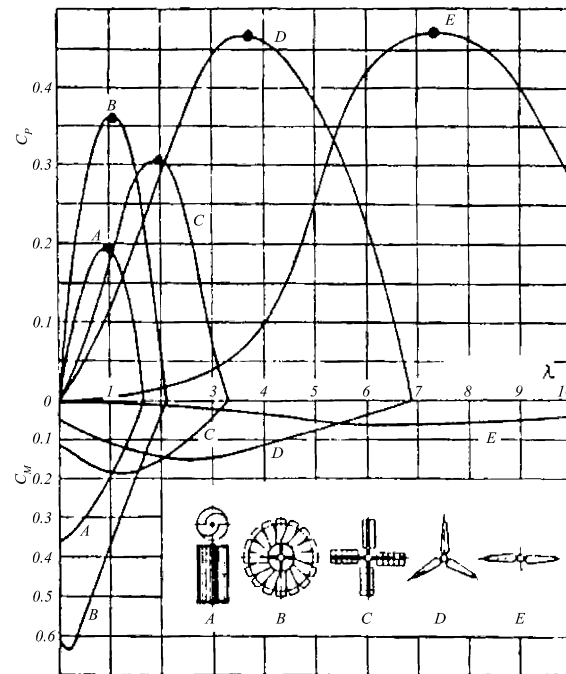


Fig. 9. Power coefficient ( $C_p$ ) and torque ( $C_M$ ) of windwheels varying in construction versus tip speed ( $V_{tip}$ ); A, B, C = typical windwheels with a low tip speed ratio; D, E = typical windwheels with a high tip speed ratio [26].

## 5.2. Main technological challenges

Wind turbine technology experienced an important series of challenges. These issues are related to loading and size increases. For this reason, both technology and design are continuously evolving. At the present status, wind energy technology has to face different challenges in order to pursue development. These challenges could be grouped into four areas, namely, design, installation, integration of new technologies and size increase.

Wind turbine design is based on aeroelastic simulation, which includes aerodynamic profile and elastic structural characteristics of the blades. Substantial technological work is necessary in the issues related to the dynamic behavior of the profile, because the natural frequencies and characteristic of the aerodynamic processes have comparable magnitude with the turbine size increases. This has great importance in analyzing system stability and stochastic response to the wind. In component design, stability is of great importance. Structure buckling has great importance in the design of blades and towers. Some standards are being used for design and finite element analysis with non-linear calculations, which provide a better understanding of the process. Standards define the operating and extreme conditions with the partial safety factors for the design of wind turbines. These are responsible for the safety of

the present-day wind turbines, and for the positive effects of the currently existing data. Complex terrain is also an important challenge in design activities.

The integration of new technologies includes improvement and influence on design. It is impossible to conceive wind turbines of the size and performance without the use of other industrial technologies. In order to detect worse situations further developments are emerging. They need specific performances and could help in maintenance activities and reliability improvements.

Variable rotor speed control is essential to achieve maximum power extraction from the potential wind power. While automatic controls have long been known to increase power quality and reliability, most existing controls are restricted to classical/linear model-based methods which exhibit only limited capability in dealing with varying operational points and external disturbances inherent in such systems.

### 5.3. Design approaches

Horizontal-axis wind turbines are designed in different ways. Robert and Darrell [170] distinguish three design philosophies (see Table 6). Modern grid-connected wind turbines usually follow the ‘C’ approach, because of better power quality, lower TSRs approach ‘B’, hence lower visual disturbances, and finally, lower material requirements than in approach ‘A’, as the structure does not need to withstand high wind loads, hence lower cost.

Table 6  
Basic design approaches [26,170]

#### A. Turbines designed to withstand high wind loads

- optimize for reliability
- high solidity, but non-optimum blade pitch
- three or more blades
- lower rotor TSR

Precursor: Gedser mill

#### B. Turbines designed to compliant and shed loads

- optimize for performance
- low solidity, optimum blade pitch
- one or two blades
- higher rotor TSR

Example: Hütter turbine

#### C. Turbines designed to manage loads mechanically and/or electrically

- optimize for control
- mechanical and electrical innovation (flapping or hinged blades, variable speed generators, etc.)
- two or three blades
- moderate rotor TSR

Example: Smith-Putnam

Different companies investigate combinations of the different approaches. However, the ‘C’ approach currently dominates the commercial market.

Each design approach leaves a high degree of freedom regarding certain design details. Depending on the wind environment, different aerodynamic rotor diameters are utilized. On strong wind speed sites, usually smaller rotor diameters are used with an aerodynamic profile that will reach the maximum efficiency between 14 and 16 m/s. Low-wind sites have larger rotors with an aerodynamic profile that may reach maximum efficiency between 12 and 14 m/s. The main aim is to maximize yearly energy output. Wind turbine manufactures have to consider the overall cost including the maintenance cost over the lifetime of the wind turbine.

Important design variables are discussed in detail concerning the number of blades, power control and generation/transmission systems [10,12,13,170,171].

### 5.4. Two- or three-bladed wind turbines

Wind turbines are large structure and so weight is very important. Blade weight is especially important, as savings in rotor weights allow related reductions in the weight of the hub, nacelle and tower structure. A wide range of blade materials have been used for blade manufacture, including aluminum, steel, wood epoxy and glass-reinforced plastic. The two last materials are now most common as they have the best combination of strength, weight and cost. It is essential to keep weights to the minimum, as the weight of a wind turbine has a strong influence on its overall cost [172].

Currently, three-bladed wind turbines dominate the market with horizontal-axis and they have the advantage of lighter top and, therefore, the whole supporting structure has lower cost. On the other hand, in three-bladed wind turbines the rotor moment of inertia is easier to understand. Furthermore, these turbines are often attributed ‘better’ visual aesthetics with a lower noise level than two-bladed wind turbines. Both aspects are important considerations for wind turbine utilization in highly populated areas. Wind turbine components and some of their properties are given below.

- Rotor diameters range up to 82 m. Smaller machines (around 30 m) are typical in developing countries,
- Wind turbines have three, two or just one rotor blades. Most have three,
- Blades are made of fiber glass reinforced polyester or wood-epoxy,
- Most machines operate at a constant speed between 15 and 50 rpm,
- Power is controlled automatically as wind speed changes. Turbines are stopped at very strong wind speeds to protect them from damage,
- Most have gear boxes although there are increasing numbers with direct drive,



- The yaw mechanism turns the turbine so that it faces the wind. Sensors are used to monitor wind direction, and the tower head is turned to line up with the wind, and
- Towers are mostly tubular and made of steel, generally painted with light gray. Lattice towers are used in some locations and range from 25 to 80 m in height.
- Direct drive turbines require multi-pole (4 or 6) with large diameter (up to 6 m) generators. Induction usual, 4 or 6 pole. Variable speed machines use ac/dc/ac systems.

In the definition of turbine technology, the installation requirements play an important role. The development of wind turbines for specific use in offshore applications requires different specifications. In these applications, building requirements are no longer applicable and noise problem is not significant in the design process. This leads to an increase in tip speed and a resultant reduction in loading. There is no reason for a break in this direction other than wind turbine economics. This is the major decision variable for achieving an equilibrium between the improvement due to scale and the problems due to the cost. Up to the 75-m diameter the improvements have provided more profitable equipment [173,174].

Martinez and Parts [173] analyzed the technological characteristics and main challenges. Present day wind turbine is something radically different from what it was 15 years ago. These differences are in profitability that is the main design driver during the development period. Wind power technology is sharpening the unfocused image of the different designs existing 15 years ago. It is easy to detect a trend towards horizontal axis, three blades and cylindrical tower. From this point, the design solutions are diverging. Nothing or very little remains of cylindrical-axis turbines but two-bladed rotors represent a small percentage of the overall installed power.

Wind turbines today have very reduced prices, operate with one fifth of the downtime and achieve about one third more energy per unit of installed power or even swept surface. These figures demonstrate the maturity of present day technology applied to wind energy installations. The achievements of the last decade have been produced in a highly multi-disciplinary technology solidly based on modern mechanics and material science, sensoria techniques, wide use of microcomputers, integration of new simulation and production techniques.

The final corollary of technological maturity is the way the development has taken place in the last few years in the field of wind energy. The design process of wind turbines and their application have affected another substantial and unreported change. The path to a final product has been dramatically shortened. Now, brand-new wind turbines enter the market with a very short development and test phase.

The goal for future development of wind turbines is to increase wind capture and at the same time decrease, or eliminate loads (i.e. mechanical stress). Already today, wind

turbines in the range 500–2500 kW are commercially available. Furthermore, technological development will include incremental improvements and conceptual changes to existing wind turbine concepts, which will probably take place concurrently but for different market segments.

Increased flexibility can be achieved with a two-bladed turbine that includes some flexibility in the rotor suspension device, which will reduce the load at maintained energy capture. Moreover, the two-bladed turbine is cheaper, lighter, and operates at a higher speed than three-bladed turbines. On the other hand, two-bladed turbines are noisier and considered less aesthetic than three-bladed turbines. Improved flexibility may also result from advanced blades and control systems. Advanced blades that are made of soft, flexible materials, will allow changes in the shape of the blades in response to wind conditions, in order to increase energy capture and reduce loads. However, the development of advanced blades will require continuous material development. Advanced control systems will include systems that make it possible to predict the direction and speed of the wind in order to increase energy capture. The development of such control systems has just started. It can be said that the development of flexibility is still at an early stage. The development of new wind turbines will also involve material development and preparation, in addition to the development of wind turbine manufacturing methods [173].

### 5.5. Power control

The ability of a wind turbine to extract power from varying wind is a function of three main factors, namely, the wind power availability, the power curve of the machine, and the ability of the machine to respond to wind fluctuations. Control design for wind power generation systems represents an interesting yet challenging research topic. In contrast to conventional power generation where input energy can be scheduled and regulated, wind energy is not a controllable resource, due to its intermittent and stochastic nature. Most wind turbines operate at fixed rotational speeds. However, fixed-speed operation means that the maximum coefficient of performance is available only at a particular wind speed. A low coefficient of performance is observed for all other wind speeds, which reduces the energy output below what might be expected from variable speed operation. Apparently, if the turbine speed could be adjusted in relation to the wind speed, a higher power output could be realized. Therefore, variable speed control of wind turbines is of practical interest and increasing numbers run at variable speed (using power conditioning equipment) or run at two speeds, with pole switching on the induction generator. The advantage of using lower speeds in low wind is that noise levels are reduced and, in addition, aerodynamic efficiency—and hence energy yield—is slightly increased. Increasing



numbers of machines dispense with a gearbox and use a direct drive to a multipole generator [172].

#### 5.5.1. Stall and pitch control

There are two main power output control methods from the rotor blades. The angle of the rotor blades can be adjusted actively by the machine control system, which is known as pitch control. This system has built-in braking, as the blades become stationary when they are fully 'feathered'. Wind turbines reach the highest efficiency at the designed wind speed, which is usually between 12 and 16 m/s. At these wind speeds, the power output reaches its rated capacity. Above this wind speed, the power output of the rotor must be limited to keep the power output close to rated capacity and to reduce thereby the driving forces on the individual rotor blade as well as the load on the whole wind turbine structure. Currently, three options for the power output control are used.

*Stall regulation.* This is sometimes described as passive control, since it has the inherent aerodynamic properties of the blade, which determine power output with no moving parts to adjust. The twist and thickness of the rotor blade vary along its length in such a way that turbulence occurs behind the blade whenever the wind speed becomes too strong. This turbulence causes some of the wind's energy to be shed, minimizing power output at higher speeds. Stall control machines also have brakes on the blade tips to bring the rotor to a standstill, if the turbine needs to be stopped for any reason.

By pitching the rotor blades around their longitudinal axis, the relative wind conditions, and subsequently, the aerodynamic forces are affected in a way so that the power output of the rotor remains constant after rated power is reached. The pitching system in medium and large grid-connected wind turbines is usually based on a hydraulic system, which is controlled by a computer. Some manufacturers also use electronically controlled motors for pitching the blades. This control system is able to adjust the pitch of the blades by a fraction of a degree at a time, corresponding to a change in the wind speed, in order to maintain a constant power output.

The rotor thrust on the tower and foundation is substantially lower for pitch-controlled turbines than for stall-regulated turbines. In principle, this allows for reductions in material and weight. Pitch-controlled turbines achieve a better yield at low-wind sites than stall-controlled turbines, as the rotor blades can constantly be kept at optimum angle even at low wind speeds.

Stall-controlled turbines have to be shut down once a certain wind speed is reached, whereas pitch-controlled turbines can gradually change to a spinning mode as the rotor operates in a no-load mode, i.e. it idles at the maximum pitch angle. An advantage of stall-regulated turbines consists in that, in strong winds, when the stall effect becomes effective, the wind oscillations are converted into power oscillations that are smaller than those of

pitch-controlled turbines in a corresponding regulated mode. Particularly, fixed-speed pitch-controlled turbines with a grid-connected induction generator have to react quickly to gusty winds. This is possible within certain limits, otherwise huge inertia loads counteracting the pitching movement will be caused.

Pitch control has the potential for producing the highest level of interaction because of the diesel and wind turbine control loops presence. The pitch control system consists of a power measurement transducer, a manual power set point control, an adaptive feedback function, and a hydraulic actuator, which varies the pitch of the blades. Turbine blade pitch control has a significant impact on the dynamic behavior of the system. This type of control only exists in horizontal axis machines. Variable pitch turbines operate efficiently over a wider range of wind speeds than fixed pitch machines. However, cost and complexity are higher.

Jurado and Saenz [175] deal with the development of a neuro-fuzzy controller. The controller inputs are the engine speed error and its derivative for the governor part of the controller, and the voltage error and its derivative for the automatic voltage regulator [175]. Adaptive schemes appear to be a particularly attractive choice [176–178]. In addition to the traditional linear Autoregressive Moving-Average (ARMA) models and the commonly used feed forward and recurrent neural networks, other approaches are also examined including the Adaptive Neuro-Fuzzy Inference Systems (ANFIS) and Neural Logic Networks [179,180]. The hill-climbing method, among adaptive control methods, is also adopted [181]. Bonnett and Wozniak [182] described the application of an adaptive control methodology that provides uniformly closed loop response over a wide range of operating conditions.

The control systems of wind turbines were also summarized [183]. The paper by Riziotis and Voutsinas [184] studied issue of fatigue loads on wind turbines of different control strategies operating in complex terrain. The impact of complex terrain wind conditions on the loading of wind turbines is examined.

Ekelund [185] explored the potential for active attenuation of structural dynamic load-oscillations by means of continuous control of the yaw servo. The study involved two structural dynamic modes, namely the tower bending and the motion of turbine with a teetered hub. The results show the importance of the yaw stiffness for the tower bending.

Automatic control is essential for the efficient and reliable implementation of wind power conversion systems. The major challenge in control design for wind power systems stems from the intermittent and stochastic nature of the resource. Active turbine control through the use of variable speed operation and full-span blade pitch are becoming standard methods to help maximize energy capture and minimize transient load effects.

The paper by Song [186] explicitly addressed the problem of variable speed operation of wind turbines

using memory-based pitch control method. Varying operation conditions were considered and simulated. In the paper by Muljadi et al. [187], a control strategy for variable-speed stall-regulated wind turbines was studied. Computational models were developed and tested. Wind turbines exhibit fairly rich non-linear dynamics. In the paper by Song et al. [188], a non-linear excitation control method was investigated. Based on rotor and excitation dynamics, non-linear and adaptive excitation control algorithms were derived. This method is shown to be able to achieve smooth and asymptotic rotor speed tracking, as justified by both analysis and computer simulation.

Wind turbine blades can be damaged by fatigue or other causes. It is important to detect the damage before the blade fails catastrophically which could destroy the entire wind turbine. The paper by Ghoshal et al. [189] presents different techniques for structural health monitoring of wind turbine blades. The methods are based on vibration signal processing using piezoceramic sensor slactuators and a laser vibrometer. Laboratory experiments performed are successful in detecting damage to a blade section, and indicate the potential for monitoring blades for damage during operation of the wind turbine.

Traditionally, most wind turbines operate at fixed speeds except when starting and stopping. Fixed-speed operation means that the maximum coefficient of performance is available only at a particular wind speed. A low coefficient of performance is observed for all other wind speeds, which reduce the energy output below that which might be expected from variable speed operation [167,190–196].

As noted by several researchers, in order to effectively extract wind power while at the same time maintaining safe operation, the wind turbine should be driven according to the following three fundamental modes associated with wind speed, maximum allowable rotor speed and rated power, i.e. [190,194,195],

Mode 1—operating at variable speed/optimum TSR:

$$u_C \leq u \leq u_B$$

Mode 2—operating at constant speed/variable TSR:

$$u_B \leq u \leq u_R$$

Mode 3—operating at variable speed/constant power:

$$u_R \leq u \leq u_F$$

These are illustrated in Fig. 10, where  $u_C$  is the cut-in wind speed,  $u_B$  denotes the wind speed at which the maximum allowable rotor speed is reached,  $u_R$  is the rated wind speed and  $u_F$  is the furling (cut-out) wind speed at which the turbine needs to be shut down for protection [175].

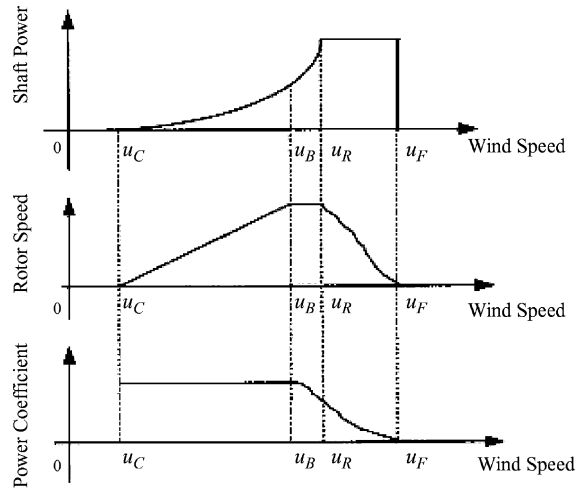


Fig. 10. The operation modes of turbine speed.

It is seen that if high-power efficiency is to be achieved at lower wind speeds, the rotor speed of the wind turbine must be adjusted continuously against wind speed.

A common practice in addressing the control problem of wind turbines is to use linearization approach. This method allows the linear system theory to be applied in control design and analysis. However, due to the stochastic operating conditions and the inevitable uncertainties inherent in the system, such a control method comes at the price of poor system performance and low reliability [195,196].

As the demand for wind-energy conversion increases, industry members search for ways to lower production costs while improving reliability. One area currently under investigation is the design of variable-speed wind turbines. Although most utility-scale wind turbines are operated at constant-speed, there is of considerable interest in variable-speed turbines, as demonstrated in commercial applications by Kenetech, Enercon, Zond, and other wind turbine manufacturers.

Typically, variable-speed turbines use aerodynamic controls in combination with power electronics to regulate torque, rotor speed (rpm), and power. The primary advantages claimed for variable-speed turbines cause to increased energy capture and reduced drive train loads. Secondary benefits are acoustic signature and power quality. The aerodynamic control systems, usually variable-pitch blades or trailing-edge devices, are costly and complex and become even more so as turbines get larger. This situation provides an incentive to consider alternative control approaches. The more that is learned about variable-speed turbines, the more it becomes apparent that their behavior is significantly affected by the control strategy employed in their operation [197,198]. The potential benefits of this strategy include lower energy costs resulting from lower capital costs, improved reliability, and reduced maintenance expenses.

Song [186] presented a memory-based method for variable speed control of wind turbines. This approach has been applied to various engineering problems such as pattern classification, weather prediction, speech recognition, medical diagnosis, protein structure prediction and others [199–204]. He also focused on the development of short-term (low-order) memory-based control algorithms that allow variable speed operation of WECSs. The proposed control consists of two parts, one for preliminary compensation and other for memory-based compensation. The salient feature of the proposed method lies in its simplicity in design and implementation.

Riziotis and Voutsinas [184] developed software, which is used specifically for wind turbine applications. It contained three basic modules, namely, the wind simulator which provides the wind inflow in the form of time series over the entire rotor plane, the aerodynamic model, which calculates the aerodynamic loads, and finally, a structural model which accounts for flexibility effects and introduces the dynamics of the whole configuration.

### 5.6. Wind generator

A modern large electric WECS may generate up to 2.5 MW. The cost, weight, and maintenance needs of mechanical gearing between the wind turbine and the electrical generator pose a serious limitation to the further increase in WECS power ratings. Wind power plants are, generally, used to convert wind energy into electrical energy. These plants consist of a wind turbine, an electrical generator and a control system. The wind turbine converts wind kinetic energy into mechanical energy and the latter into electrical energy by means of an electrical generator.

Conceptual changes will incorporate new generators, variable-speed operation, and more flexible wind turbines. A promising development is the direct-drive generator, which makes it possible to exclude the gearbox. Furthermore, the direct-drive generator could be combined with variable-speed operation, which will increase energy capture and reduce loads, i.e. an improvement in rotor efficiency by allowing the rotor speed to vary with wind speed. Wind turbines with variable-speed operation will be increasingly competitive as the cost of solid-state electronic decreases.

Permanent magnet excitation is favored for developing new designs because of higher efficiency, high-power densities, availability of high-energy permanent magnet material at reasonable costs, and the possibility of rather smaller turbine diameter. Other advantages include the absence of brushes, slip rings, excitation windings, and excitation losses. For DC power generation, the lack of excitation control is not a limitation for terminal voltage and power control, since a diode rectifier and a DC–DC converter system, with various control strategies, permit load voltage and/or load power control.

The flow field around a wind turbine is unsteady and three-dimensional. Mathematical models are available in the literature for solving the equations for such a complex flow. These may be divided into momentum, vortex, and finite-difference models. The momentum models use actuator surfaces to approximate wind-turbine effects and subdivide the flow domain into finite numbers of stream-tubes [205–209]. Vortex models simulate the wind-turbine blades and use bounded and distributed vortices [210–213]. Finally, finite difference models solve the fluid-dynamic governing equations by means of finite-volume or finite-difference methods [214,215].

In order to control these plants, a control system must yield an asymptotic reduction of the disturbances in order to minimize the differences between the actual and reference values of the output voltage and frequency. Applications of classical controls to wind-power plants may be found in the literature with reference to open-loop and closed-loop schemes [216].

A complete dynamical model of the rotor and stator windings will be employed where the voltage of the rotor winding is the only control variable [217]. The wind-power plant is considered to be an isolated source of power and is composed of a wind-turbine linked to a synchronous generator by means of a gearbox. Hence, the control algorithm has to counterbalance the effects of wind speed and electric load changes (disturbance variables). One-step-ahead adaptive control of a wind-driven, synchronous generator system was also applied [218–220].

Considerable attention has been focused on use of ANN on system modeling and control applications [221,222]. The ANN has several key features that make it suitable for controlling non-linear systems. These features include parallel and distributed processing, and efficient non-linear mapping between inputs and outputs without an exact system model. Also ANNs are characterized by the rapidity of response and robustness, which make them attractive to control WECS. However, in the field of generators, the application of ANN has been developed recently [223–226]. The first ANN was used for input output mapping, while the second ANN was used for voltage regulation. ANN was used to develop a saturation model for a synchronous generator [223]. On the other hand, an ANN observer was developed for on-line tracking of synchronous generator parameters [226]. ANN was used for modeling rotor parameters of a round rotor synchronous generator [227]. Additionally, it was also proposed to predict the maximum value of wind turbine coefficient  $C_p$  as function of the TSR' and the blade angle, to maximize the power captured from the wind [226].

Eskander [227] proposed a control strategy for maximum power tracking (MPT) and output voltage regulation of a WECS employing a PMG. The PMG output was connected to a diode bridge rectifier followed by two buck-boost converters. A 4-neuron input, 8-neuron hidden layer,

and 2-neuron output layer neural network controller (NNC) was also developed.

In rural and isolated areas, stand alone power systems are used. When conventional machines are used as generators in these isolated systems, the output voltage will be of variable magnitude and frequency. Electronic converters are then necessary to obtain a constant frequency supply.

Synchronous and induction generators are widely used in wind energy systems [228,229]. Each type of these machines has its own advantages and disadvantages and also has its own method of control. This control, whether mechanical or electrical, is necessary to obtain a voltage of constant magnitude and frequency, which can be connected to the grid. On the other hand, alternative current (AC) commutator machines have proved to be better competitors than conventional AC machines, synchronous and induction, when used as generators in wind power plants. This is due to the fact that these machines generate a constant frequency voltage irrespective of their shaft speeds when excited from a constant frequency supply. This eliminates the need for electronic converters, which must be used with conventional machines. Thus, AC commutator machines, 3-phase and 1-phase, are used as generators in wind energy systems [230].

Metwally [231] investigated theoretically and experimentally potential capability of the single phase commutator machine as a self-excited stand alone generator for wind energy systems.

## 6. Economics of wind energy

Generating electricity from the wind makes economic as well as environmental senses. Producing and selling electricity from the wind is no different from any other businesses. To be economically viable, the cost of making the electricity has to be less than its selling price. In every country, the price of electricity depends not only on the cost of generation, but also on many different factors that affect the market, such as energy subsidies and taxes. Generally, the cost of generating electricity is made up from,

- Capital cost—building the power plant and connecting it to the grid,
- Running costs—operating, fuelling, and maintaining the plant, and finally,
- Financing—the cost of repaying investors and banks.

For wind turbines, there are no fuel costs, as the wind is free. Once the project has been paid for, the only ongoing expenses are for operation and maintenance. The capital cost is between 75 and 90% of the total.

As the market has grown, wind power has shown a dramatic fall in cost. The production cost of a kilowatt hour (kWh) of wind power is one fifth of what it was 20 years ago. In 1982, the average list price of Danish-produced wind

turbines was 1770 US\$/kW, and in 1997 the average price reduced to 850 US\$/kW. The price, however, varies for different turbine sizes and producers. In 1997, the list price of a Danish 150–500 kW wind turbine (with a height of 30–40 m) ranged from 750 to 1200 US\$/kW and the list price of a 550–750 kW wind turbine (with a height of 40–45 m) ranged from 690 to 850 US\$/kW. Moreover, prices of wind turbines seem to vary from one country to another. According to a Danish study, the average price in 1995 was 790–980 US\$/kW in Europe and 630 US\$/kW in the USA [163].

Over the past 5 years alone, costs have reduced by some 20%. Wind is already competitive with new coal-fired plants and in some locations it can challenge gas, currently the cheapest option. Wind energy production continues to improve in ways, which reduce cost and improve efficiency. Electricity from the wind costs about 5–8 ECU cents per kWh and is predicted to fall to about 4 ECU cents per kWh. Wind energy projects are simple and cheap to maintain. Land rental fees paid to farmers provide valuable additional income in rural communities. The construction work is mostly undertaken by local companies providing local employment and long-term jobs are created for maintenance work. In the UK, for instance, developers have contracted to build wind farms for a price of less than 3 US cents/kWh, comparable with that of gas.

The cost of wind power generation falls as the average wind speed rises, and it is shown that at an average site with a speed of 7.5 m/s and a cost per installed kilowatt of \$700, wind can be cost competitive with gas [47].

### 6.1. Cost comparison with other generation technologies

How do the costs of wind energy compare with other generating technologies already in widespread use? The most recent data in Fig. 11 is from the annual survey of cost comparisons by Wind Power Monthly, published in January 2002. At current electricity prices, the cheapest wind plant,

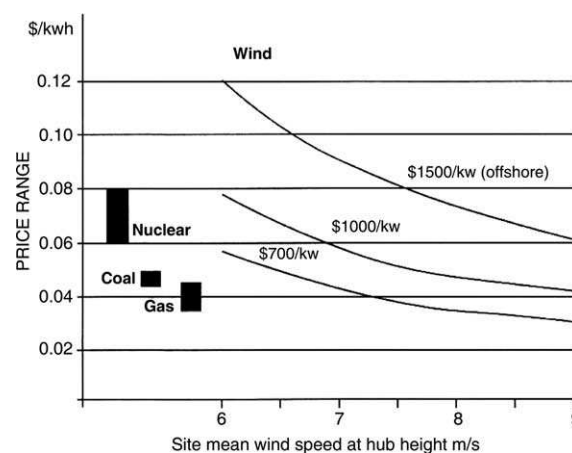


Fig. 11. Cost comparison for different energy sources [49].



those with easy access and economies of scale are now fully competitive with gas, if sites have an average good wind speed of 7.5 m/s. The price of electricity from new thermal plant is based on European data, and has changed little since 2001 with gas on an upward price trend. The costs of nuclear do not account for public sector liability, waste and decommissioning issues.

One other factor should also be taken into account in these comparisons. The lower capacity factor of wind power means that to produce a given quantity of electricity, it is necessary to install 2–2.5 times more generating capacity than with fossil fuel plants. This tends to make wind energy more expensive in the initial phase of the life cycle. On the other hand, there is no fuel cost during the lifetime of a wind power generating plant (Fig. 11).

Producing electricity from the wind is a new industry and 15 years ago there was no commercial wind power in Europe. In some countries, wind energy is already competitive with fossil and nuclear power even without accounting for the environmental benefits of wind power. The cost of electricity from conventional power stations does not usually take full account of its environmental impact (acid rain, oil slick clean up, the effects of climate change, etc.).

As its economic attraction has increased, wind energy has become a big business. The major wind turbine manufacturers are now commissioning multi-million dollar factories around the world in order to satisfy the demand. Five of the leading companies have been floated on the European stock market, prompting keen interest in their shares.

Most importantly, the wind energy business is attracting serious interest from outside investors. At the beginning of 2002, for example, a consortium of banking, insurance and legal interests announced that it would invest up to \$1.3 billion in wind farms planned round the UK coastline. A number of oil companies have taken decisions to take a stake in wind power. These deals are evidences that wind is becoming established in the mainstream of the energy market [49].

Wind energy is a fast-growing world industry. There are approximately 60 manufacturers and most of these are in European. More than 10 major European banks and 20 European utilities have invested in wind energy, as have individuals and companies. In Denmark, over 100,000 individuals have made their own investments in wind.

The wind industry is also a major employer. A recent study by the Danish Wind Turbine Manufacturers Association concludes that the Danish wind industry alone employs 8500 Danes and has created a further 4000 jobs outside Denmark. The Danish wind industry is now a larger employer than the Danish fishing industry.

## 6.2. External cost

To determine the true cost of generating electricity, the cost of pollution and other ‘external costs’ should be

included in the calculations. External costs are the costs to human health and the environment, which are not reflected in the price of the electricity. They are also referred to as ‘social costs’. Society bears the cost of pollution in terms of poorer health, leading to higher health service costs funded by the tax payer, and a degraded environment, which increases the cost of food and farm products. As yet, no universally accepted method has been found to put a price on these costs. Some countries, like Norway, Sweden and Denmark, have introduced a tax loaded against electricity produced by fossil fuels, but the European Union has not yet agreed on a universal ‘carbon tax’.

One way of comparing the environmental impact of different energy technologies is to look at their ‘external’ or ‘social costs’. The external costs of producing power by conventional means—such as air pollution, long-term damage to health, and oil spillage clean-up—are not generally included in calculations of electricity costs. When cost comparisons are made on this basis, wind energy produces cheaper electricity than new coal and nuclear power plants.

Other examples of the external costs of burning coal include occupational health problems from mining, and the damage caused to buildings, agriculture, fisheries, and ecosystems from acid rain. Furthermore, the external costs of climate change will be enormous. It is very difficult to calculate the costs of environmental and other categories of damage. The ‘ExternE’ project recently undertaken by the EC and United States Department of Energy acknowledges these difficulties, but concludes that there are significant external costs for both fossil fuels and nuclear energy, whereas for wind energy these costs are: ‘smaller than those of competing conventional’ fuels. Wind energy is largely free of environmental impacts, which have long-term, inter-generational or serious ecological impacts. Furthermore, the impacts of well-sited wind farms are temporary and reversible. Unlike the fossil and nuclear fuel cycles, there is no potential conflict with sustainable development. Sustainable development has been defined as ‘meeting the needs of present generations, without compromising the ability of future generations to meet their own needs’.

Wind energy is completely sustainable, unlike conventional energy technologies, since we will never run out of wind.

El-Kordy et al. [232] analyzed the external cost of emissions from different generating systems. A proposed large-scale photovoltaic (PV) plant of 3.3 MW, and a wind farm 11.25 MW grid connected at different sites were investigated. A life cycle cost (LCC) analysis for each system was performed using the present value criterion. Their comparison results showed that wind energy generation has the lowest cost. For conventional electricity generation, a combined cycle natural gas-fired system has the lowest cost per kWh, which is nearly compatible to wind energy costs without considering any external costs.

Emissions from electric power plants are generally evaluated based on the plant specifications. However, it is difficult to estimate a ‘typical’ set of emissions for any resource type. Emissions depend on several factors other than the plant type. These factors include age and type of the plant, fuel type, grade, sulfur contents, installed emissions control technology, plant operation, including heat rate, combustion temperature and steam or limestone injection. Emissions from PV and WECS through their life cycles depend mainly on the country heat and power mix, and energy combustion pattern in different sectors.

The external costs, as defined by Hohmeyer [233], are the costs of the impact caused to the environment due to the pollutants emitted from the specified technology. It is expected that the environmental impacts and damages will be approximately proportional to the emissions produced by electricity generation. The significant contributors from fossil fuels to these damages are sulfur oxides ( $\text{SO}_x$ ), nitrogen oxides ( $\text{NO}_x$ ), total suspended particulate (TSP) and carbon dioxide ( $\text{CO}_2$ ). The determination of external costs due to these emissions is necessary in order to specify the cost of each kWh and compare it with the cost of each kWh from RE systems (wind and PV).

In order to assess the externalities of pollutants during energy generation, the reports reviewed estimate the following values, in dollars per kg of emissions, such as \$5.666/kg  $\text{SO}_x$ , \$2.293/kg  $\text{NO}_x$ , \$3.306/kg particulate, and \$0.018/kg  $\text{CO}_2$ . Primarily, the estimated health effects, material damage and other environmental consequences influence these values, which provide a good starting point for further evaluations. Table 7 shows the external costs of the considered pollutants from fuel oil, solar energy and natural gas. The values of these emissions are taken from El-Kordy et al. [232].

### 6.3. External costs evaluation of conventional systems

The externality values of two oil-fired technologies (steam and gas turbines), and three natural gas-fired technologies (steam, gas turbine and combined cycle) are predicted. The results are considered without the use of pollution control equipment. The external cost per generated

energy (\$/kWh) for each plant is the value of the external cost per unit energy input multiplied by the heat rate of each plant. The external cost per delivered energy (\$/kWh) is calculated assuming 15% marginal energy losses. The results show that externalities of oil-fired systems are affected by sulfur contents and particulate emissions. Heat rate is also considered as the main factor in determining externalities of the different generation systems.

### 6.4. External costs evaluation of renewable systems

PV and WECSs have no emissions during the operational stage. Emissions are borne through the non-operational stages of the PV and WECS life cycle [234]. The external costs (\$/kWh) of the renewable systems are shown in Table 8.

### 6.5. Electric power systems

Various technologies are currently available candidates for expanding electrical generating systems. The most common generating technologies, other than conventional, are solar (PV and solar thermal) and wind energy converters (WECS).

There are several reasons to use LCC analysis rather than simply to compare the initial cost of each supply option. Capital cost (equipment and installation expenses) is one of many cost components. Power systems also require varying amounts of maintenance, repair, and fuel costs. The external costs due to environmental consequences also differ greatly especially when comparing conventional and renewable systems. As an example, wind power system may have a higher initial cost than gas turbines, but it requires no fuel, and much less maintenance or other external costs. LCC analysis was used to analyze electricity generation systems. This analysis also allows the evaluation of all the costs associated with installing and operating any power system over its lifetime, thus giving a realistic assessment of a system's lifetime costs and allowing a reasonable

Table 7  
External cost for fuel oil, solar oil and natural gas [232]

Pollutants	Externality (\$/kg)	Emission factor (kg/GJ)		
		Fuel oil	Diesel oil	Natural gas
$\text{SO}_x$	5.666	0.4643	0.0688	0.0003
$\text{NO}_x$	2.293	0.1234	0.2141	0.1806
Particulate	3.306	0.0387	0.0155	0.0013
$\text{CO}_2$	0.018	72.662	69.2224	47.2948
Total externality (\$/GJ) input		4.35	2.18	1.27

Table 8  
External cost (\$/kWh) for renewable energy systems [232]

Pollutant type	Externality (\$/kg)	Emission factor (g/MWh)	
		PV	WECS
$\text{SO}_x$	5.666	126.124	19.575
$\text{NO}_x$	2.293	115.603	62.76
Particulate	3.306	7.457	2.074
$\text{CO}_2$	0.018	68,600	18,060
External cost generated (\$/kWh)		0.00224	0.00059
External cost generated (\$/kWh) <sup>a</sup>		0.002573	0.000674

<sup>a</sup> Assuming 15% marginal energy loss.



comparison of different power sources. The same analysis permits the study of changing economic variables impact, such as interest or inflation rates and escalation rates.

#### 6.6. Life cycle cost technique

This approach can be represented by the following equation

$$LCC = C_{pw} + M_{pw} + F_{pw} + X_{pw} - S_{pw} \quad (23)$$

where pw is a subscript that indicates the present worth of each factor.  $C$  is the capital cost and includes the initial capital expense for equipment, system design, system engineering, and installation. This cost is considered as a single payment occurring in the initial year of the project, regardless of how the project is financed.  $M$  is the operation and maintenance cost which is figured as the sum of yearly scheduled maintenance and operation costs. It includes salaries for operation, inspections, and insurance.  $F$  is the fuel cost equal to the sum of the yearly fuel costs.  $X$  is the external costs including damage prevention, or damage cost, if occurred. Finally,  $S$  is the salvage value of a system, which is its net worth in the final year of the lifetime period (15% original cost).

Using these four cost factors and the final salvage value, the LCC can be calculated for each type of power generation systems.

#### 6.7. Economical evaluation results

The suggested abbreviations that are used in the analysis are as follows [232]

Conventional steam fuel oil fired: CSFO  
 Conventional steam natural gas fired: CSNG  
 Gas turbine diesel oil fired: GTDO  
 Gas turbine natural gas fired: GTNG  
 Combined cycle natural gas fired: CCNG  
 Photovoltaic: PV  
 Wind energy converter: WEC

Data of LCC factors, the external costs due to the airborne emissions from Tables 7 and 8 are used to calculate the costs of kWh of electricity production from different generation technologies. The results of these computations are presented in Table 9 which shows the four cost factors (capital cost  $C$ , operation and maintenance cost  $M$ , fuel cost  $F$  and external cost  $X$ ), and the LCC excluding and including external COSPS (LCC-X and LCC, respectively).

Examination these results indicates that when external costs are ignored, then the LCC-X for conventional steam natural gas-fired system has the lowest cost as 1.3804 cent/kWh which is followed by combined cycle system with 1.4807 cent/kWh. The highest cost is that of PV system as 13.782 cent/kWh, because of its high capital cost and limited yearly operating hours. For conventional systems, gas turbine units have the highest cost of kWh 2.8438 and 2.5038 cent for diesel oil and natural gas fired, respectively.

When the external costs are considered then the LCC shows that WECS has the lowest cost as 1.8085 cent/kWh followed by the combined cycle system cost of 2.3555 cent/kWh. Conventional steamfuel oil fired and gas turbine diesel oil fired have the similar costs as 5.4256 and 5.4266 cent/kWh, respectively. The PV system still has the highest cost of 13.9612 cent/kWh. Examination of the external costs per generated kWh ( $X$ ) in Table 9 shows that for conventional systems, natural gas-fired units have lower values than that of petroleum products fired units. The highest external cost is that for conventional steam fuel oil fired 3.8328 cent/kWh. The lowest external cost is that of combined cycle natural gas fired at 0.8748 cent/kWh. For the renewable PV and WECS, the external costs per kWh are very low at 0.1792 and 0.0469 cent/kWh, respectively. These costs are due to airborne emissions through the life cycle of the renewable systems [234].

#### 6.8. Future cost reduction of wind-generated electricity

Neij [163] described an analysis of the prospects of reducing the cost of wind-generated electricity. Special attention has been paid to the dynamic development of wind

Table 9  
Cost factors and life cycle cost for different systems (cent/kWh)

System	Cost factors and life cycle cost (cent/kWh)					
	Capital cost ( $C$ )	Maintenance cost ( $M$ )	Fuel cost ( $F$ )	External cost ( $X$ )	Total cost no external (LCC-X)	Total cost with external (LCC)
CSFO	0.5969	0.1371	0.8924	3.8328	1.5928	5.4256
CSNG	0.4974	0.1217	0.7843	1.0496	1.3804	2.4300
GTDO	0.751	0.5124	1.6318	2.5829	2.8438	5.4266
GTNG	0.751	0.5124	1.2918	1.5047	2.5038	4.0085
CCNG	0.5333	0.2797	0.6977	0.8749	1.4807	2.3555
PV	13.351	1.1817	0	0.1792	13.782	13.9612
WECS	1.6689	0.1865	0	0.0469	1.7616	1.8085

turbines, i.e. development based on experience gained in the production and use of wind turbines. Historical and future cost reductions associated with wind turbines are described using experience curves. The results of the analysis show that although the experience curve for wind turbines indicates relatively moderate cost reductions, there is potential for considerable cost reductions in wind-generated electricity. This is due to the fact that the cost of wind-generated electricity will be affected by improved performance and reduced operating and maintenance costs, in addition to the reduction in cost of wind turbines. The results indicate that the average cost of wind-generated electricity will almost be reduced by half, during 2020, on the assumption of 15–20% annual market growth.

The deployment of modern wind turbines has resulted in experience in the production and use of wind turbines, which has led to improved turbines and reduced costs of wind-generated electricity. Thus, wind-generated electricity has become increasingly competitive and a widespread adoption, i.e. diffusion, of wind turbine technology has started.

Neij [163] objected to analyze the prospects for future reductions in the cost of wind-generated electricity. The dynamic nature of wind turbine development, i.e. the role of experience gained in the production and use of wind turbines, is given special attention. It is assumed that experience will affect cost of wind turbines, performance (efficiency, availability, load factor), lifetime of wind turbines, and operation and maintenance (O&M) costs. These factors, in turn, are assumed to affect the future cost of wind-generated electricity.

The analysis of wind turbines is general, but is based on Danish wind turbines, which represent approximately half of the wind turbines in operation throughout the world [163]. Grid-connected wind turbines with a capacity of 55 kW or more are considered.

#### 6.9. Market incentives

The experience curves for wind turbines show that the price of a wind turbine has declined with cumulative sales. The increase in cumulative sales has, in turn, depended on satisfactory performance of the technology. The progress in wind turbine technology has been the result of research, development and demonstration (RD&D) programmes, and especially accumulated experience in producing and using wind turbines. Experience in producing and using wind turbines has been partially gained by market-stimulation incentives [235]. The most important of these incentives has been some kind of guaranteed electricity purchase prices, defined either as a certain percentage of the consumer price of electricity (as done, for example, in Germany and Denmark) or through competitive bidding (as in the UK). Tax relief has been used extensively, either within the income tax system (for example, in The Netherlands and India) or in the form of energy tax refunds (as used in

Sweden and Denmark). Governments have subsidized investments (for example, in Sweden) or electricity production (as in the USA). Several countries have combined market-stimulation incentives with utility and national targets (for a better environment and/or an increase in wind power capacity) resulting in a domestic market for wind energy. A home market can be considered advantageous, since it secures a certain market volume, leads to an important network of actors, and provides a reference for new wind turbines produced in the country.

The overall result of various incentives has been that countries that spent more on market incentives and less on R&D generated more wind energy than vice versa; and countries that guaranteed a market for the produced electricity generated more wind energy than those that used investment incentives [235]. Moreover, certification programmes, i.e. requirements on technical quality guaranteed by test and research centers (cf. Risø in Denmark, ECN in The Netherlands, Germanischer Lloyd in Germany), have made strong market incentives possible, i.e. preventing investors from making quick profits with inferior technology. RE incentives in some countries are shown by shades in Table 10 [236–240].

#### 6.10. Cost reduction of wind-generated electricity

Accumulated experience in producing and using wind turbines has not only resulted in a reduction of wind turbines cost, but also improved wind capture, and reduced O&M costs. This, in turn, has resulted in a reduction in wind-generated electricity cost. In Denmark, the average cost of wind-generated electricity was reduced by 60% in the period 1979–1994. Moreover, wind turbines installed at windy sites are already generating electricity at a cost lower than 4.5 US¢/kWh [163]. This is within the range of costs of electricity from conventional power plants [241].

Further experience in producing and using wind turbines, resulting in reduced costs for wind-generated electricity, will depend on further sales of wind turbines. Thus, the reduction in cost of wind-generated electricity will be limited by the potential for market growth. However, the recoverable resources of wind energy are huge. According to Grubb and Meyer [242], the global potential for wind-generated electricity is almost 500,000 TWh/year. Considering social, environmental, and land-use constraints (including visual impact), the potential is estimated to be at 53,000 TWh/year [242]. (The worldwide electricity production was approximately 13,100 TWh in 1995 [243].) According to these estimates, wind resources will not be a limitation in the near future for the diffusion of new wind turbine technology. In some countries, however, there are difficulties in obtaining approval for the siting of turbines due to cumbersome regulatory processes.

Table 10

Renewable energy incentives at some countries [236]

Country	Finacial incentives		Tax incentives		Production incentives		
	Investment	Govermantal	Tax discount (Relief)	Duty Discount (Relief)	Renewable Portfolio	Incentive to produced electricity	Fixed Tarrif
Austria							
Belgium							
Canada							
China							
Denmark							
UK							
Finland							
France							
Germany							
Greece							
The Netherland							
India							
Ireland							
Italy							
Luxemburg							
Philippines							
Portagual							
Spain							

### 6.11. Calculated cost of electricity

In this section, the cost of wind-generated electricity is calculated for the year 2020. The cost per kWh is dictated by the annual cost of installed capacity plus annual operational and maintenance costs divided by generated electricity per year.

The cost of installed capacity is estimated by extrapolation of the measured experience curve for Danish wind turbines, and an experience curve with a PR of 95% is used. Cost reduction is assumed to be the result of further upscaling, reduced weight and material use, improved production, etc. In all, future technological developments can be characterized as incremental, including the introduction of flexible two- or three-bladed turbines and variable-speed operations. It is not likely that new wind turbines will be radically different from the wind turbines of today. Thus, extrapolation of the experience curve is reasonable.

Moreover, the total cost of installation is assumed to decline according to the experience curve for wind turbines. The total cost of an installed wind turbine includes the wind turbine itself, foundation, roads, electrical grid connection, land, control building and miscellaneous costs. The cost of

the wind turbine itself accounts for approximately 75% of the total installation cost. Improved wind turbines, resulting from experience in production and use, are assumed to lead to an increase in lifetime from 20 to 25 years.

The O&M costs, including insurance, administration, service, and repair, have been shown to decrease with size and increase with age [244,245]. The average O&M costs of installed wind turbines is approximately 2–3% of the investment cost per year. However, the O&M cost of a new wind turbine is estimated to be approximately 1% of the investment cost [245]. In this study, it was assumed that the average O&M cost over the lifetime of the turbine is 2.5% (1.1 US¢/kWh) of the investment cost of today and that this cost will be reduced to 1.5% (0.6 US¢/kWh) of the investment cost of today by the year 2020. The reduction in O&M costs will be the result of advanced control systems and a reduction in the insurance cost, which is likely to decrease due to experience in use of wind turbines.

The sitings of the wind turbines have decisive influence on the cost of the generated electricity. For example, an average 600 kW wind turbine (with a turbine cost of 820 US\$/kW) will generate electricity at a calculated cost of 3.3 US¢/kWh in roughness class 0; 4.9 US¢/kWh, in

roughness class 1; 6.1 US¢/kWh, in roughness class 2; finally 8.7 US¢/kWh, in roughness class 3 (using a discount rate of 6% and an economic lifetime of 20 years). Over time, improved wind capture will result from upscaled wind turbines, increase in hub height, improved performance and improved siting. Cost reduction due to improved siting may be limited due to the fact that the best sites are becoming occupied in most countries. In the present calculations, it was assumed that normalized electricity production is, on the average, 2000 kWh/kW for new wind turbines (e.g. a 500 kW wind turbine; 37 m rotor diameter, roughness class 1.5). It was further assumed that improved wind capture, due to further upscaling and use of flexible two- or three-bladed turbines with variable-speed operations, will improve normalized electricity production to 2500 kWh/kW (e.g. a 1500 kW wind turbine; 60–69 m rotor diameter, roughness class 1.5).

In two scenarios described below, the calculated cost of electricity in the year 2020 is based on a market growth for wind turbines of 15 and 20% per year which correspond to the WECS scenarios in energy for tomorrow's world, where the current policy scenario assumes a contribution of 376 TWh and the ecologically driven scenario assumes a contribution of 967 TWh of wind power in the year 2020. This market growth will result in worldwide installed capacities of 188 and 483 GW in the year 2020 (assuming that the average operating time at rated power is approximately 2000 h per year).

Moreover, it is of interest to illustrate the sensitivity in calculated electricity cost to the estimated increase in wind capture. The figures used in the calculations may appear somewhat optimistic, due to the fact that siting in good wind areas may be limited, since the best sites are becoming occupied in most countries. If wind turbines are assumed to be situated in less windy areas on average, and the average wind capture is estimated to be 2350 kWh/kW (approximately with roughness class of 1.8), the cost of wind-generated electricity in the year 2020 will be 3.6 US¢/kWh (assuming a discount rate of 6%), using an average cost approach and a market growth of 15%.

The worst case, assuming a PR of 97%, a market growth of 15%, and a wind capture of 2350 kWh/kW, results in a calculated cost of electricity in the year 2020 of 3.9 US¢/kWh, using an average cost approach. This is a reduction of 36% of the calculated cost of electricity relative to the calculated average cost of wind-generated electricity in 1997.

## 7. Special systems and applications

### 7.1. Offshore wind plants

The difference between winds measured over land and adjacent waterbodies is non-linearly related to the strength

of the wind, atmospheric stability, fetch (distance from the coastline along the prevailing wind direction), and contrasts in heat, water vapor and momentum fluxes. In order to ensure correct assessment of the offshore wind resource, it is necessary to fully characterize the entire wind speed probability distribution. Smedman–Hogstrom and Hogstrom [246] developed a technique for determining wind speed frequency distributions within a layer extending approximately 200 m from the surface from measured data at a reference height of 10 m. The technique requires knowledge of the upstream roughness length ( $z_0$ ) and is based on the rate of growth of internal boundary layers (IBL) from surface discontinuities and assumptions regarding the shape of the wind profile. They assumed that the vertical wind profile is comprised of N IBL associated with terrain discontinuities upstream of the measurement location. Within each layer, they used the power law to describe the wind profile, and the growth of the IBL was described using a simple formulation where the height of the IBL is a function of  $z_0$  and stability.

Under offshore flow, flow above 30 m height is not fully adjusted to reduce surface roughness even after over water distances of 20 km. This is in accordance with analyses presented by Smith and MacPherson [247] and indicates that the maximum change in wind speed is not fully realized at this distance from the coastline. However, there is substantial acceleration of the flow even within 2 km of the coastline. Observations are presented which indicate that for offshore flow, the mean wind speeds of 2 and 11 km offshore are approximately 30 and 50% higher than those from an onshore coastal site at 10 m, 6 and 25% higher at 30 m and 5 and 24% higher at approximately 50 m.

The term persistence has been used within two contexts in the study of atmospheric flow variability. First, for quantifying the steadiness of the wind direction (where persistence is defined as the ratio of vector wind speed to scalar wind speed [248]). Second, for indication of the duration of surface wind speeds within specified wind speed classes [249].

An accurate assessment of the feasibility of wind resource utilization is dependent on the persistence of wind speeds, because the reliability and predictability of generated power and duration of time without power generation have implications for network design and meshing of technologies to continuously meet electricity demand.

Magnitude of offshore wind energy benefits has yet to be fully quantified. Installation and maintenance of wind turbines at great distances from land, represent a significant economic burden and present many technical challenges [250]. The first offshore wind turbines were being installed in coastal environments (i.e. typically <10 km from the coast) in a region of horizontal inhomogeneity where the flow may not have fully adjusted to the different fluxes from the water surface compared to those from land [251,252].

There are a lot of reasons and necessity for offshore wind plants. First of all, wind turbine technology has developed

Table 11  
Offshore wind energy potential for some European countries

State	Offshore potential (TWh/year)
UK	986
Denmark	550
France	477
Germany	237
Ireland	183
Italy	154
Spain	140
The Netherlands	136
Turkey	130
Greece	92
Portugal	49
Belgium	24
Total	3158

rapidly with increasing efficiency and wind speed values are stronger on sea than lands. In addition to strong wind speed values, turbulence intensities have taken lower magnitude at these smooth surfaces. Another advantages of offshore wind plant is the lifetime, in other words, lifetime offshore winds turbines are longer than lifetime of onshore. Of course, these kind of plants are costly than onshore wind plants. However, generally increasing trend in the electricity production at wind turbines gives a new trend to built offshore wind plants.

These new technologies are constructed rapidly at high ratio human population countries, which have high wind speed at offshore regions such as Denmark, Sweden, Holland and UK. At sea surface areas turbulence intensity is lower and wind profile does not show high variations with height. This means that at these areas, wind turbine hub height should be lower than onshore wind turbine hub height. This situation adds another advantage to offshore power plants. Turbulence intensity is the main factor to decrease lifetime of wind turbines. Metal fatigue occurs depending on external effects, especially, non-stationary effects. At offshore surface turbulence intensities are lower

and wind turbine lifetime is estimated between 25 and 30 years. Contrary to this, wind turbines, which are located at onshore have lifetime between 15 and 20 years. High efficiency and more continual electricity production on offshore sites are other important advantages of these wind farms. One of the disadvantages is high mounting, maintenance, and construction costs because of offshore effects. Another one is the difficulty, in grid connections with national grid network [47,253]

#### 7.1.1. Offshore wind energy potential in Europe

European wind atlas is prepared at Riso National Laboratory in Denmark. In this atlas, offshore wind speed values are estimated through 10 km offshore (Table 11).

It is obvious that UK is the leader for offshore wind energy potential, which covers 33% in Europe. This energy source was three times greater than consumption in UK during 1998. Wind energy technology has developed rapidly since 1990, and offshore wind farms have been constructed slowly than onshore wind farms during last years. Constructed wind plants in the world are presented in Table 12. These wind plants are, generally, distributed in Holland, Denmark and Sweden. In addition to these values, in these countries, 2724 MW wind power plants are constructed and planned to product electricity until 2006. The first offshore wind power plant in Europea has 420 MW ( $170 \times 2.5$  MW) total capacity at near Nantucket Island in USA and it will produce electricity in 2005 [253–255].

#### 7.2. Wind–diesel system

Wind turbines, if used with diesel generators, significantly reduce the cost of fuel consumption and greenhouse gases emission. The load efficiency of the diesel generator is low and this is a source of pollution.

Tariq [256] explained that there are over 300 remote communities in Canada with a total population of about 200,000. Newfoundland hydro operates many isolated diesel powered generating stations. Total generating capacity is about 25 MW. These prices are much higher as compared to the price that a grid-connected user pays

Table 12  
Offshore power plants installed capacity in the world

Location	Installed year	Capacity (MW)	Water depth (m)	Distance from coast (m)
Nogersund (Sweden)	1991	$1 \times 0.22$	7	250
Vindeby (Denmark)	1991	$10 \times 0.45$	3–5	1500
Medemblik (The Netherlands)	1994	$4 \times 0.5$	5–10	750
Tuno Knob (Denmark)	1996	$10 \times 0.5$	3–5	6000
Dronten (The Netherlands)	1996	$28 \times 0.6$	5	20
Bockstigen (Sweden)	1998	$5 \times 0.5$	6	3000
Middelgrunden (Denmark)	2000	$20 \times 2$	3–6	3000
Utgrunden (Sweden)	2000	$7 \times 1.425$	7–10	8000
Blyth (United Kingdom)	2000	$2 \times 2$	8	800
Yttre Sten. (Sweden)	2001	$5 \times 2$	6–10	5000



i.e. about 6 cents/kWh or less. Newfoundland has annual average wind speed of 6.5 m/s. Diesel generating stations are costly to operate and are big sources of environmental pollution. One of the suggested energy systems for isolated communities is a wind diesel system. Since the early 1980s, wind turbines have been successfully connected worldwide to large grids or to weak AC systems usually consisting of diesel units. The basic requirement in either case is to achieve fuel saving and provide a reliable power supply.

Control of autonomous diesel–wind systems is difficult because of time-varying dynamical properties. Li et al. [257] uses data collected at a wind farm to develop a neural network based prediction of power produced by each turbine. Wind velocity is treated as a random variable and assumed to have a Weibull distribution [258]. Karaki et al. [259] described the development of a general probabilistic model of a diesel–wind system composed of several diesel units, wind turbines and battery storage feeding. Wind turbine operation is simulated for typical wind speed time series [260]. Gavanidou et al. [261] present a probabilistic method for predicting the performance and the reliability of diesel–wind systems based on statistical data of the load and the wind speed. The generator dynamics model consists of a synchronous generator driven by a diesel engine through a flywheel and connected in parallel with an induction generator driven by a wind turbine. The diesel generator will act as a dummy grid for the wind generator, which is connected in parallel [262].

Variations of electrical power due to changes in wind speed should be as small as possible. This is obtained by using the induction generator as a wind turbine drive train. Unlike synchronous generators, induction generators have high compliance couplings between the machine and the electrical system. This is true for induction generators with slip of at least 1–2% at rated power. The controlled variables are turbine speed and shaft torque. Control acts on the turbine blade pitch angle (pitch control). Since the torque speed characteristic of the induction generator is nearly linear in the operating region, torque changes are reflected as speed changes. Therefore, it is possible to provide a single speed controller to control speed as well as torque [261] (see Fig. 12).

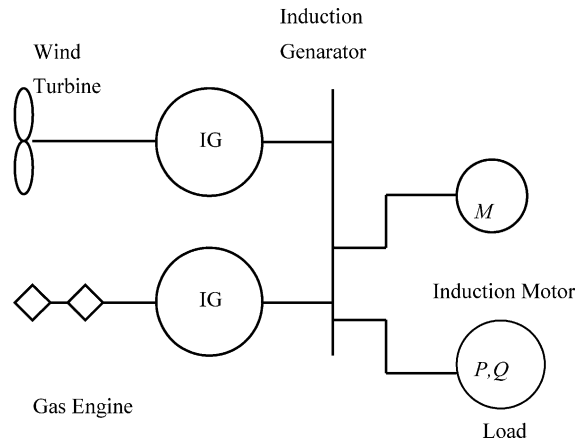


Fig. 12. Wind–diesel power system.

Few studies are related to the use of hydrogen for the electrical energy produced by RE sources such as wind and solar power [265,266]. Hydrogen is produced by an electrolyzer powered by the excess electrical energy from the RE source. The hydrogen can then be used to feed an energy conversion device (such as a fuel cell or an internal combustion engine), which will act as a secondary power source in periods of high demand. The excess energy available from the RE sources is directed to an electrolyzer. The hydrogen produced is then stored in a pressurized tank. This hydrogen is then fed to a proton exchange membrane fuel cell system that would be used as a load-leveling electrical system when unfavorable weather conditions arise [267].

Agbossou et al. [267] constructed a system, which is based on the production of hydrogen by electrolysis whereby the electricity is generated by a 10 kW wind turbine (WT) and 1 kW PV array. When available, the excess power from the RE sources are used to produce and store hydrogen. When not enough energy is produced from the RE sources, the electricity is then regenerated from the stored hydrogen via a 5 kW proton exchange membrane fuel cell system (see Fig. 13).

### 7.3. Wind–photovoltaic (PV)–hydrogen system

Wind and PV systems rely on highly transient energy sources and exhibit strong short-term and seasonal variations in their energy outputs. They, thus, need to store the energy produced in periods of low demand, in order to stabilize the output, when the demand is high. While batteries are most commonly used for this purpose, they typically lose 1–5% of their energy content per hour and thus can only store energy for short periods of time [263, 264]. There are presently no practical means available for long-term storage of excess electrical energy produced by the RE sources.

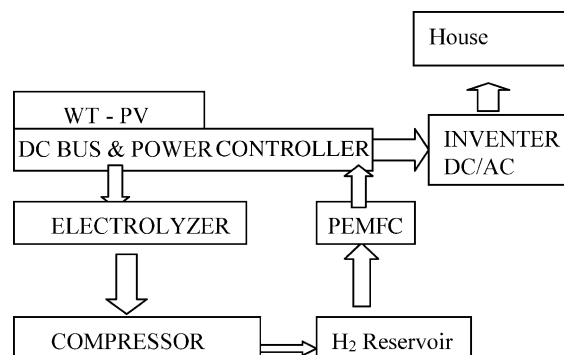


Fig. 13. RE system diagram [267].



#### 7.4. Seawater desalination

Wind turbines may be classified depending on their nominal power ( $P_n$ ) as very low ( $P_n < 10$  kW), low power ( $P_n < 100$  kW), medium ( $100 \text{ kW} < P_n < 0.5$  MW) and high power ( $P_n > 0.5$  MW) turbines [76]. All are mature technologies and they are commercially available except for the high-power systems, which still require several adjustments. In spite of such maturity, new control strategies may increase the output of the wind turbine.

Rodríguez and co-workers [268] estimated the influence of the main parameters on the levelized cost of fresh water, climatic conditions, nominal power of the wind turbine, salt concentration of seawater or brackish water, design arrangement, operating conditions, plant capacity, cost of reverse osmosis modules and cost of wind turbines. In addition, the competitiveness of wind power versus conventional energy in reverse osmosis plants was also studied. Results obtained are useful, not only to quantify the influence of the parameter studied, but also to system design and to evaluate the economic perspectives of this technology.

Garcia-Rodriguez [269] searched seawater desalination systems driven by renewable energies. There are many reasons why the use of renewable energies in seawater desalination is suitable, especially for remote areas where conventional energy supply and skilled workers are not usually available. Nevertheless, desalination systems driven by renewable energies are scarce and they tend to have a limited capacity. Coastal areas have a high availability of wind power resources, and wind power is the most competitive RE technology in power generation. Therefore, wind power desalination is a promising alternative.

Reverse osmosis (RO) is the desalination process with the lowest energy requirements. Conventional systems are designed for their connection to the grid. Otherwise, shaft power may be directly used for driving a desalination plant. The fluctuations of wind power would ruin the RO system. Therefore, an intermediate energy storage system would be necessary, but it would reduce the available energy and would increase the cost of the plant. The main drawback of RO in remote areas is the complex pre-treatment, the requirement of skilled workers, chemicals and membrane replacement. Desalination systems driven by wind power are the most frequent RE plants. Some are described below.

In 1984, a wind turbine was installed at Los Moriscos (Gran Canaria, Spain) for driving a brackish water desalination plant. It is a  $200 \text{ m}^3/\text{d}$ , RO system. The plant is connected to the grid as auxiliary energy when the wind power is not enough for plant operation. Energy consumption is  $5 \text{ kWh}/\text{m}^3$  [270].

In 1993, a wind driven seawater desalination system began operation at Pajara (Fuerteventura Island, Spain). It is a RO plant with a capacity of  $56 \text{ m}^3/\text{d}$  driven by a hybrid diesel wind system. It consists of two diesel engines and a wind turbine of 225 kW. This hybrid system provides the energy requirements for a village of 300 people.

Its main purpose is the study of RE-driven desalination. The first project developed consists of a RO system with a variable load [81]. They planned to study other desalination systems such as vapor compression and electrodialysis [271].

In 1986, the installation of a RO plant in the Middle-East began. It is a  $25 \text{ m}^3/\text{d}$  plant connected to a hybrid wind–diesel system [272]. In Drepanon, Achaia, near Patras (Greece), in 1995 the operation of another wind-powered RO system began [273]. Finally, Stahl [272] presents other facilities at:

- Island of Suderoong (North Sea) with  $6\text{--}9 \text{ m}^3/\text{d}$ ,
- Island of Drenec, France ( $10 \text{ kW}$  wind energy converter),
- Ile du Planier, France Pacific Islands, with  $0.5 \text{ m}^3/\text{h}$ ,
- Island of Helgoland, Germany ( $2 \times 480 \text{ m}^3/\text{h}$ ), and
- Island of St Nicolas, West France (hybrid wind–diesel);

Although mechanic vapor compression (MVC) consumes more energy than RO, it presents fewer problems due to the fluctuations of the energy resource than RO. MVC systems are more suitable for remote areas, since they are more robust, they need fewer skilled workers and chemicals than RO systems. In addition, they need no membrane replacement and offer a better quality product than RO. On the other hand, in case of contaminated waters, the distillation ensures the absence of micro-organisms in the product. In Borkum Island in the North Sea, one such plant was implemented with fresh water production of about  $0.3\text{--}2 \text{ m}^3/\text{h}$ . In Ruegen Island (Germany) another one with a  $300 \text{ kW}$  wind energy converter and  $120\text{--}300 \text{ m}^3/\text{d}$  of fresh water production was installed [272].

Finally, the electro dialysis process is interesting for brackish water desalination. Such desalination systems are driven by wind power and are more suitable for remote areas than RO plants.

## 8. Current status

### 8.1. Wind energy in Europe

The European Union has called for an increase in the contribution of RE sources from 4 to 8% of total energy demand by 2005. Wind energy will play a major part in achieving this target and is assisting in reducing  $\text{CO}_2$  emissions.

The installed wind energy capacity in Europe has increased by about 40% per year in the past 6 years. Today, wind energy projects across Europe produce enough electricity to meet the domestic needs of 5 million people. The wind energy industry has set a goal for 40,000 MW of wind energy capacity to be installed by 2010, which would provide electricity for about 50 million people.

The wind energy resource in Europe is sufficient in theory, to provide all of Europe's electricity. Technical limitations mean that this will not happen, but detailed studies suggest that most companies could accommodate between 10 and 20% of their total production from wind without any technical modification to the existing system.

Wind is a significant and valuable RE resource. It is safe, abundant and can make an important contribution to future clean, sustainable and diversified electricity supplies. Unlike other sources of energy, wind does not pollute the atmosphere and does not create any hazardous waste. The infrastructural requirements of wind are modest, whilst the potential direct gains in employment are considerable. It is a 'high-tech' industry. Almost 90% of the world's wind turbine manufacturers are in Europe, with a combined annual turnover of more than one billion EUROS. The overall economic profile of wind power compares favorably, whereas the cost of most forms of energy are bound to rise with time, the costs of wind energy are actually coming down.

Today wind energy projects across Europe produce enough electricity to meet the domestic needs of 5 million people. The wind energy industry has set a goal for 60,000 MW of wind energy capacity to be installed by 2010, which would provide electricity to about 75 million people. In 1991, the European Wind Energy Association (EWEA) calculated that the development of wind energy on a European basis at a responsible rate would yield 4000 MW by the year 2000. However, by the end of 1997, when more than 4600 MW had been installed in Europe, EWEA doubled its earlier target to 8000 MW by the year 2000. In fact, more than 9500 MW were installed in Europe before the end of 1999 (see Table 13).

In 1997, the EWEA also set a target of 40,000 MW installed capacity by the year 2010. In September 2003, it decided to increase the target for 2010 to 75,000 MW to reflect the past rates of growth.

Wind power is now a mature industry with a growing potential to make a significant impact on the energy scene in Europe and develop a major export industry. The task of EWEA is to strengthen wind energy's position in the market place. Wind is a limitless resource and it will be the fuel of the future [47,274].

## 8.2. Wind energy in America

Most of the new wind development in the United States is occurring outside of California, the home of the wind energy boom of the 1980s. At the end of 2003 the total installation reached to 4645 MW in the USA (Table 14).

## 8.3. Wind energy in Asia and Pacific

Among the countries of the developing world, India has pioneered the use of wind energy as a vital alternative to its increasing dependence on fossil fuels. With an installed

Table 13

Operational wind power capacity in Europe [274]

Country	Installed capacity (MW)	
	Start-2002	Start-2003
Germany	8753	12,001
Spain	3335	4830
Denmark	2417	2889
Italy	697	785
Netherlands	483	686
UK	485	552
Sweden	280	328
Greece	272	302
Portugal	127	194
France	85	147
Austria	95	139
Ireland	125	137
Norway	17	97
Poland	28	58
Belgium	31	46
Ukraine	40	44
Finland	39	41
Latvia	1	23
Turkey	19	19
Luxembourg	15	16
Russia	5	7
Switzerland	5	5
Czech Republic	5	3
Hungary	1	2
Romania	1	1
Total	17,361	23,357

capacity of over 1450 MW, India is already the fifth largest producer of wind power in the world. Japan is another new important market in Asia (Table 15).

## 8.4. Wind energy in Middle-East and Africa

There is no important wind power installation in Middle-East and Africa except Egypt and Morocco (Table 16).

Table 14

Operational wind power capacity in America [274]

Country	Installed capacity (MW)	
	Start-2002	Start-2003
USA	4245	4645
Canada	207	236
Costa Rica	51	71
Brazil	20	22
Argentina	24	26
Caribbean	13	13
Mexico	5	5
Chile	2	2
Total	4567	5020

Table 15  
Operational wind power capacity in Asia and Pacific Region [274]

Country	Installed capacity (MW)	
	Start-2002	Start-2003
India	1507	1702
China	399	468
Japan	300	384
Australia	73	103
New Zealand	37	37
South Korea	8	8
Sri Lanka	3	3
Taiwan	3	3
Total	2330	2708

### 8.5. General trend

Since 1996, global wind power capacity has continued to grow at an annual cumulative rate close to 40%. Over the past decade, installations have roughly doubled every two and a half years. During 2002 alone, close to 9297 MW of new capacity was added to the electricity grid worldwide (Table 17). By the end of 2002, global wind power installed had reached a level of almost 34,224 MW. This is enough power to satisfy the needs of around 20 million households, over 47 million people (Table 18).

Germany is the market leader. During 2001, German wind capacity grew by a record 2627 MW, taking the country's total up to 8734 MW. This represents 3.3% of national electricity demand, a proportion increase to approximately 5% during 2003. Spain has also continued to expand, the latter by more than 1400 MW during 2003. On current form, the Spanish wind industry will continue to pursue Germany for the European crown. Denmark has meanwhile succeeded in being able to satisfy 18% of its electricity demand from the wind, the highest contribution of any country in the world. In the Americas, the United States market has experienced a major revival, leaving

Table 16  
Operational wind power capacity in Middle-East and Africa [274]

Country	Installed capacity (MW)	
	Start-2002	Start-2003
Egypt	69	69
Morocco	54	54
Iran	11	11
Israel	8	8
Africa	3	5
Jordan	2	2
Total	147	149

Table 17  
Growth in world wind power market (1996–2003) [47]

Year	Installed (MW)	Increase (%)	Cumulative (MW)
1996	1292	–	6070
1997	1568	21	7636
1998	2597	66	10,153
1999	3922	51	13,932
2000	4495	15	18,449
2001	6824	52	24,927
2002	9297	27	34,224
2003	6690	21	41,048
Average growth over 5 years			33.2

previous records in the dust with 400 MW installed during 2003. Over half of that was in the 'Oil State' of Texas. Total US capacity has now reached 4645 MW (Table 19).

## 9. Future prospect

From what has been mentioned in the previous sections on wind energy technology. It is possible to identify some major steps in for future development. These steps have been related up to now with increases in size and performance of wind technology and commersion. The technological development has received strong influences from market and political decisions. During the modern wind energy development significant steps have been triggered by political decisions. The way of the political decisions modulates the direction in which the technology has developed. European decisions have produced large and silent turbines according to the needs of the sites where they are to be used.

In trying to detect future trends, probably the best way to forecast technological developments will be to take a look at

Table 18  
Tap wind energy market during 2003 [47]

Country	New installation (MW)	Total installation 2003 (MW)
Germany	3248	12,001
Spain	1495	3550
USA	400	4645
Denmark	333	2889
Italy	88	785
India	195	1702
Japan	217	357
UK	67	552
Netherlands	203	686
China	69	468
Total	6315	276,357

Table 19

Four years growth rates in the ‘Top-Ten’ wind energy markets [47]

Country	End 1998 MW	End 1999 MW	End 2000 MW	End 2001 MW	End 2002 MW	Growth rate (%)
Germany	2874	4442	6107	8734	12,001	4,814,207
Spain	880	1812	2836	3550	4830	5,189,531
USA	2141	2445	2610	4245	4645	3,929,497
Denmark	1420	1738	2341	2456	2890	3,716,313
India	992	1035	1220	1456	1702	1,249,522
Netherlands	379	433	473	523	686	1,356,224
UK	338	362	425	525	552	1,134,807
Italy	197	277	424	697	785	2,848,218
People’s Republic of China	200	262	352	406	468	1,894,516
Greece	55	158	274	358	362	3,302,357

the political and marketing decisions being taken. Probably the three most important points are,

- Offshore potential development,
- Support for wind energy in Asia and Africa, in addition to USA wind energy exploitation
- Development of the MW range of turbines supported by the EC.

In the next few years, there will probably be bigger turbines for offshore applications, faster tip speeds for non-populated areas and the development of new manufacturers outside Europe. It is also expected that the requirements for onshore projects may not be satisfied by the turbines designed specifically for offshore applications. We will probably witness the splitting of wind turbine technology because of the radically different requirements to be fulfilled.

- Wind speed properties should be re-analyzed carefully, especially variability of wind speed must be studied again and again. Continuity of wind speed research and development can be achieved by making artificial surfaces. Since wind occurrences depend on heating and cooling. It is necessary to make experiments coupled with different roughness and densities. Artificial surfaces with high heating and cooling differences give artificial wind speed values and accordingly wind speed continuity can be evaluated.
- In recent years, neural network, genetic algorithms and fuzzy logic approaches started to appear as applications for improved wind speed evaluations. These methods yield better results in modeling, control and optimization problems. It is recommended that for wind power applications these approaches should be applied.
- Wind speed prediction is an important subject in power meteorology before and after installment of wind turbines. It is, therefore, very significant to impart all climatological, meteorological and atmospheric

motions into efficient wind energy potential evaluations. On the other hand, spatial and temporal relations must be searched for uncertainty decrease in order to minimize the overall prospect costs.

## 10. Conclusion

In this review paper, wind engineering subjects are explained in detail. The literature of wind energy is first reviewed and then wind power meteorology is presented in detail. Additionally, wind turbine technology with wind energy economics and hybrid wind systems are evaluated. Wind energy current states are given year by year for some countries where electricity generation by wind energy increases in an unprecedented manner.

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