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Review Article

Wind Resource Estimation—An Overview

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This article gives an overview of the different ways the wind resource at a site can be estimated. Eight separate ways have been identified. Each of these will be described in some detail, and advantages and disadvantages of each of them will be discussed. Copyright © 2003 John Wiley & Sons, Ltd.

Introduction

One of the first actions needed when interested in wind energy in a region is to establish an overview of the available wind resource. This overview should make it possible to identify areas of high and low winds. It should also quantify these, making it possible to evaluate whether wind energy is economically viable in the area. The problem is that different areas will have very different sources of information about the wind. This is not a problem if one has the option to establish a dense measuring network, wait for 5–10 years and then evaluate the wind resource. In practice this is not possible, of course, so other methods must be applied.

In the following, eight methods for estimating the wind resource of an area will be described. First, however, the term 'wind climate' will be defined.

Defining the Regional Wind Climate

In Table I the definition of the regional wind climate is given. It is put into context by defining the wind resource and the wind atlas as well.

The regional wind climate is calculated from measurements by removing the *local effects*. Local effects are all effects specific only to the site, namely:

- shelter from near-by obstacles;
- effects of roughness and changes in roughness;
- effects of the orography on scales less than ~10 km;
- thermally driven flow.

The main advantage of using this definition is that it is virtually scale-independent, i.e. small features in the landscape (hills, valleys, forests, lakes, etc.) do not affect the regional wind climate.

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Table I. The definition of the three wind resource terms. For each term some comments are also given relating to scale and/or scope

Term	Definition	Comments
Atlas[a]	Collection of regional wind climates for a large area	Scope: 100–10 000 km Scale: O(50 km)
Regional climate	Wind statistics, temporal and spatial variation. Reduced to standard conditions	Scale: O(50 km) Regional validity Must be modelled
Resource	The actual long-term kinetic energy content of the wind at a specific location and height	Scale: O(1 m)

[a] 'Atlas' is also used as the term describing the WAsP. LIB-file.

Table II. The eight different ways of wind resource estimation. Refer to the text for an explanation of the different methods. 'Measurements' refers to traditional on-site measurements taken at e.g. airports. 'WAsP terrain' means local orography and roughness out to 10 km. An example of a database of geostrophic winds could be the global one of NCEP/NCAR, and of a database of land-use (i.e. the roughness of an area) the CORINE database

Method Components	1	2	3	4	5	6	7	8
Measurements		√	√		√	√		√
Database geostrophic winds				√			√	√
Database land-use							√	√
Database orography							√	√
WAsP terrain					√	√		√
Mesoscale model							√	√
CFD					√	√		√
Microscale model					√	√		√
Geostrophic drag law				√				
Statistical models			√					
'Folklore'	√							

Overview

In Table II the different methods are outlined. In the following subsections each of the methods will be described and their applicability will also be discussed.

Method 1: Folklore

This method could base itself on interviews with people with local knowledge, and the aim is to identify areas with high and/or low wind speeds. The method can be used if all else is not possible, and has the advantage of being very cheap and fast. Of the large number of shortcomings this method has, only two will be mentioned. First, there is almost always a tendency to overestimate the wind in windy areas, mainly—we speculate—because of the chill factor: when it is cold, even moderate winds feel strong. The other problem with this method is that it is not certain that the entire area in question is traversed by humans. The reasons for this can be many. One could be high winds! Another could be inaccessibility. In conclusion, this method should be used only if no other is available, and important decisions should not be based on evidence obtained from it alone.

A derivative of this method is *onomatology*, where areas with potentially high winds are located by finding geographical names indicating this. An example is 'Windy Standard' in Scotland. Another's 'Vindeby' in Denmark.

Another related method is locating high-wind areas by studying the local vegetation. For example, trees in very windy areas tend to take shape after the prevailing wind, the so-called 'flagging' of trees.

Method 2: Measurements Only

Basing a regional study on measurements only is indeed possible. However, great risk exists of either severely over- or under-determining the resource. The resource will be under-determined if the study is based mainly on observations in built-up (or other high-roughness or otherwise sheltered) areas. Conversely, the overall resource will be over-determined if the observations are mainly from low-roughness, very exposed areas.

Method 3: Measure–Correlate–Predict

A method often used in estimating the resource at a site is measure–correlate–predict (MCP). The idea is that the resource at a potential site can be determined by using a short measuring campaign at the site and then correlating these measurements with an overlapping but climatologically representative time series. Climatological representativity is obtained by measuring for at least 5 but preferably 10 years.

The way the correlation is established varies from method to method, but many use a simple linear relation.[1] References to other methods can be found in Reference 2.

This method could also, in principle, be used for regional wind resource estimations, but it suffers from the same drawbacks as method 2: risk of severe under-/over-determination of the resource.

Once the resource at the site has been determined, modelling is required to carry out the micro-siting. This can be done using any of the micro-siting models: WAsP,[3] MS-Micro,[4] and Raptor,[5] Raptor-NL.[6] Even CFD models (see below) could be employed.

Often the correlation between the on-site and the climatological time series is quite low, meaning that the resulting expressions that link the two could be quite erroneous. Advantages of the method include the fact that only short-term on-site measurements are required, bringing the cost of assessing the wind resource of a particular site down. Furthermore, it also in many cases gives results which for many purposes are adequate.

Method 4: Global Databases

Using global databases of winds has first been possible within the past 4–5 years with the appearance of databases such as those from NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research)[7] and ECMWF (European Centre for Medium-range Weather Forecasting)[8] (Figure 1). These databases are the result of the huge reanalysis effort carried out by the institutions.

The databases typically contain wind, temperature and pressure at several heights in a grid covering the entire globe. To ensure that local effects on the measurements are avoided to the greatest extent, wind in the free atmosphere is normally used. To extrapolate these winds to the surface (given its roughness), the geostrophic drag law can be employed. The geostrophic drag law connects the geostrophic wind to the friction velocity at the surface according to

$$G = \frac{u_*}{\kappa}\sqrt{\left(\frac{u_*}{f z_0} + A\right)^2 + B^2} \tag{1}$$

where G is the geostrophic wind (i.e. the wind derived from the balance between the pressure force and the Coriolis force), u_* is the friction velocity, κ (=0·4) is the von Karman constant, f is the Coriolis parameter and z_0 is the surface roughness. A and B are constants equal to 1·8 and 4·5 respectively.

This method has several advantages. Firstly, since the databases are globe-spanning, the method can be applied to any area. Secondly, since high-level winds are used, the local effects are not introduced in the first place. Thirdly, since the database contains typically around 10 years or more of measurements, the estimates are climatologically stable. This, potentially, makes the estimates very close to the actual wind resource. The method also has some drawbacks, however, the main ones being the low resolution, typically of the order

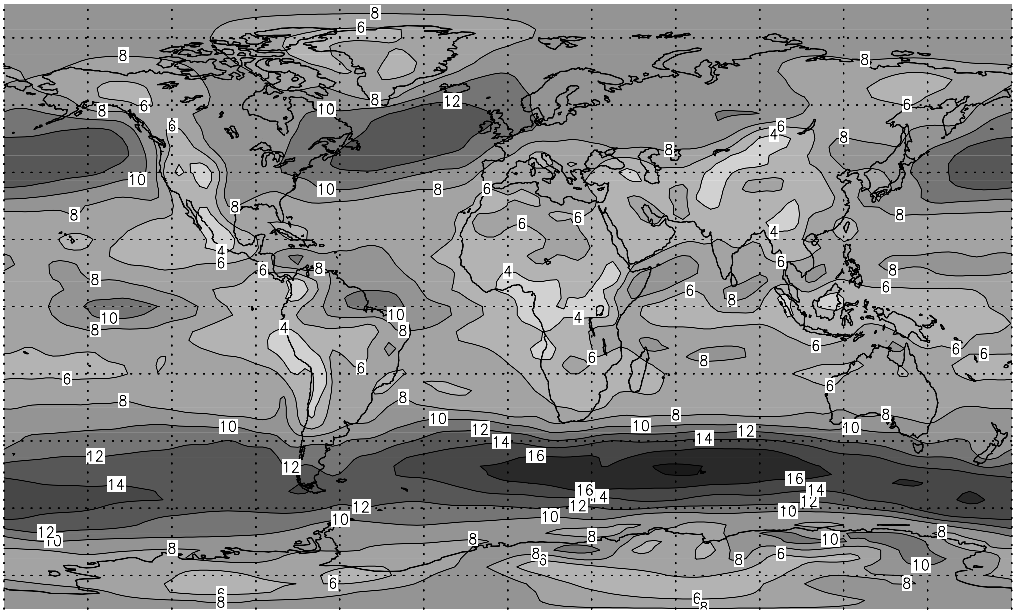

Figure 1. Mean wind speed at 850 mbar for the years 1976–1995 from the NCEP/NCAR reanalysis database

of degrees (i.e. 100s of km), and the fact that not all wind climates near the ground are determined by the winds aloft. Furthermore, in equatorial regions, f is small or even zero.

Method 5: Wind Atlas Methodology

For countries with a tradition of long records and dense networks of observations of the wind, the wind atlas methodology[9] is the preferred method for wind resource studies. The method has been applied to a large number of countries (all of EU Europe, Russia, countries in northern Africa), making it the *de facto* standard, (Figure 2). The method directly corrects existing long-term measurements for three of the four local effects listed above (Figure 3). The fourth (thermally driven winds) is not very dominant in many areas of the world. In areas where they do occur, the wind atlas methodology can be applied—as long as care is taken to only use wind climate data sets for areas of *similar* thermal influence.

The normal way of applying the wind atlas method is by using WAsP.[3] It is possible, however, in principle to use any microscale model, e.g. MS-Micro,[4] and Raptor,[5] Raptor-NL,[6] as well as CFD models (see below).

The advantages are many: first, by being the *de facto* standard, different wind atlases can be compared and understood directly by a large community. Secondly, using the method in reverse (the so-called application part; the down-ward arrow in Figure 3) makes it possible to determine the specific winds at a site to a high accuracy.

CFD Models

The application of computational fluid dynamics (CFD) techniques for wind resource prediction is currently being explored. The growing computing power allows for increasingly complex mathematical models to be used for microscale modelling. Using CFD is expected to enhance prediction accuracy as compared with models such as WAsP, especially in highly complex terrain where flow separation occurs or when thermal stability effects become important. The CFD technique is based on solving the Reynolds-averaged Navier–Stokes (RANS) equations in combination with a turbulence closure model, such as linear and non-linear two-equation models[10–12] or second-moment closure,[13] using numerical methods. Also, the RANS equations can be utilized within a thin layer near the ground only as part of the more advanced detached eddy simulation (DES) method,[14,15] which offers a better resolution of the upper layer. DES is computationally

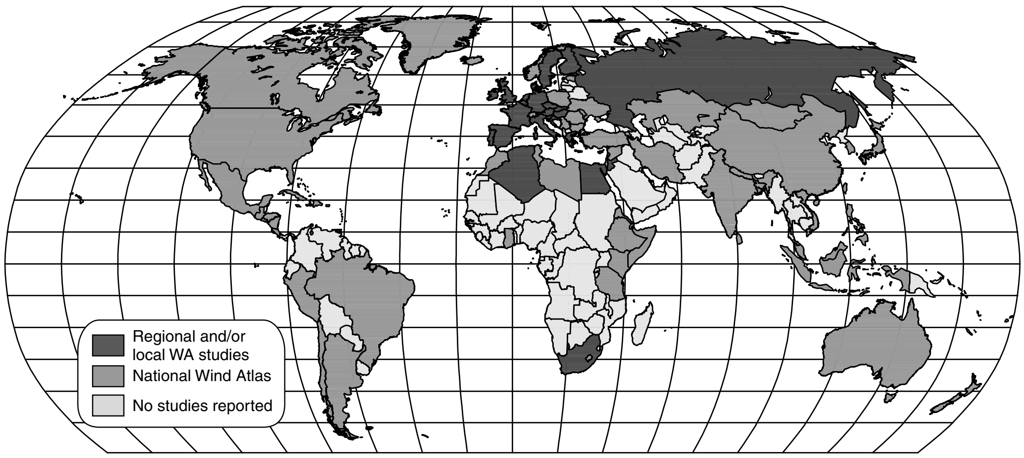

Figure 2. Worldwide status of the wind atlas methodology. National wind atlases have been published for the countries marked in dark grey, and regional and/or local studies exist for the countries marked in black. No wind atlas studies have been reported so far for the other countries

demanding but is a promising method for strongly separating flows. Whereas the RANS equations provide a steady solution, the DES model is able to calculate unsteady flows—this feature is important for predicting loads on structures such as wind turbines.

Calculation of atmospheric flow over complex terrain is extremely difficult. The wind field must be resolved on very fine scales in order to achieve a high accuracy within the lower part of the atmosphere. The high spatial resolution involves significant modelling challenges owing to the interaction of the surface wind with detailed features such as ridges, escarpments and steep hills. The performance that can be achieved by using turbulence closures remains an open question.

Method 6: Site Data-based Modelling

It is often the case that some kind of on-site measurements exist, either from a short-term measuring campaign or from an MCP calculation, or both.

Many models take advantage of this fact by using the on-site observations as the forcing input to a microscale model. These types of models include LINCOM,[16] MS-Micro and CFD models. WAsP could also be used in this way.

The advantage of this is that the estimate is free from extrapolation errors (in the case of non-MCP'ed data) and no non-on-site data are required.

Disadvantages include a possible lack of climatological representativity (in the non-MCP case) and a risk of enhancing any measurement or correlation errors.

Method 7: Mesoscale Modelling

With the increasing speed of computers it has become possible to use atmospheric mesoscale models to estimate the wind resource of a region. The grid size of the models is of the order of a few kilometres. A region of a few hundred by a few hundred kilometres is typically modelled (Figure 4).

Mostly, a statistical dynamical approach of regionalisation of large-scale climatology[17] is used to calculate the regional surface wind climate. It is assumed that the regional surface layer climate is determined uniquely by a few parameters of the larger, synoptic scale and parameters of the surface. Representative combinations of the parameters are found and simulations of these situations are performed with the mesoscale model. Then the mesoscale climatology is calculated from the results of the simulations together with the frequency of the situations.

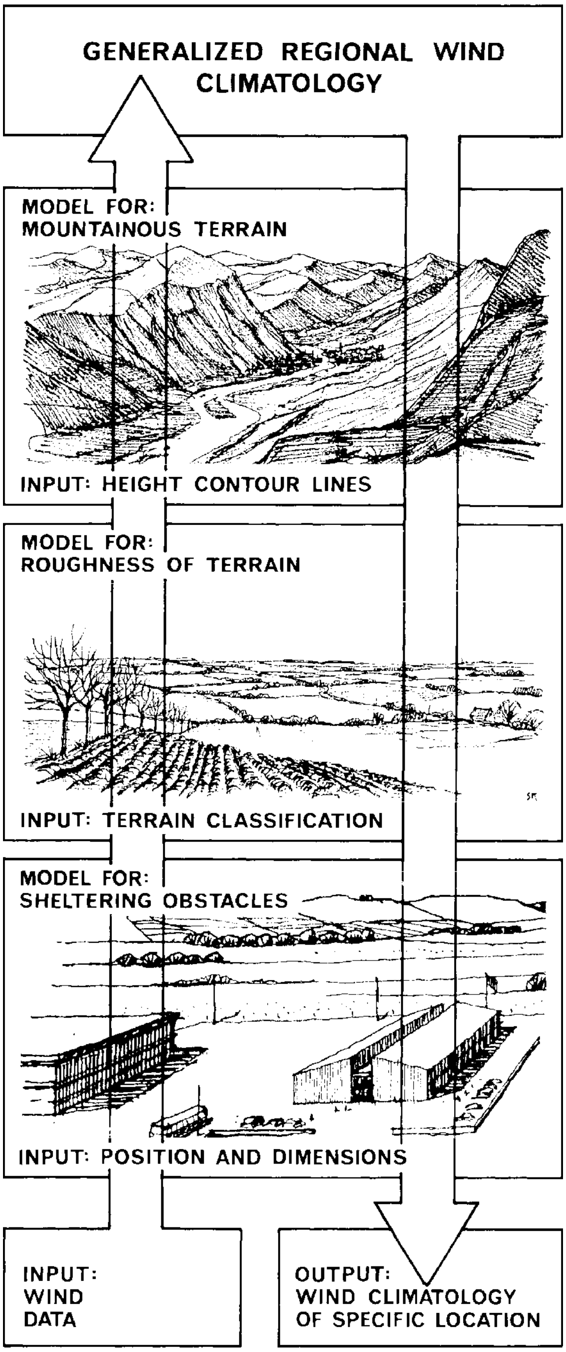

Figure 3. The wind atlas methodology. From Reference 9

Required input data are orographic and land-use grid maps. The surface roughness is determined from the land-use. The external forcing of the model is via boundary conditions from the larger scale, e.g. the large-scale pressure gradient or geostrophic wind. It is determined either from radio-soundings[18] or from large-scale models, e.g. reanalysis data.[7,8]

In principle, the method can be applied worldwide, as global data coverage is now available.

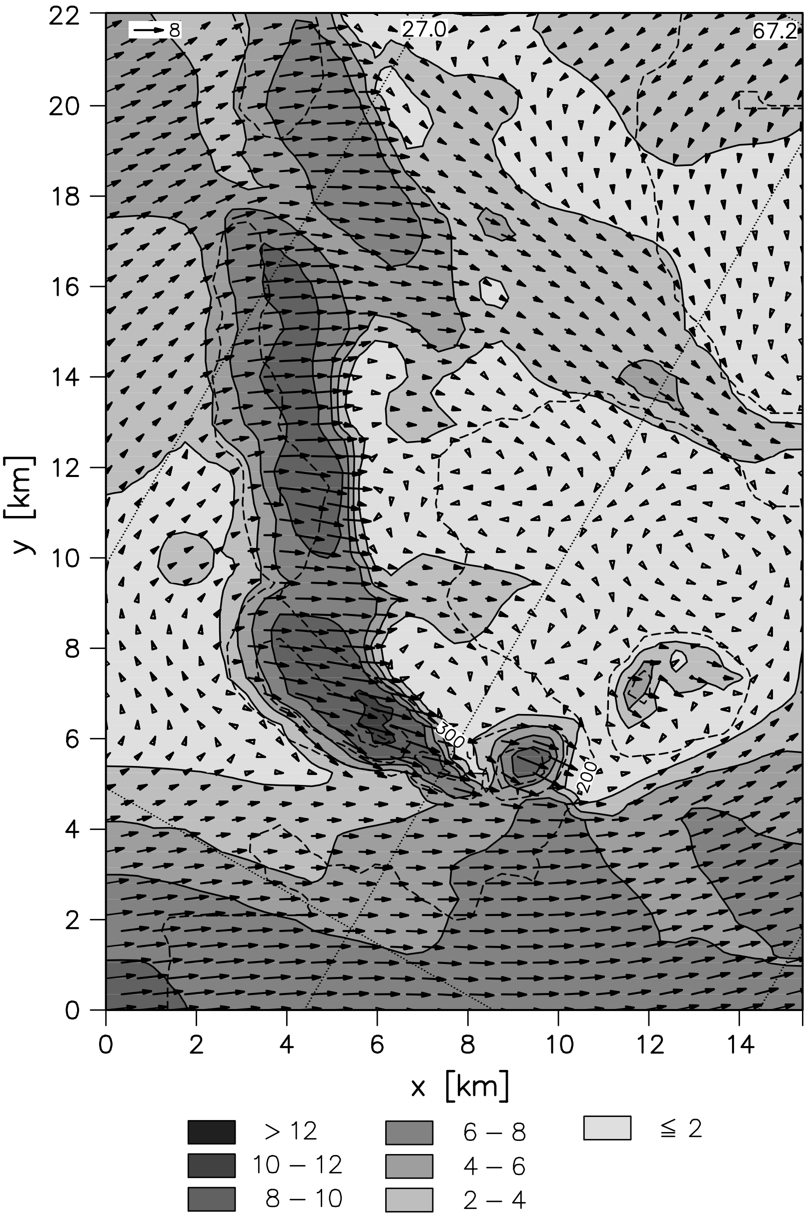

Figure 4. Simulated wind field at 61 m a.g.l. around Pyhätunturi Fell in northern Finland for a geostrophic wind of 10 m s^{-1} from the left under conditions of very strong inversion. The KAMM model[19] has been used. The contours show wind speed. Height contours are shown as broken lines. Note the eddies in the wake of the mountains which are approximately 300 m higher than the surroundings. Further details on the calculations can be found in Reference 25

The most common mesoscale models used for wind energy calculations are KAMM,[19] MM5 (www.mmm.uear.edu/mm5/mm5-home.html) and MC2 (www.cmc.ec.gc.ca/rpn/modcom/en/index_en.html).

Major problems are the determination of the important external parameters and the definition of the most representative situations. Also, a resolution of several kilometres cannot resolve the microscale terrain features which influence the surface wind. Resolutions of 1 km or less require a tremendous amount of computing.

Method 8: Combined Meso/Microscale Modelling

A slightly different use of mesoscale modelling is made by combining a mesoscale model (e.g. KAMM) with a microscale model (e.g. WAsP). Instead of trying to resolve all small-scale terrain features, the mesoscale modelling stops at a resolution of approximately 5 km. Local predictions are made with a microscale model such as WAsP, using output from the mesoscale model as input to the small-scale model. This approach is followed in References 20 and 21, and the KAMM/WAsP method has been thoroughly validated in Reference 22.

The method produces wind atlases such as Method 5, which makes comparisons between regions possible. Also, users with experience in wind resource estimation with WAsP can readily use the output from the mesoscale model. An example of the application of the method is shown in Figure 5.

Another similar meso/microscale approach is that of WindScape,[23] which employs the TAPM mesoscale model[24] and then uses Raptor and/or Raptor-NL for resolving the microscale flow.

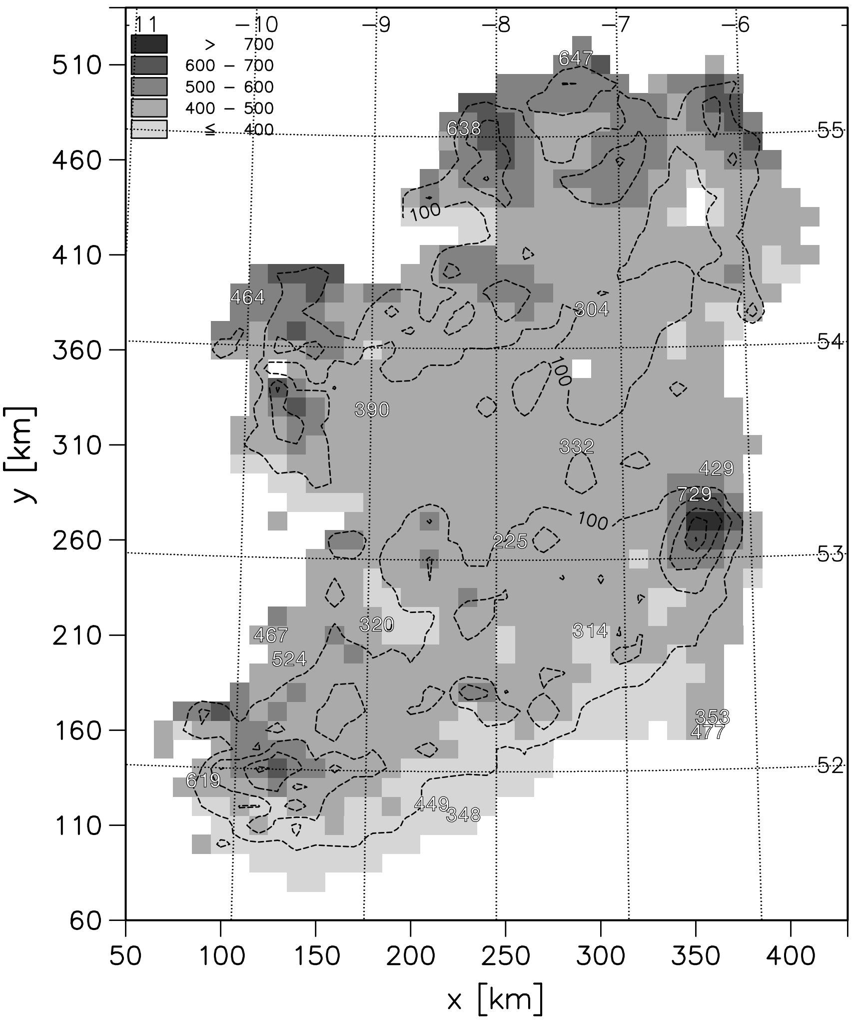

Figure 5. Simulated mean wind power density E in W m^{-2} at 50 m above a surface with roughness length $z_0 = 3$ cm for Ireland. Numbers show values determined from observations generalised with WAsP. Height contours are shown as broken lines. Further details can be found in Reference 20

Challenges

The increasingly widespread utilization of wind energy throughout the world, with its many different terrain types, presents a number of challenges to classical wind resource estimation based on fast but simple flow models. The most obvious of these challenges are discussed below.

Complex Terrain

Complex terrain is here understood as mountainous terrain with steep slopes and sharp ridges. Classical wind resource estimation was developed for terrain with at most smooth 'rolling' hills with moderate slopes, where the wind flow may be assumed to follow the terrain, i.e. 'attached flow'. In complex terrain, however, the wind flow may be separated from the terrain at steep slopes, thus creating less terrain-induced acceleration ('speed-up') than that produced by a flow attached to the steep slopes. Also, flow separation will create lee regions with zero mean flow but dominated by recirculation and eddies, giving rise to loss of kinetic energy not accounted for by classical wind resource estimation. Such flow situations may possibly be treated by comprehensive and detailed CFD calculations, which, however, will be very resource-consuming. The challenge for wind resource estimation is here to find flow models and numerical schemes which can pick up the main features of the wind flow in complex terrain—the reduced speed-up and the existence of lee regions—while keeping the calculational effort at an acceptable level by concentrating on the details of the wind flow pertinent to wind energy issues. Probably, the wind field resolution must be improved and turbulence must be treated explicitly to meet this challenge. Exactly how far one can reach by such an approach is yet to be answered.

Offshore

At offshore sites the controlling terrain effect is of course the surface roughness—and not orographic effects. Classical wind resource estimations would only treat offshore sites on shallow water, relatively close to the coasts, and with moderate (<50 m) relevant elevation (hubheight of the turbines). This meant that the variation in roughness of the water surface due to waves was neglected—sufficient precision in wind resource prediction could be obtained by assuming a suitable constant surface roughness. With modern offshore wind farms, however, these two simplifying assumptions no longer apply and the dependence of the surface roughness on the wind speed itself and on water depth, stability and upwind distance to the coast ('fetch') must be taken into account. Also, it should be considered that wind speed profiles (up to heights of modern wind turbines) may be different from those found onshore.

High Elevation

High elevation is a challenging issue, because modern wind turbines have hub heights considerably larger than those of the time when the classical wind resource methods were developed. Thus classical wind resource estimation methods have not been developed for and verified up to elevations of more than 50–60 m above terrain, whereas the blade tips of modern wind turbines reach elevations of 150 m or more. This is especially serious for the modelling of the stability effects on the vertical wind profile. To meet future requirements, the modelling of the wind speed profile—especially the impact from atmospheric stability and the temperature profile—in reality should be improved and verified at least up to the maximum blade tip elevation of modern wind turbines (~150 m).

Forest Sites

Clearings on forest-covered mountain slopes are to an increasing degree being considered as candidate wind farm sites, and consequently wind measurements are also performed in such localities. Until recently, such sites were either avoided or treated by *ad hoc* methods.

When far from forests—i.e. at distances many times the tree height—it is sufficient to consider the high roughness of the forest canopy. The future challenge is to include also the near-field effects of forests and of forest clearing boundaries for sites within forest clearings. Thus one must systematically take into account the effective zero-level displacement of the terrain (i.e. the level at which the wind speed tends to zero). Also, forest clearing boundaries can mimic orographic effects such as speed-up and lee effects.

Conclusions

This article has attempted to give an overview of the various ways the wind resource of a site or an area can be estimated. It should be obvious to the reader that the possibilities are ample and great care should be taken in choosing the methods and in using the results from the application of these methods.

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