Chapter 1
Introduction

The available power from the wind, P_{wind}, i.e. the kinetic energy of the air, 0.5 ρu^2 advected with the wind, u is quantified by the following relation:

$$P_{\text{wind}} = 0.5\rho A_{\text{r}} u^2 u = 0.5\rho A_{\text{r}} u^3 \tag{1.1}$$

where ρ is air density, A_{r} is the rotor area of the turbine and u is the average wind speed over the rotor area. Equation (1.1) gives the available wind power over the rotor disk in Watt when the air density is given in kg/m^3, the rotor area in m^2 and the wind speed in m/s. Theoretically, turbines can extract up to 16/27 of this power (Betz 1920, 1926). This limit is known as Betz limit today, although other scientists (namely Frederick W. Lancaster in 1915 and Nikolay Zhukowsky in 1920) derived the same limit at about the same time (van Kuik 2007). It is an engineering issue how close one can come to this theoretical limit (see, e.g. Kaltschmidt et al. 2013). This is not discussed in this book. The other challenge is that wind speed and air density are not a constant. This book is mainly about how wind speeds vary with space (especially in the vertical direction) and time in the atmospheric boundary layer. Air density is addressed in Sect. 2.7. These meteorological issues relevant for wind energy have become part of an emerging wider discipline called 'Energy Meteorology' today (see, e.g. Troccoli et al. 2014). We will start with some basic thoughts on wind energy and a description of the structure of this book in this introduction before we will start to determine the wind speed and air density and its variations in Chap. 2.

1.1 Scope of the Book

Mankind's need for energy will persist or even increase for the foreseeable future. A sustainable supply will only be possible from renewable energies in the long run. The presently used fossil energies are limited in their resources, produce air

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pollutants during combustion and endanger the Earth's climate. Renewable energies comprise water power, wave and tidal energy, geothermal energy, biomass, solar energy and—last but not least—wind energy. This volume focuses on the atmospheric conditions which permit the generation of electricity from wind energy by wind turbines. It has been written from the viewpoint of a meteorologist who has many years of experience with the demands in wind energy generation.

Systematic electricity generation from the wind has been performed for more than 25 years now. The first usage of wind energy had already begun earlier in the United States after the two oil price crises in the 1970s and 1980s but had not led to a steady further development of this technique. In the early years, the turbines were small, rotor diameters being much smaller than the vertical extent of the atmospheric surface layer. In those times, it was relatively easy to assess the local wind climate in order to calculate turbine loads and energy yields. The knowledge of the frequency distribution of the mean wind speed at hub height and the overall turbulence intensity was sufficient to supply the necessary background information for the siting of single turbines and small wind parks.

In the meantime, the size of turbines has increased. The hub height of multi-MW turbines is often above the atmospheric surface layer (roughly 80–100 m offshore and 100–150 m onshore) and rotor diameters of more than 100 m are frequently found. Offshore turbines with diameters of more than 180 m and a power of up to 9 MW have already been designed and will be deployed in the near future. This leads to much more complicated interactions between the turbines and the lower atmosphere. Meteorological features which had been considered as irrelevant for a long time are now becoming decisive for planning and running single large turbines and increasingly larger wind parks. In particular, vertical gradients in mean wind speed as well as the spatial size of turbulence elements or gusts have to be known in order to compute a rotor-effective wind speed which determines yields and loads (see, e.g. Bos et al. 2014).

Furthermore, the vertical range for which these wind parameters must be obtained has now moved to heights which are hardly reachable by masts. New measurement techniques are required to collect the necessary wind information. This has led to a boom in surface-based remote sensing techniques (see Emeis 2011). The economic success of wind turbines depends on a precisely determined trade-off between erection and operation costs and wind energy yields. Each additional metre in hub height is only meaningful if the higher yields pay the additional costs.

Additionally, especially in European countries adjacent to the North Sea and the Baltic, the main area for wind park development has moved from land to marine sites. Here, offshore wind parks will probably deliver most of the wind energy in the future. This means that wind parks are now erected in areas where many details of the vertical structure of the atmospheric boundary layer are not sufficiently known yet. Experimental data from the marine boundary layer are available—if any—for only a shallow layer previously explored from buoys, ships and oil racks. A few masts, like the three German 100 m high FINO masts (see, e.g. Türk et al. 2008) or the Dutch 116-m high OWEZ mast off Egmont aan Zee (Brand et al. 2012) which have been erected between 2003 and 2009 in the North Sea and the Baltic, are presently delivering long-term information on a deeper layer of the marine boundary layer for the first time.

This book tries to analyse and summarize the now existing information of atmospheric boundary layers—onshore and offshore—with respect to wind power generation. The presentation will focus on the vertical profiles of wind and turbulence. It tries to explain the physical processes behind the observable vertical profiles. It will not display wind climatologies for certain regions of the world. The analysis will include features like vertical profile laws beyond those power laws which had been suitable for the surface layer assessment for a long time, instationary phenomena like nocturnal low-level jets, the wind speed-dependent roughness and turbulence conditions in marine boundary layers, and the complex wind–wakes interactions in and behind larger wind parks.

1.2 Overview of Existing Literature

Long-term research challenges in wind energy have been listed in a concise way in van Kuik et al. (2016). Chapters 2 and 3 out of the 11 chapters in van Kuik's overview are devoted to atmospheric and meteorological issues. This demonstrates the importance of meteorology for wind energy. But no monograph solely devoted to the meteorological basics of wind energy generation was available when preparing the first edition of this book apart from a WMO Technical note on 'Meteorological Aspects of the Utilization of Wind as an Energy Source' which appeared in 1981 and did not anticipate the size of today's turbines. In the meantime, a book by Landberg (2016) has appeared which summarizes meteorological aspects relevant for wind energy. But this is still seen from an engineering point of view while the present book looks at these issues from a meteorological point of view. Especially the marine atmospheric boundary—which is extremely relevant for the fast-growing branch of offshore wind energy generation—is treated much more extensively in the present book.

There is a larger body of literature on winds and turbulence in the atmospheric boundary layer appearing in many monographs and journals, but only a smaller number of these papers make reference to wind energy generation (see, e.g. Petersen et al. 1998a, b). On the other hand, there are already many books and papers on wind energy generation itself. These existing books mainly concentrate on technical and engineering issues and cover the wind resources in just one or a few chapters.Recent examples are the second edition of the 'Wind Energy Handbook' by Burton et al. (2011) or the book on 'Airborne Wind Energy' by Ahrens et al. (2013). For instance, Chap. 2 of Burton et al. (2011) book summarizes wind-speed variations, gusts and extreme wind speeds, wind-speed prediction and turbulence within 30 pages. Likewise, Hau in his book on 'Wind turbines', published by Springer in 2006, summarizes the wind resources in Chap. 13 in 34 pages. A monograph on the special field of wind-speed forecasts is 'Physical approach to short-term wind power prediction' by Lange and Focken 2006, which was published by Springer in 2006. Current issues in wind energy meteorology have also been summarized in Emeis (2014).

1.3 History of Wind Energy Generation

Mankind has always used the power of the wind for its purposes. This started with the separation of chaff from wheat and other cereals and the air conditioning of buildings in subtropical and tropical areas. Winds were used to maintain fires and to melt metals. Sailing ships were invented in order to travel over the seas and to establish trade relations with remote coasts. The nearly constantly blowing winds in the subtropical belts of the Earth are still named "trade winds" today.

Winmills date back at least 2000 years. Heron of Alexandria, who lived in the first century AD, is said to be the first to have invented a wind-driven wheel. His machine was merely used to drive organ pipes (Brockhaus 2001). Windmills in Persia are said to have existed from the seventh century AD (Neumann 1907) or from the tenth century (Brockhaus 2001). Those were cereal mills with a vertical axis (Hau 2000). The first windmill in France is mentioned in 1105 (Neumann 1907). From there, this technology spread into England, where the first ones arose in 1140 (Neumann 1907). They appear in growing numbers in eastern parts of England and Northern Europe in the thirteenth century, e.g. 1235 in Denmark. The climax of this development is found between 1500 and 1650 when the arable surface of the Netherlands could be extended by 40% due to the use of wind-driven drainage pumps (DeBlieu 2000). The first German windmill is said to have been erected in Speyer in 1393 (Neumann 1907). About 100,000 windmills were operated in Europe for the purpose of pumping water and producing flour in the eighteenth and nineteenth century, an era ending however, with the advent of steam engines and electricity. See Ackermann and Söder (2000) for further historical notes.

The history of producing electrical energy from the wind is much shorter. The Dane Poul la Cour (1846–1908) built the first wind turbine in Askov (Denmark) in 1891. But it is not before the last three decades of the twentieth century that wind turbines have been erected in larger numbers and growing sizes starting in the United States in the 1970s and 1980s. An early failed attempt for a real large turbine was the construction of the German 3 MW turbine 'Growian' (große Windenergieanlage) in 1983. It was a two-blade turbine with a rotor diameter of 100 m. It produced electricity for only 17 days due to a number of technical problems and was removed in 1988. Development was then re-started beginning with small turbines. This 'evolutionary' approach was successful so that today much larger turbines than Growian are standard, especially for offshore wind parks.

1.4 Potential of Wind Energy Generation

Wind energy is a renewable form of energy. It is available nearly all over the world, though having considerable regional differences. Wind energy forms from solar energy and is replenished by it continuously. Solar energy is practically available without any limits. The transformation from solar energy into wind energy does not involve the carbon cycle either, with the exception of the production, transport, erection and maintenance of the turbines. Wind energy results from horizontal air pressure differences which in turn are mainly due to latitudinal differences in solar irradiation. In the natural planetary atmospheric energy cycle, wind energy is mostly dissipated by friction occurring mainly at the Earth's surface and is thus transformed into the last and lowest ranking member of the planetary energy chain: heat. Generation of electrical energy from the wind does not really disturb this planetary energy cycle. It just introduces another near-surface frictional force which partially produces higher valued electrical energy and only partially heat. When this electrical energy is used by mankind it is also transformed into heat and the planetary energy cycle is closed again. As electrical energy is practically used without any delay and the conservation law for energy is not disturbed, the global planetary energy cycle seems to be undisturbed by energy production from the wind. Therefore, wind power can be considered as a sustainable form of renewable energy. But the entropy budget is affected as well. Large-scale energy production from the wind increases the entropy in the Earth system and could slow down atmospheric circulations. See Sect. 7.4 for further discussions on the interaction between wind power generation and climate.

The globally available energy in the wind can be estimated from the chain of energy conversions in the Earth's atmosphere [the numbers given here are based on earlier seminal publications such as by Lorenz (1955) and Peixoto and Oort (1992)]. The incoming solar power at the top of the atmosphere is roughly 174,300 TW (*342 W/m^{2}). 1743 TW (*3.5 W/m^{2} or 55,000 EJ/year) of this power is available in form of kinetic energy that will eventually be dissipated in the atmosphere. About half of this dissipation takes place in the boundary layer (871 TW or 1.75 W/m^{2}). This yields 122 TW of potential power assuming that one-fourth of the Earth's surface is accessible for wind energy generation and that wind turbines can theoretically extract up to 59% of this energy (Betz' limit). Practically, maybe 50% of this is realistic, meaning that the total potential wind power extractability is about 61 TW (1925 EJ/year). Other estimates which use similar approaches come to energy amounts of the same magnitude (see e.g. Miller et al. (2011) who derive 18–68 TW). A more pessimistic evaluation by de Castro et al. (2011) starts with 1200 TW for the global kinetic energy of the Earth's atmosphere. 8.3% of this energy is available in a 200-m deep surface layer giving 100 TW. 20% of the land surface is suitable for the extraction of this surface layer energy giving 20 TW. Restricting wind parks to areas with reasonable wind resources halves this further to 10 TW. Then de Castro et al. estimate that only 10% of this energy can be extracted by wind turbines. Thus, their estimation is that just 1 TW (32 EJ/year) is the amount of energy extractable from the wind.

While the estimate of the global kinetic energy in the atmosphere is rather robust and yields probably more than 1000 TW, the two critical assumptions in these calculations are the share of this energy that is dissipated at the surface (here varying between 8 and 50%) and the share which can be extracted from this near-surface kinetic energy due to technical aspects of the turbines (here varying between 10 and 50%). Probably a single-digit number given in TW is a realistic estimate for the wind energy available from the Earth's atmosphere. This fits to estimations given in Barthelmie and Pryor (2014) who assume about 5 TW electric energy generation capacities from the wind in 2050. Such a development in the generation of renewable energies would delay the crossing of the 2° threshold in global warming by 3–10 years. In the (unfortunately unlikely) case of RCP 4.5, this development would avoid passing this threshold altogether.

These numbers have to be compared to the total energy demand of mankind which presently is roughly 15 TW (443 EJ/year) and which is expected to rise to about 30 TW (947 EJ/year) by the middle of the century and 45 TW (1420 EJ/year) by the end of the century (CCSP 2007). This comparison makes clear that wind energy can only be part of the solution for a supply of mankind with renewable energies. Other forms of renewable energies have to be exploited in parallel. Furthermore, it can be expected that energy extractions of even 10% of the available wind energy will already have considerable effects on the Earth's climate (see Sect. 10.6).

1.5 Present Status of Wind Energy Generation

The installed worldwide wind energy conversion capacity reached 487 GW by the end of the year 2016, out of which 54.6 GW were added in 2016. The largest share of this has been erected in China (168.7 GW) followed by USA (82.2 GW) and Germany (50.0 GW). India has an installed capacity of 28.7 GW and Spain of 23.0 GW.[1] China has more than doubled its capacity since the end of 2012. These 487 GW are about 7% of the global installed power generation capacity (World Energy Council 2016).[2] In Germany, the installed wind energy generation capacity was about 25.5% of the total installed electrical energy generation capacity in 2016. In the same year, the generated energy from the wind (77.8 TWh) was about 14.3% of the totally generated electricity.[3]

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[1] http://www.gwec.net/global-figures/graphs/ (read 26 April 2017).

[2] https://www.worldenergy.org/wp-content/uploads/2016/10/WECJ4713_Resources_ShortReport_311016_FINAL_corr4_WEB.pdf (read 7 March 2017).

[3] https://www.energy-charts.de/energy_de.htm (read 7 March 2017).

Offshore wind energy production is still in its infancy although gigantic plans for this have been developed. In Germany, 5.3 GW have been installed at the end of 2017, which is about 9.5% of the total installed wind energy generation capacity in Germany.[4] Nevertheless, offshore wind parks delivered 17.3% of the total electrical energy generated from the wind in 2017 (16.6 of 97.3 TWh).[5]

The globally installed capacity of 487 GW is already a considerable fraction of the globally available wind energy in our atmosphere of a few TW. The present growth rate of this installed capacity by extrapolating the numbers for 2016 gives roughly 10% per year. This rate would lead to a doubling within the next 7–8 years and to a tenfold value in nearly 24 years. A steady increase of the installed capacity with this rate of 10% per year would meet the estimated limits in Sect. 1.4 in about 20–30 years. Thus, it cannot be expected that the present growth rate will prevail for a longer time. Therefore, the available wind energy should be extracted in a most efficient way. Understanding the meteorological basics for the extraction of wind energy gathered in this book shall help to reach this efficiency.

1.6 Structure of This Book

This publication is organized as follows. Chapter 2 explains the origin of the large-scale winds in our atmosphere and presents the main laws driving atmospheric motion in the free atmosphere. Additionally, the determination of air density is addressed. Chapters 3–5 present the vertical profiles of wind and turbulence over different surface types. Chapter 3 reviews classical boundary layer meteorology over flat natural homogeneous land surfaces. Emphasis is laid on the vertical extension of wind profiles from the surface layer into the Ekman layer above, since large multi-MW wind turbines reach well into this layer today. This includes the description of nocturnal low-level jets, which lead to nocturnal maxima in wind energy conversion with large turbines. Internal boundary layers forming at step changes of the surface properties, forest boundary layers and urban boundary layers are shortly addressed at the end of this chapter. Chapter 4 highlights the peculiarities of flow over complex terrain, especially of orography. Basic features such as speed-up over hills are derived using a simple analytical model. A separate description of flow over this surface type is relevant, because the near-coastal flat areas are often sufficiently used today and sites more inland have to be analysed for future wind energy production.

The deployment of turbines far away from the coasts closer to urban and industrial areas also helps to reduce the erection of massive power lines connecting generation and consumption areas. The last of these three chapters on vertical profiles, Chap. 5 deals with a surface type which presently is becoming more and

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[4] https://www.energy-charts.de/power_inst_de.htm (read 18 December 2017).

[5] https://www.energy-charts.de/power_inst_de.htm (read 18 December 2017).

more important: the marine boundary layer over the sea surface. The planning of huge offshore wind parks requires that considerable space is devoted to this surface type. Chapter 6 looks into the features and problems which come with large wind parks over any of the aforementioned surface types. This is no longer a pure meteorological topic, because the properties of the wind turbines and their spatial arrangement in the park become important as well. This chapter will present another simple analytical model which can be used to make first estimates on the influence of surface roughness and thermal stability of the atmosphere as well as the influence of the turbines' thrust coefficient and the mean distance of the turbines within the wind park on the overall efficiency of the wind park.

Chapters 3–9 all end with a short summary on the main aspects which should be taken into account from a meteorological point of view when planning and running wind turbines. Chapter 7 describes available data sources for wind data from in situ and remote sensing measurements and from various types of flow models. Chapter 8 addresses the meteorological aspects of an environmental problem related to wind turbines and wind parks: the propagation of noise from the operating turbines. Chapter 9 addresses further meteorological issues such as icing and lightning influencing the generation of energy from the wind and Chap. 10 gives an outlook on possible future developments and certain limitations to large-scale wind energy conversion.

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