Sathyajith Mathew

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Fundamentals, Resource Analysis and Economics

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with 137 Figures and 31 Tables

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Dr. Sathyajith Mathew
Assistant Professor
& Wind Energy Consultant
Faculty of Engineering, KCAET
Tavanur
Malapuram, Kerala
India

E-mail : windbook@gmail.com

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Who has gathered the wind in his fists?

*…………………………………………..................***Proverbs 30:4**

Dedicated to my parents,
wife Geeta Susan and kids Manuel & Ann

Preface

Growing energy demand and environmental consciousness have re-evoked human interest in wind energy. As a result, wind is the fastest growing energy source in the world today. Policy frame works and action plans have already been formulated at various corners for meeting at least 20 per cent of the global energy demand with new-renewables by 2010, among which wind is going to be the major player.

In view of the rapid growth of wind industry, Universities, all around the world, have given due emphasis to wind energy technology in their undergraduate and graduate curriculum. These academic programmes attract students from diversified backgrounds, ranging from social science to engineering and technology. Fundamentals of wind energy conversion, which is discussed in the preliminary chapters of this book, have these students as the target group. Advanced resource analysis tools derived and applied are beneficial to academics and researchers working in this area. The Wind Energy Resource Analysis (WERA) software, provided with the book, is an effective tool for wind energy practitioners for assessing the energy potential and simulating turbine performance at prospective sites.

The introductory chapter narrates the historic development of wind energy technology along with its present status and future prospects. This is followed by Chapter 2, which presents the basic principles of wind energy conversion. Descriptions on different types of wind machines and their performances are briefed here. Basics of wind rotor aerodynamics and its application in the turbine design are also presented in this chapter.

The third chapter is devoted to the methods of measurement and analysis of wind spectra for energy use. Statistical methods for wind energy analysis are introduced here. These are further extended for developing models for estimating the wind energy potential of a prospective site.

Constructional features of various systems and sub-systems of a Wind Energy Conversion System (WECS) are described in Chapter 4. Along with wind electric generators, wind powered water pumping systems are also considered. Features of wind farms, both onshore and offshore, are also discussed in this chapter.

Chapter 5 deals with performance models of WECS. Tools to simulate the field performance of wind powered generators and water pumps are presented in this section. Optimal matching of WECS with the site is also discussed.

Sixth chapter is devoted to the environmental aspects of wind energy conversion. While highlighting the environment related merits of wind energy, the recent concerns over avian issues, visual impacts, noise etc. are not overlooked. A life cycle based approach is adopted for these discussions.

Economics of wind energy conversion is analysed in Chapter 7, following the present worth method. Factors affecting the costs and benefits of wind generated electricity are discussed and indices for economic appraisal are evolved.

Wind Energy Resource Analysis (WERA) software, which comes along with the book, is beneficial to readers who are not familiar with the numerical techniques applied in wind resource analysis. Illustrative examples included in all the chapters compliment the concepts presented in the text.

Subjects presented in this book are primarily derived from my experiences in teaching undergraduate and graduate engineering students. Research and field experiences on WECS have also helped me in formulating the materials presented. Further, serving as a resource person for various wind energy training programmes has also helped me in adopting a multi-disciplinary approach, which is essential for tackling a subject like wind energy. Hence, I would like to thank my students for their contribution.

Compiling information from various sources is essential for developing a book of this nature. I thank the authors of research papers and reports, which are referred in various chapters of this book. Several industries and organizations have supported me by providing information and materials which were essential for this project. Special thanks are due to Hawaiian Electric Company, Renewable Energy Systems Ltd, THALES instruments GmbH, Vaisala Oyj, Siemens Wind Power A/S, ReSoft, and Wikipedia, on this account.

I am fortunate to have the wholehearted support from my professors and colleagues for this project. Let me thank Prof. K.I. Koshy, Prof. C.P. Muhammad and Prof. Jippu Jacob for perusing the manuscript. Contribution of Prof. Anilkumar V and Dr. Damodar Rao in developing WERA is thankfully acknowledged. Thanks are also due to Prof. John D Burton, Prof. K.P Pandey, Prof. Ashok Alex Philip, Prof. Vishnu B, Dr. Dhalin D and Er. Nisha T.V, for their helps at various stages of this work.

As ‘to err is human’, suggestions for improving the content of this book in future are most welcome.

Sathyajith Mathew

Contents

1 Introduction

"Of all the forces of nature, I should think
the wind contains the greatest amount of power"

........Abraham Lincoln

Energy is one of the crucial inputs for socio-economic development. The rate at which energy is being consumed by a nation often reflects the level of prosperity that it could achieve. Social and economic well being can be gauged by the Human Development Index (HDI), developed under the United Nations Development Programme (UNDP). It is found that most of the developed nations, showing high HDI, have per capita energy consumption in the range of 4000 to 9000 kilograms of oil equitant per annum [14]. On the other hand, the developing nations with lower per capita energy use (below 500 kgoe for most of the countries) could achieve HDI only below 0.5. For an HDI higher than 0.8, the per capita energy use has to be enhanced, at least to a level of 1000 kgoe.

Global population is increasing day by day. The population growth is more rapid in developing countries than the industrialized nations [4]. As a result of this population growth and developmental activities, the energy demand is also increasing. During the past 10 years, the primary energy use in the industrialized countries increased at a rate of 1.5 per cent per annum. The corresponding change in developing nations was 3.2 per cent [14]. With this trend prevailing, the global energy demand would increase considerably in the coming years. Future projections indicate that the Total Primary Energy Supply (TPES) should be increased to12,100 Mtoe by 2010 and 16, 300 Mtoe by 2030 [5].

The global energy demand is met from a variety of sources. Fossil fuels consisting of coal, oil, and natural gas meet around 80 per cent of the needs [15]. Share of nuclear power is approximately 7 per cent. The renewables supply 13.7 per cent to which traditional bio-mass and large hydro contribute the major share. At present, share of new renewables (wind, solar, etc.) is only 2.2 per cent. Hence, if the current scenario continues, we have to rely heavily on the fossil fuels to meet our energy needs.

Unfortunately, these fossil fuels are finite resources and will be completely exhausted one day or the other. The proved reserves of coal are only 566 Gtoe. Similarly, the reserves of oil and natural gas are limited to 143 Gtoe and 138 Gtoe respectively. Even at the current consumption rate of 2.26 Gtoe per annum, the proven coal reserve is sufficient for only the next 250 years.

Reserves of oil and natural gas also face similar situation. Though we could discover new reserves of these resources, the rate of discovery has been declining for the past 40 years. Hence, while our energy demand is increasing day by day, the available resources are depleting. This will definitely lead us to the much discussed energy crisis. However, the crisis may not be an imminent reality as the time scale may prolong due to discoveries of new resources.

Environmental ill effects of fossil fuel based power plants add another dimension to this problem. These power plants load the atmosphere with greenhouse gases (GHG) and particulates, resulting in global warming and climate change. Generation and consumption of energy is responsible for 50 to 60 per cent of GHG released into the atmosphere on a global basis. With the increase in energy use, atmospheric pollution from the energy sector is expected to increase further in the near future. Several deliberations are being made globally to chalk out means and measures to reduce the level of atmospheric pollution due to human activities. The Kyoto Protocol and the Johannesburg summit are considered as few positive steps towards a carbon free world. It is widely agreed that, to reduce the emission levels, at least 10 per cent of our energy supply should come from renewable sources.

Here comes the significance of sustainable energy sources like wind. The quantum of energy, associated with the wind is enormous. With today's technology, wind is an environment friendly and economically viable source of energy, which can be tapped in a commercial scale.

History of wind energy conversion along with its present status and future prospects are discussed briefly in the following sections.

1.1 History of wind energy

Human efforts to harness wind for energy date back to the ancient times, when he used sails to propel ships and boats. Later, wind energy served the mankind by energising his grain grinding mills and water pumps. During its transformation from these crude and heavy devices to today's efficient and sophisticated machines, the technology went through various phases of development.

There is disagreement on the origin of the concept of using wind for mechanical power. Some believe that the concept originated in ancient Babylonia. The Babylonian emperor Hammurabi planned to use wind power for his ambitious irrigation project during seventeenth century B.C. [3]. Others argue that the birth place of wind mills is India. In Arthasastra, a classic work in Sanskrit written by Kautiliya during 4^{th} century B.C., references are seen on lifting water with contrivances operated by wind [12]. However, there are no records to prove that these concepts got transformed to real hardware.

The earliest documented design of wind mill dates back to 200 B.C. The Persians used wind mills for grinding grains during this period. Those were vertical axis machines having sails made with bundles of reeds or wood. The grinding stone was attached to the vertical shaft. The sails were attached to the central

Fig.1.1. An ancient windmill in the British Isles (Author: Michael Reeve, source: Wikipedia, http://wikipedia.org. GNU Free Documentation License applies to this image)

shaft using horizontal struts. The size of the sails was decided by the materials used for its fabrication, usually 5 m long and 9 m tall.

By the 13th century, grain grinding mills were popular in most of Europe. The French adopted this technology by 1105 A.D. and the English by 1191 A.D. In contrast with the vertical axis Persian design, European mills had horizontal axis. These post mills were built with beautiful structures. The tower was circular or polygonal in cross-section and constructed in wood or brick. The rotor was manually oriented to the wind by adjusting the tail. The mill was protected against high winds by turning the rotor out of the wind or removing the canvas covering the rotor.

The Dutch, with renowned designer Jan Adriaenszoon, were the pioneers in making these mills. They made many improvements in the design and invented several types of mills. Examples are the *tjasker* and *smock mills*. The rotors were made with crude airfoil profile to improve the efficiency. Apart from grain grinding, wind mills were employed to drain marshy lands in Holland. These wind mills reached America by mid-1700, through the Dutch settlers.

Fig.1.2. An ancient Spanish ‘wind farm’ (Author: Lourdes Cardenal, source: Wikipedia, http://wikipedia.org. GNU Free Documentation License applies to this image)

This is followed by the water pumping wind mill, which is still considered as one of the most successful application of wind power. The so-called American multi bladed wind turbine appeared in the wind energy history by the mid-1800. Relatively smaller rotors, ranging from one to several meters in diameter, were used for this application. The primary motive was to pump water from a few meters below the surface for agricultural uses. These *water pumpers*, with its metallic blades and better engineering design, offered good field performance. Over six million of such units were installed in US alone, between 1850 and 1930.

The era of wind electric generators began close to 1900’s. The first modern wind turbine, specifically designed for electricity generation, was constructed in Denmark in 1890. It supplied electricity to the rural areas. During the same period, a large wind electric generator having 17 m ‘picket fence’ rotor was built in Cleveland, Ohio. For the first time, a speed-up gear box was introduced in the design. This system operated for 20 years generating its rated power of 12 kW.

More systematic methods were adopted for the engineering design of turbines during this period. With low-solidity rotors and aerodynamically designed blades, these systems could give impressive field performance. By 1910, several hundreds of such machines were supplying electrical power to the villages in Denmark. By about 1925, wind electric generators became commercially available in the American market. Similarly, two and three bladed propeller turbines ranging from 0.2 to 3 kW in capacity were available for charging batteries.

Turbines with bigger capacity were also developed during this period. The first utility-scale system was installed in Russia in 1931. A 100 kW turbine was installed on the Caspian sea shore, which worked for two years and generated about 20,000 kW electricity. Experimental wind plants were subsequently constructed in other countries like United States, Denmark, France, Germany, and Great Britain. A significant development in large-scale systems was the 1250 kW turbine fabricated by Palmer C. Putman. The turbine was put to use in 1941 at the Grandpa's Knob, near Rutland, Vermont [8]. Its 53 m rotor was mounted on a 34 m tall tower. This machine could achieve a constant rotor speed by changing the blade pitch. The machine operated for 1100 hours during the next five years, i.e., till the blades failed in 1945. The project is considered to be a succuss as it could demonstrate the technical feasibility of large- scale wind-electric generation.

Some interesting designs of wind turbine were experimented during this period. Darrieus G.J.M, a French engineer, putforth the design of Darrieus turbine in 1920, which was patented in United Sates in 1931 [9]. In contrast with the popular horizontal axis rotors, Darrieus turbines had narrow curved blades rotating about its vertical axis. During the same period, Julius D. Madaras invented a turbine working on Magnus effect. Magnus effect is basically derived from the force on a spinning cylinder placed in a stream of air. Another significant development at this time was the Savonius rotor in Finland, invented by S.J. Savonius. This rotor was made with two halves of a cylinder split longitudinally and arranged radially on a vertical shaft. The transverse cross-section of the rotor resembled the letter 'S' [10]. The rotor was driven by the difference in drag forces acting on its concave and convex halves, facing the wind.

Intensive research on the behaviour of wind turbines occurred during 1950's. The concept of high tip speed ratio-low solidity turbines got introduced during this period. For example, light-weight constant-speed rotors were developed in Germany in 1968. They had fibre glass blades attached to simple hollow towers supported by guy ropes. The largest of this breed was of 15 m diameter with a rated output of 100 kW.

In the later years, cheaper and more reliable electricity, generated from fossil fuel based plants became available. When the electricity generated from wind costed 12 to 30 cents/kWh in 1940, the same generated from other sources was available at 3 to 6 cents/kWh [7]. Cost of electricity from fossil fuels further declined below 3 cents/kWh by 1970. Fossil fuels were available in plenty at a relatively cheaper rate at that time. Several nuclear power projects were also embarked on, believing that it would be the ultimate source for the future energy needs. Thus, the interest in wind energy declined gradually, especially by 1970.

The oil crisis in 1973, however, forced the scientists, engineers and policy makers to have a second thought on the fossil fuel dependence. They realised that political tampering can restrict the availability and escalate the cost of fossil fuels. Moreover, it was realised that the fossil fuel reserve would be exhausted one day or the other. Nuclear power was unacceptable to many, due to safety reasons. These factors caused the revival of interest in wind energy. Research on resource analysis, hardware development, and cost reduction techniques were intensified. United States entrusted its National Aeronautics and Space Administration (NASA) with the development of

1.3. The MOD OA wind turbine (Courtesy of Hawaiian Electric Company, Inc., http://heco.com)

large wind turbines. As a result, a series of horizontal axis turbines named MOD-0, MOD-1, MOD-2 and MOD-5 were developed [6]. These projects were stopped by mid-1980's due to various reasons. During the same period, scientists at Sandia Laboratories focussed their research on the design and development of the Darrieus turbine [11]. They fabricated several models of the Darrieus machine in different sizes during 1980's.

Research and development on wind energy are seen intensified in the later years. A few innovative concepts like the vortex turbine, diffuser augmented design, Musgrove rotor etc. were also proposed during that time. Prototypes of these turbines were constructed and tested. However, only the horizontal axis propeller design could emerge successfully on a commercial scale.

1.2 Current status and future prospects

Owing to our commitment to reduce GHG emissions and provide adequate energy to the developing world, efforts are being made to supplement our energy base with renewable sources. Several countries have already formulated policy frameworks to ensure that renewables play an impressive role in the future energy scenario. For example, the European Union targets to meet 22 per cent of their

1.4 A wind farm (Hamish Hill/Courtesy of Renewable Energy Systems Ltd., www.res-ltd.com)

demand from renewables by 2010. Wind, being the commercially viable and economically competitive renewable source, is going to be the major player in meeting this target.

Wind is the world's fastest growing energy source today and it has been retaining this position consecutively for the last five years. The global wind power capacity has increased by a factor of 4.2 during the last five years. The total global installed capacity is 39434 MW in 2004. Installed capacity in different regions is shown in Fig. 1.5. Over 73 per cent of the global installations are in Europe. Germany is the European leader, followed by Spain and Denmark. The five countries, leading in wind energy generation are listed in Table 1.1.

With the increasing thrust on renewables and reducing cost of wind generated electricity, the growth of wind energy will continue in the years to come. According to European Wind Energy Association (EWEA), wind with its expected 230,000 MW installation, can supply 12 per cent of the global energy demand by 2010 [1]. This indicates a market worth around 25 billion Euros. The installed capacity may reach a level of 1.2 million MW by 2020.

Table 1.1 Global leaders in wind energy generation

Country	Installed capacity, MW
Germany	14609
United States of America	6352
Spain	6202
Denmark	3115
India	2120

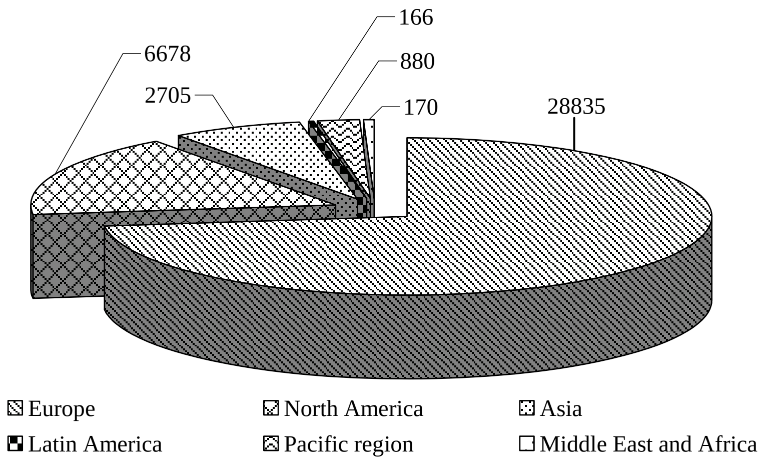

Fig. 1.5. Installed Wind energy capacity (MW) in different regions [13]

In tune with the growth of the industry, the wind energy technology is also changing. One apparent change is the shift towards offshore installations. Several ambitious offshore projects are in the pipeline. For example, 20 offshore projects are planned to be installed in UK by 2006, with a total capacity of 1400 MW [16]. In Germany, around 30 offshore projects worth 60,000 MW are in various stages of processing. In United States also, the offshore activities are intensifying.

Another trend in the industry is to go for larger machines. As bigger turbines are cheaper on a unit kW basis, the industry is growing from MW to multi-MW scale. The 2 MW+ sector is rapidly growing. Several manufactures like the RE Power Systems AG are coming up with turbines of even 5 MW size. The RE Power model is equipped with a huge 125 m rotor having each blade weighing around 19 tonnes [2]. Efforts are also on to reduce the total head mass (THM) which is the total mass of nacelle and rotor. Reduction in THM has positive impact on system dynamics. By clever engineering design, NEG Micon could restrict the THM of their 4.2 MW model to 214 tonnes, which is a remarkable achievement. Owing to the active grid support and better efficiency, the variable speed option with double fed induction generator is getting more prominence in the industry. Another innovative concept that may prove effective in future is the direct drive machines.

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2 Basics of wind energy conversion

Energy available in wind is basically the kinetic energy of large masses of air moving over the earth's surface. Blades of the wind turbine receive this kinetic energy, which is then transformed to mechanical or electrical forms, depending on our end use. The efficiency of converting wind to other useful energy forms greatly depends on the efficiency with which the rotor interacts with the wind stream. In this chapter, let us discuss the fundamental principles involved in this wind energy conversion process.

2.1 Power available in the wind spectra

The kinetic energy of a stream of air with mass m and moving with a velocity V is given by

$$E = \frac{1}{2} m V^2 \tag{2.1}$$

Consider a wind rotor of cross sectional area A exposed to this wind stream as shown in Fig. 2.1. The kinetic energy of the air stream available for the turbine can be expressed as

$$E = \frac{1}{2} \rho_a \, v \, V^2 \tag{2.2}$$

where ρ_a is the density of air and v is the volume of air parcel available to the rotor. The air parcel interacting with the rotor per unit time has a cross-sectional area equal to that of the rotor (A_T) and thickness equal to the wind velocity (V). Hence energy per unit time, that is power, can be expressed as

$$P = \frac{1}{2} \rho_a \, A_T \, V^3 \tag{2.3}$$

From Eq. (2.3), we can see that the factors influencing the power available in the wind stream are the air density, area of the wind rotor and the wind velocity. Effect of the wind velocity is more prominent owing to its cubic relationship with the power.

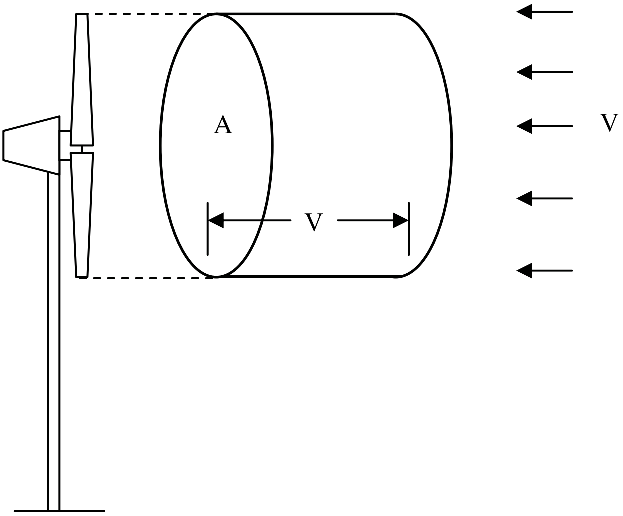

Fig. 2.1. An air parcel moving towards a wind turbine

Factors like temperature, atmospheric pressure, elevation and air constituents affect the density of air. Dry air can be considered as an ideal gas. According to the ideal gas law,

$$p\,V_G = nRT \tag{2.4}$$

where p is the pressure, V_G is the volume of the gas, n is the number of kilo moles of the gas, R is the universal gas constant and T is the temperature. Density of air, which is the ratio of the mass of 1 kilo mole of air to its volume, is given by

$$\rho_a = \frac{m}{V_G} \tag{2.5}$$

From Eqs. (2.4) and (2.5), density is given by

$$\rho_a = \frac{m\ p}{RT} \tag{2.6}$$

If we know the elevation Z and temperature T at a site, then the air density can be calculated by

$$\rho_a = \frac{353.049}{T}\, e^{\left(-0.034\frac{Z}{T}\right)} \tag{2.7}$$

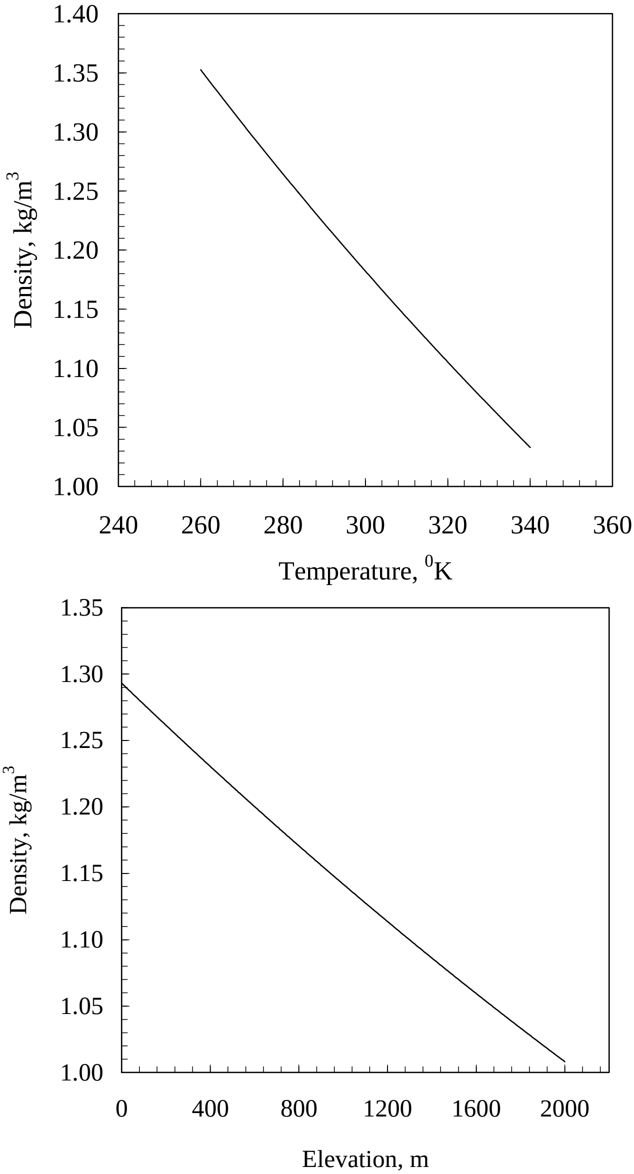

Fig. 2.2. Effect of elevation and temperature on air density

The density of air decreases with the increase in site elevation and temperature as illustrated in Fig. 2.2. The air density may be taken as 1.225 for most of the practical cases. Due to this relatively low density, wind is rather a diffused source of energy. Hence large sized systems are often required for substantial power production.