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Introduction

Energy supply is undoubtedly one of the most challenging issues facing human beings in the 21st century. Limited traditional fossil fuels are being used up gradually, let alone air pollutants and global warming caused by the combustion of those dirty fuels. Renewable energy has therefore attracted increasingly more attention in recent years. Wind energy, being one of the most commercially viable forms of renewable energy at the moment, has already played an important role in quenching our society's energy thirst. Yet there is still a long way to go before we can fully exploit the wind potential of our planet.

Wind is the 'fuel' for wind power generation. Its characteristics, that is wind conditions, are therefore of the upmost importance when it comes to determine the economics of a wind farm project. Wind conditions are set by nature, but how well we can understand or estimate them is another question. Wind resource assessment in essence is the estimation of wind conditions based on wind data available and topographical (roughness, obstacles and terrain) and meteorological (e.g. atmospheric stability, boundary layer structure, weather system) features of a given site.

Being invisible already makes it hard for us to picture the wind, and to make matters worse it varies constantly and dramatically in time and space, influenced by a great number of factors, some of which we may not even know of. However, on the other hand, building wind farms is very capital intensive and those wind farms have to generate profit for their owners. Profitability has to be predicted before wind farms are built with a reasonable risk premium. Such stringent requirements from the industry have raised sometimes almost impossible challenges for wind resource assessment professionals. After all, the results of wind resource assessment and micro-siting will determine the success of the investment of a wind power project.

This book endeavours to bring together pieces of core knowledge used in wind resource assessment and to put them into a logical order and to explain them, adding in the author's own experience obtained in day-to-day work scenarios. This kind of effort has rarely been made before, at least to the author's knowledge, even though a few publications covering a few sections of the domain can be found in the market.

Wind Resource Assessment and Micro-siting, Science and Engineering, First Edition. Matthew Huaiquan Zhang.

1.1 Wind Resource Assessment as a Discipline

From a meteorological point of view, the study of a wind resource for the purpose of energy production can be described as wind energy meteorology, which has developed into an independent division of meteorology. In fact, a monograph named *Wind Energy Meteorology* by Emeis [1] has recently been published in early 2013, a milestone of the discipline. Petersen *et al.* [2] describe wind energy meteorology as applied geophysical and fluid dynamics, a combination of meteorology and applied climatology.

Despite its importance, wind energy meteorology has not been a major area of expertise required by the industry to produce satisfactory wind resource analysis results until the last decade or so. In the last decade especially, wind turbines have substantially grown in size and height, which means that they are exposed to much more complicated atmospheric boundary layer structures. Simplified engineering models, which worked well before, have to be re-examined based on the study of wind energy meteorology. The fact that wind turbines are usually erected in more complex terrain conditions, and even offshore nowadays, has also promoted the development of the discipline. Therefore a significant portion of time will be spent on this subject in order to form a physical profile of wind resource analysis for readers.

Wind resource assessment takes us one step closer to the wind energy industry, setting off from the ivory tower of physics. The domain of wind resource assessment should at least consist of wind data analysis, site analysis, wind turbine selection, wind turbine siting (micro-siting), wind flow modelling, power production estimates, wind park optimization and uncertainly analysis. Statistical tools are predominantly used in the process owing to the stochastic nature of the wind. Therefore, statistics becomes another pillar of wind resource analysis, the first one being the physical models explained by wind energy meteorology, such as the boundary layer profile and atmospheric stability. In order to ensure quality calculations, we need to understand how the wind should be measured as well as interaction mechanisms between wind and wind turbines and amongst turbines (wake effects).

The development of wind resource assessment has been accompanied and motivated by the commercial evolution of wind turbines and the construction of large-scale wind power projects. It will continue to do so in the foreseeable future. As a matter of fact, the expertise in wind resource assessment has become a core competence for many organizations in the industry and therefore well sought after.

1.2 Micro-siting Briefing

Micro-siting is really a meteorological definition, because in the eyes of a meteorologist, a few hundred metres is really on a micro scale. Micro-siting can be defined as the process of strategically positioning wind turbines within a given project area, in order to maximise power production with minimised turbine loads, that is optimising the wind park. Petersen *et al.* give an alternative definition of micro-siting, that is an estimation of the mean power produced by a specific wind turbine at one or more specific locations [2].

A full siting procedure includes considerations such as the availability and capacity of the power grid, the present and future land use, and so on, but these aspects are not considered in this book. However, one important issue concerning the siting of wind turbines is their environmental and health impact, such as noise and flickering, which can turn into a dominant factor in some cases and is explicated in Chapter 11.

1.3 Cascade of Wind Regime

The wind in nature almost never travels along a straight line; rather its track resembles circles. Those 'circles' are of all sizes, driven or dominated by different forces and induced by various mechanisms. Bigger 'circles' break into smaller ones and then even smaller ones until dissipated into heat, that is vibration of air molecules.

The wind we feel is a superposition of all the 'circles' of air movement at one spot. The scale of wind regime (or the size of the 'circles') can be described by two dimensions: temporal and spatial. The temporal scale and spatial scale of a wind regime are closely related. We can imagine that the bigger it is in space, the longer it takes to finish a circle. This cascade of wind regime should be the first physical model of the wind one should formulate before getting into the world of wind resource assessment. Wind regime is also referred to as wind climate or wind system. Chapter 9 will present wind systems of various scales in detail.

1.3.1 Global Scale Wind Regime

The atmosphere is a very complex heat engine whose energy is supplied by the heating of the earth's surface by the sun. Because the earth is tilted and also because of its uneven surface, different parts of the earth receive substantially different amounts of energy from the sun, which in turn induces air circulations with a spatial scale of the entire globe and a temporal scale of one or many years. This partly explains why wind resources are distributed so unevenly around the globe, as shown in Figure 1.1 [2].

Long-term wind data measured around the globe are required to analyse wind climate on this scale, but such efforts are commonly hindered by poor data quality (usually measured at

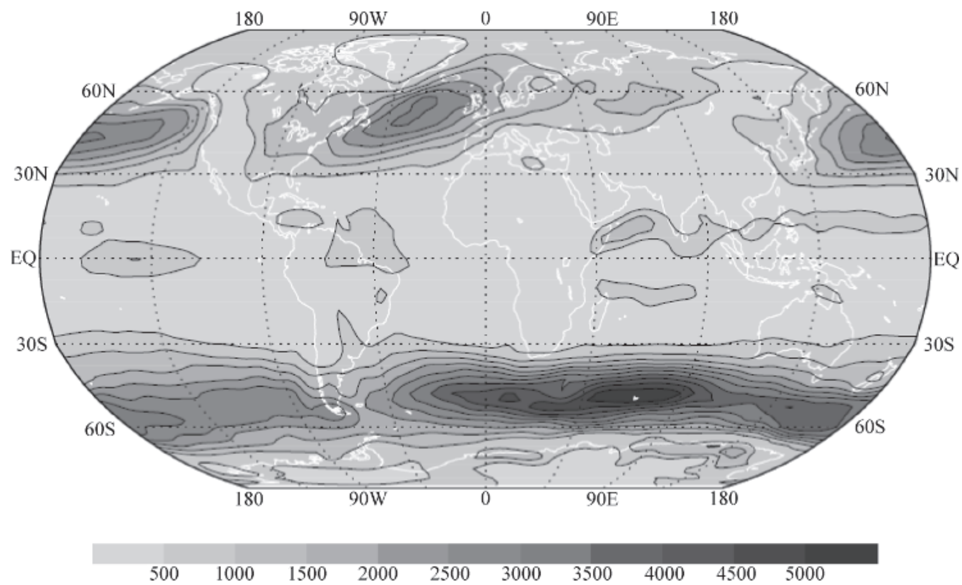

Figure 1.1 Energy flux of the wind at 850 hPa (about 1500 m.a.s.l.) in W/m^2 from 8 years of the NCEP/NCAR reanalysis [2] *Source*: Risø National Laboratory

10 m height and contaminated by local features and inconsistent through time) and insufficient measurement points.

In recent years, however, the advances in computational power, the availability of nontraditional meteorological datasets with global coverage (such as satellite data), in addition to the traditional ones used in the global meteorological network (e.g. the Global Observing System [3]), and the advances in weather prediction models have together made it possible to reconstruct the global scale weather situation at every instant over recent decades. Global meteorological models are able to provide dynamic, consistent wind data and statistics, while avoiding some of the setbacks associated with the direct use of wind data (in fact most reanalyses do not consider low-level wind data in the analysis because of their 'contamination' with local influences) [4]. Figure 1.1 [2] is a good example of such applications and indicates the global wind resource variation, though the figure is rather dated. Figure 1.2 demonstrates the distribution of wind power density in China.

Global meteorological models are usually made with spatial resolutions too coarse to be used in project-based wind resource analysis. For a higher level of spatial resolution, which includes smaller-scale phenomena of significant influence on the wind resource, it is now

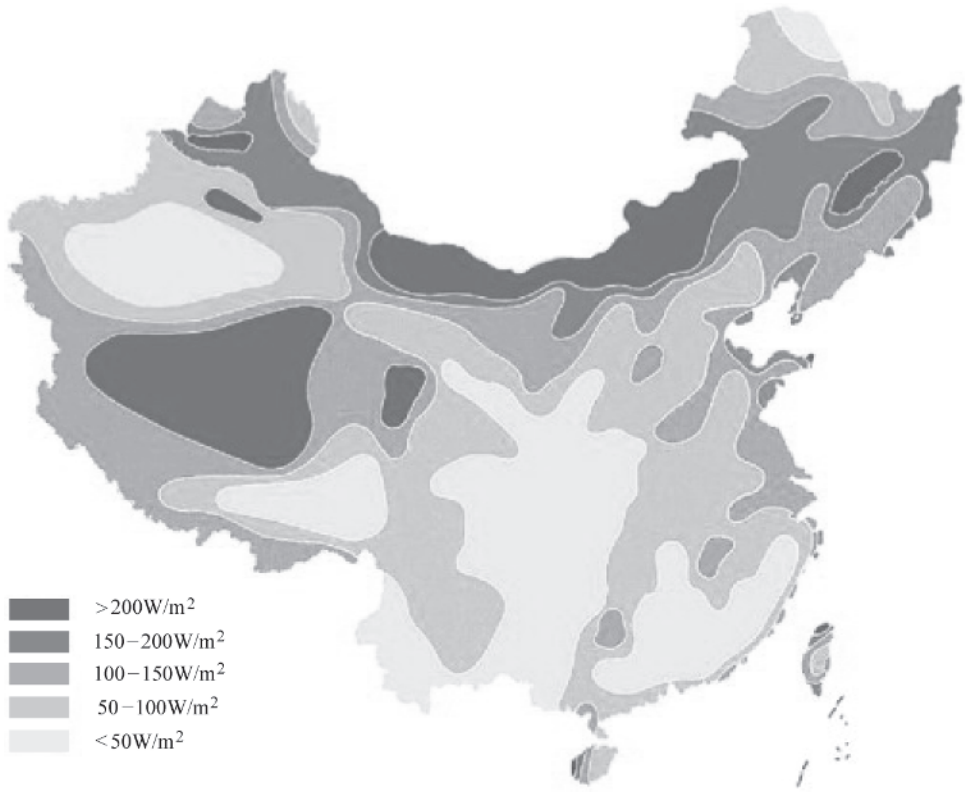

Figure 1.2 Wind power density distribution of China *Source*: China Meteorological Administration (CMA)

a common practice to use mesoscale NWP models of much higher resolutions than global reanalysis models. These models cover a smaller domain using global data as boundary conditions. From the aspect of wind resource assessment and micro-siting for wind power projects, this global scale wind climate is a rather remote application, and therefore is generally excluded in this book. However, it does indicate the importance of long-term correction of in-situ wind measurements, which typically cover only a period of one or two years.

1.3.2 Synoptic Scale Wind Regime

We are probably more familiar with the synoptic scale wind regime because of the application of weather forecasts, which frequently mention weather systems, such as fronts, pressure systems, cyclones and anticyclones. Synoptic scale wind regimes usually have a spatial scale of more than 200 km (up to thousands of kilometres) and temporal scales of over a few days (up to a few months). Large synoptic scale wind systems (e.g. westerly winds in mid-latitude, trade winds and monsoons) are in most cases the main drivers of a local wind resource, although often severely altered by smaller scale phenomena.

Synoptic scale systems are obviously also too large for the purpose of analysing wind resource conditions within a wind farm and wind turbine siting in spite of its significant impact on local winds. The analysis of synoptic scale systems for wind turbine micro-siting only becomes relatively more important in some offshore cases where the overall atmospheric stability (one of the determining factors for wind turbine spacing and layout design) is closely related to wind direction and the passage of weather systems. Even then, it is usually not studied in detail. This is not to undermine the importance of understanding synoptic scale wind systems for wind resource assessment and micro-siting; rather it is to find the right focus for professionals working in this area as well as the scope of this book.

1.3.3 Meso-scale Wind Regime

Large scale models are insufficient to capture all weather phenomena related to the local wind resource. Meso-scale models zoom in from such large scale models and look at the missing scales between large scales and local or micro-scales. It covers special wind phenomena such as land and sea breezes, tropical hurricanes and convective storms. In the meantime, the meso-scale is also commonly used to explicit large scale flows modified by terrain features such as hills, mountains and surface features, which are not resolved in the larger scale models. As large scale and global models become more and more sophisticated and of increasing resolution, the division between large scale and meso-scale becomes blurred.

Meso-scale NWP models are commonly used nowadays in wind resource assessments in terms of a site hunt, that is searching for possible sites for wind power projects. In contrast with micro-siting, which deals with the wind resource within a given project area, a site hunt using meso-scale models can be referred to as macro-siting. Meso-scale NWP models are also able to generate a long-term wind data series, which is invaluable for long-term correlation of on-site wind measurements. As a result, a wind resource analyst should know by heart the correct usage of the results from meso-scale models and their pros and cons (see Chapter 3).

1.3.4 Local Scale Wind Regime

The local wind regime reflects local wind effects down to the smallest scales superimposing on larger scale features and meteorological systems. From a meteorological point of view, it generally represents micro-scale meteorological features and wind effects, giving the origin of the term ‘micro-siting’.

Local winds are driven by local geographical features. Near the surface, medium to small hills usually have similar levels of impact on wind speed with vegetation and obstacles [5]. Figure 1.3 illustrates the slightly exaggerated variation of mean wind speed at 10 metres above ground level on a typical Danish site, indicating clearly the effects of topographical features on local winds. During micro-siting, various micro-scale topographical features have to be carefully taken into consideration.

In general, in situ wind data measured by local meteorological masts (often referred to as a met mast in short) should be sufficient for the estimation of a wind resource at the measured point. However, it is more likely that we do not have measurement data at the specific point(s) of interest (at the hub height of the intended wind turbine at their precise locations) or not over a sufficiently long time (years) to be able to directly estimate the wind resource. Therefore, it is essential to have an understanding of the most important mechanisms that influence the wind locally. Micro-scale differs from meso-scale and larger scales in that their influence in general can be assessed with respect to mean winds and wind resources by corrections based on empirical relationships and simple physical models [4].

Local influences that must be considered include sheltering by obstacle(s) (more important at relatively low heights), speed-up effects of orography (e.g. hills, valleys), roughness and surface thermal conditions (or atmospheric stability, which is especially important for assessing the wind resource at higher heights above the surface). Chapter 2 will elaborate on these effects in terms of analytical models and engineering applications, while Chapter 3 is dedicated

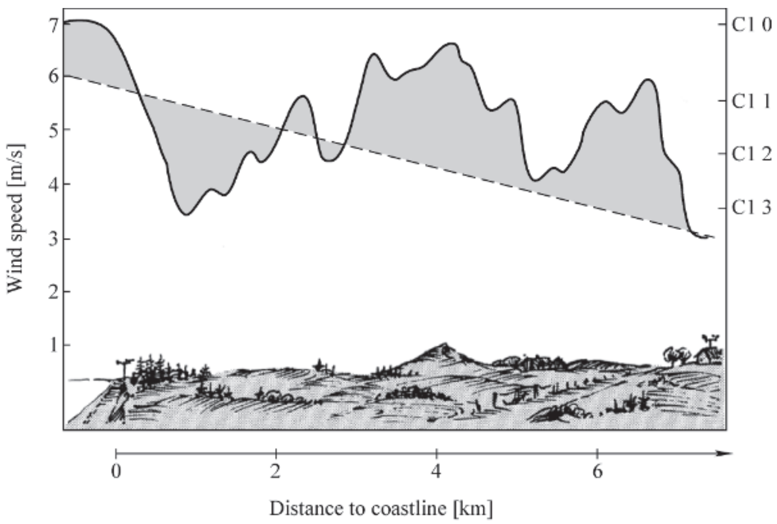

Figure 1.3 The variation (slightly exaggerated) of mean wind speed 10 m.a.g.l. due to topographical effects (full line) for typical conditions of Denmark [5] *Source*: Risø National Laboratory

to numerical wind flow modelling. The more theoretical roots of those effects will be presented later in Chapter 9 and Chapter 10.

In most areas of the world, the local wind resource is essentially determined by large synoptic scale wind systems (they determine the overall long-term trend of a wind resource) with smaller scale features superimposed on them. The study of large scale wind systems requires long-term wind measurement, whereas local in situ wind measurements can be as short as merely one year. Therefore, long-term correlation of wind data is to some extent the study of the correlation between local effects and large scale systems. Chapter 6 will elaborate on this topic in detail.

Wind resource is a statistic quantity. Thus, the assessment of wind resource starts with the statistics of local wind speed and direction. In an overwhelming majority of cases, an on-site met mast(s) must be installed in order to reduce uncertainties of the wind resource assessment and turbine load calculations. The number of necessary masts depends on the complexity of the site. The measurement height should be as close to the expected wind turbine hub height as possible. Measuring the wind at multiple heights is necessary in order to evaluate local influences on the wind better. Due to the difficulty of constructing met masts in many cases (e.g. offshore), ground-based remote sensing (lidar and sodar) capable of measuring wind up to hundreds of metres high have been deployed more widely in recent years. Wind measuring techniques will be introduced in Chapter 8.

1.4 Uncertainty of Wind Resource

The complexity of wind resource assessment to a great extent is due to the uncertainty of the wind in nature and the uncertainty of the tools we use to predict it. It is thus something we should always keep in mind. The characteristics of statistics itself also imply that the wind, as a statistical quantity of stochastic variables, must bring in various intrinsic uncertainties as well.

The random nature of wind resources makes wind energy commercially unique to traditional fossil fuels. The price of fossil fuels fluctuates substantially with the market, which is risky for the business, whereas wind is free and never changes in price. Therefore the revenue generated by a wind power plant is not affected much by the unpredictable energy market; instead it tends to grow in the long run as electricity price generally follows an upward trend over years. On the other hand, the risk of investing in wind energy lies on how well we can estimate the wind resource and calculate the power production before erecting wind turbines and investing real money. This explains the significant role wind resource analysis and micro-siting plays for delivering a commercially successful wind power project.

To help us understand the uncertainty of wind resource better, let us take a look at a well-known example of wind speed variations at a point in Ireland, as shown in Figure 1.4. The line of monthly mean wind speed in the upper frame in Figure 1.4 indicates violent fluctuations. Yearly mean wind speeds calm down significantly, but still vary dramatically from year to year, shown more clearly by the slash blocks in the lower frame in Figure 1.4. Even averaged over 10 years, the means still do not seem to be stabilised. Noting the fact that the energy content of wind is proportional to the third power of the mean wind speed, one can imagine the magnitude of the variation in available wind energy due to fluctuating wind conditions. For example, a 1% decrease in the mean wind speed can be expected to yield about 2% less energy.

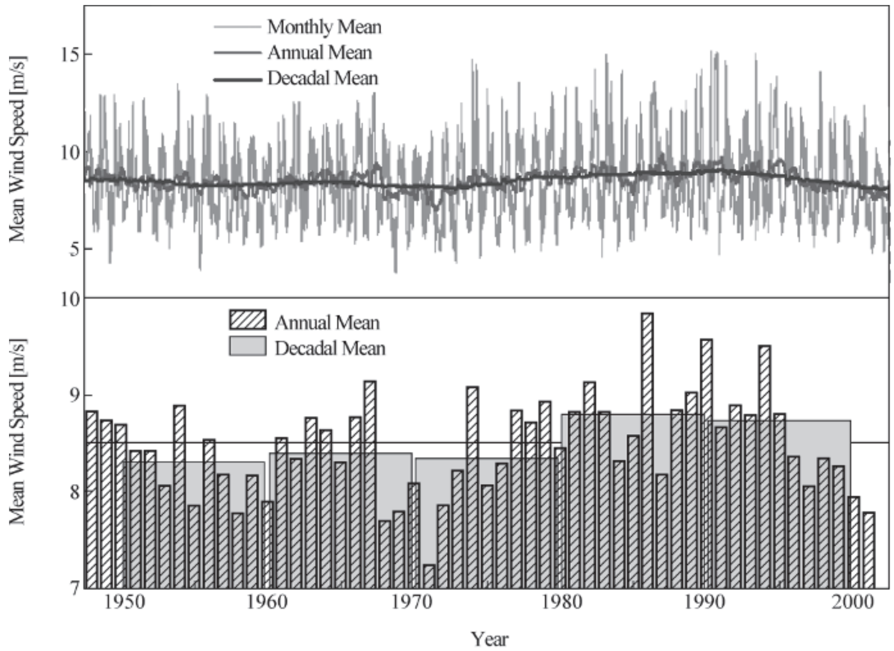

Figure 1.4 Reanalysis data for a point in Ireland showing the variability of the mean wind speed *Source*: Risø National Laboratory, created by Gregor Giebel

Unfortunately, we typically have only one or two years of in situ wind measurements, representing only wind conditions in the past. Then how can we accurately assess the mean wind speed over the next 20 years (the commonly expected life time of wind turbines) and predict power production and the profit of the wind power project for its entire life cycle? As we can see from Figure 1.4, the annual mean wind speed in 1971 was only about 7.2 m/s whereas it hiked to approximately 9.5 m/s in 1986. The peaks and troughs of annual wind climates not only make the profitability assessment of wind power investment a risky business but they may also cause a wrong selection of wind turbine types. According to the mean wind speed in 1971, this should be an IEC III site, but the data in 1986 points to IEC I, although the wind in the long term should actually be IEC II [6]. If IEC I wind turbines were chosen, the efficiency of the wind farm would be dampened. If IEC III turbines were chosen, the wind loads could be unbearable for the turbines, which would increase wear and tear and maintenance costs and even shorten the machines' lifetime.

Consequently, long-term correlation and correction of in situ wind data based on long-term reference data become extremely important. A method often used to reduce the uncertainty resulting from measurements over a short period is the so-called Measure−Correlate−Predict (MCP) method, which uses the statistical relation established between the wind data in a long term 'reference' dataset and a shorter time overlapping dataset measured at a 'target' site to estimate the target site wind statistics over the long reference period [3,7]. This methodology of MCP will be presented in Chapter 6, while the uncertainty study of wind resource assessment is placed later in Chapter 7.

1.5 Scope of the Book

As put by EWEA in the report *Wind Energy – The Facts* in 2009 [7], 'The wind is the fuel for the wind power station. Small changes in wind speed produce greater changes in the commercial value of a wind farm . . . . Commercial evaluation of a wind farm is required, and robust estimates must be provided to support investment and financing decisions . . . . Once the wind speed on the site has been estimated, it is then vital to make an accurate and reliable estimate of the resulting energy production from a wind farm that might be built there.' This generally summarizes the standpoint of this book.

Wind resource assessment ranges from synoptic scale to micro-scale. It is inclined more towards scientific meteorology for larger scale wind resource assessment. This book, on the other hand, focuses on micro-scale analysis and its engineering applications, providing practical and theoretical guidance for wind resource assessment and micro-siting. The theories presented in the book are also designed for a better conduct of day-to-day engineering work. Each chapter of the book can easily fill its own book, but the scope of this book is to sufficiently elaborate each topic for engineers and establish a platform for those who wish to dig deep in research. A professional working in this field does not have to be a specialist in meteorology or a statistician, but the knowledge put together in this book is critical and should be acquired.

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