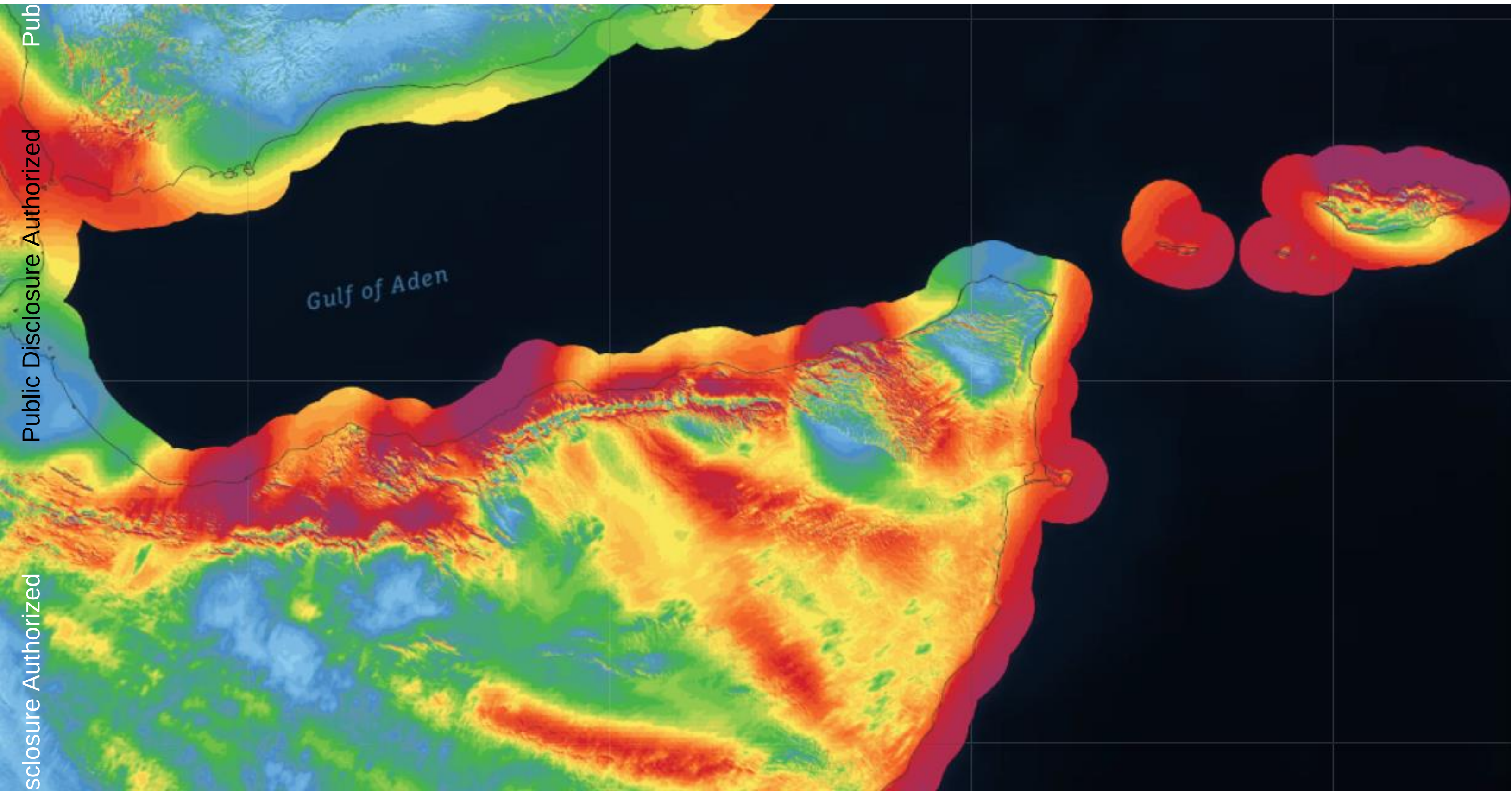
WORKING PAPER

GUIDANCE ON MESOSCALE WIND MAPPING

November 2018



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This paper was prepared by **Søren Krohn**, a consultant to the World Bank, and the content is the sole responsibility of the author. As it is a working paper the content is still under development, is likely to be updated by the author over time, and has not undergone peer review. Users are therefore advised to exercise caution when utilizing the information and data contained. Note that this working paper replaces a previous document on the same topic by the author, which can be found in archive format on the World Bank website via this link.

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CONTENTS

FOREWORD

The Energy Sector Management Assistance Program (ESMAP) published a paper in 2010 with a set of best practice guidelines for mesoscale wind mapping projects with a view to how best to contract such studies for use in developing countries.[1] The present paper supersedes that paper.

A number of technological advances during the past few years make it necessary to reconsider what is best practice when planning mesoscale modeling and wind mapping projects. These include:

- Within the field of meteorology, the global weather model *WRF*[2] (Weather Research and Forecasting Model) has become widely accepted as a de facto standard global modeling framework for mesoscale wind resource analysis. Several research institutes and commercial vendors now have experience and a good track record using the WRF model. This modeling framework also allows time-series modeling, enabling users to forecast wind resource variability and gives them the ability to find sites that are time-correlated with electricity demand.
- Global *reanalysis datasets* of historical weather patterns have become available in the public domain with better horizontal and vertical geographical resolution as well as better time scale resolution. This is notably the case for the recently published ERA5 reanalysis dataset. [3]
- More global datasets of *topography* and *land cover* from earth observation satellites have been debugged and cleaned up in higher resolution for larger areas of the globe. Presently the View-Finder dataset offers a void-filled [4] dataset with very large geographical coverage. [5]
- Advances in computing technology hardware and software have made supercomputers more cost-effective and have allowed mesoscale modeling with better spatial and time resolution.
- Improvements in computer software have made microscale wind resource modeling practically feasible over vast areas, even covering the entire globe.[6]
- Internet and computer-based Geographical Information Systems (GIS) have been improved, standardized, and become open-source and accessible in the public domain.
- More GIS data is publicly available from governments and various institutions, and there is a greater emphasis on »open data«.

This paper is based on the experience gained from planning and executing twelve national renewable energy resource mapping projects under the ESMAP Initiative on Renewable Energy Resource Assessment & Mapping, a US$22.5 million global program launched in 2013.[7] Subsequent experience was gained from developing the Global Wind Atlas (GWA) versions 2 and 3. Version 2.3 of the GWA is currently available at https://globalwindatlas.info.

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[1] (ESMAP 2010)

[2] (UCAR u.d.) The first versions of the modeling framework appeared around 2000.

[3] (ECMWF 2018)

[4] i.e. data missing from NASA's SRTM dataset have been patched, mostly with Russian satellite data.

[5] (Viewfinder 2018)

[6] (DTU u.d.).

[7] An additional US$2.6 million was allocated by the Asia Sustainable and Alternative Energy Program (ASTAE).

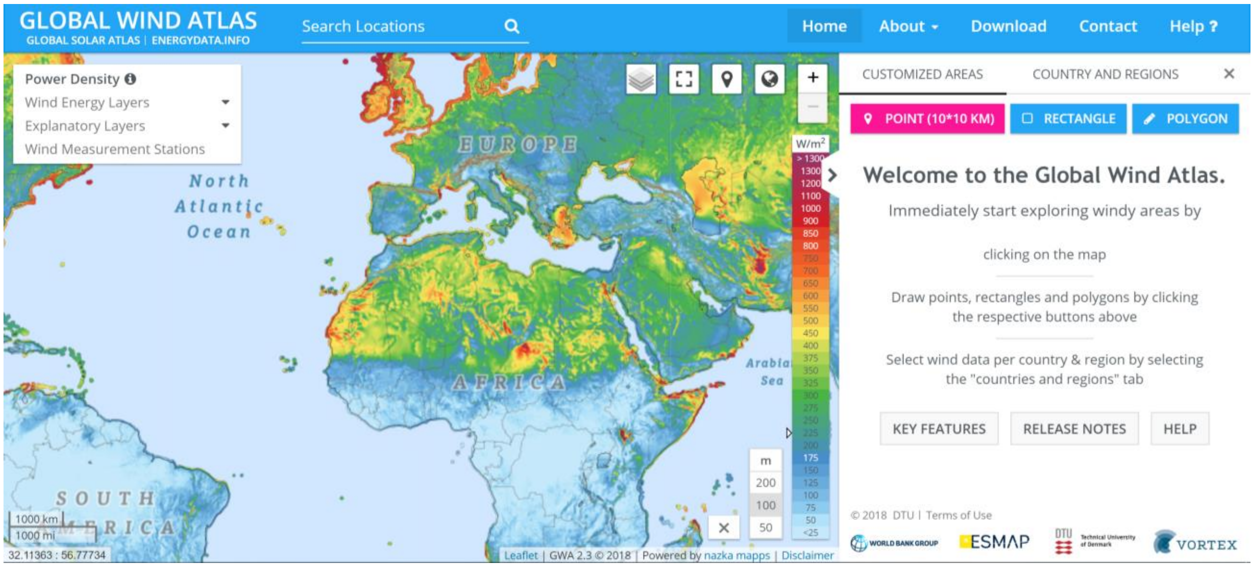

Figure 1. Screenshot of the Global Wind Atlas website (version 2.3)

ACRONYMS, ABBREVIATIONS AND CONCEPTS

a.g.l.	Above ground level
Anemometer	Instrument that measures wind speed. Usually cup anemometers of high-precision, scientific quality (First Class) are used for measuring for wind power applications.
Atmospheric stability	A measure of the atmosphere's tendency to encourage or deter vertical motion. Local stability conditions (mixing or no mixing of air from different heights) have an influence on *wind shear*.
CFD	Computational fluid dynamics. A branch of the physics science of fluid mechanics that uses mathematical methods to solve and analyze problems that involve fluid flows (air, water etc.)
CFD microscale model	See also *microscale model*. This type of model uses the same type of non-linear CFD equations that *mesoscale models* do. Although this type of modeling may give more accurate results in *complex terrain* than simplified linear models, it usually requires supercomputers and is thus more expensive to run. The results are less robust than linear models, i.e. different modelers may get different results depending on how their models are set up.
Complex terrain	Hilly, rugged terrain, often with steep slopes that create *turbulence and flow separation.*
Coriolis effect	The bending of paths of objects, when seen from the rotating surface of the earth.
Data assimilation	The process by which observations of a system are incorporated into the model state of a numerical model of that system.
Electrical load	The demand for electrical power (in the integrated national electricity grid) at a given moment in time, usually expressed in MW.
Elevation	Terrain height above sea level – different concept from *height above ground level*
ESMAP	Established in 1983, the Energy Sector Management Assistance Program (ESMAP) is a global, multi-donor technical assistance trust fund administered by the World Bank and co-sponsored by thirteen official bilateral donors.
Extreme wind atlas	An extreme wind atlas shows the expected extreme winds during a 50-year time period. This information is important for the choice of wind turbine class for a site.
GIS	Geographical information system. A computerized system designed to capture, store, manipulate, analyze, manage, and present spatial or geographical data.
Geostrophic wind	The theoretical wind that would result from an exact balance between the *Coriolis force* and the pressure gradient force. The geostrophic wind flows parallel to *isobars*.
Height (above ground	In this text sometimes abbreviated as »height« or »height a.g.l.«. Different

level)	concept from *elevation.*
IEC	International Electrotechnical Commission. Prepares and publishes international standards for all electrical, electronic and related technologies. The IEC/ISO 61400 family of standards are related to wind turbines, and are essential to any activity related to wind energy.
IPP	Independent power producer. Privately owned (wind farm) company that sells power to the integrated national electrical grid.
Isobar	A contour line of equal pressure
Land cover	A classification system describing the land surface type. Land covers include grass, asphalt, buildings, trees, bare ground, water, etc. Land cover for the entire globe has been mapped (with some uncertainty) by satellites and aerial imagery and is available in the public domain in databases such as Globcover, the USGC database, Corine or Modis. This data is used to assign *surface roughness lengths* to the different types of land cover.
m	meter, unit of length
Mesoscale model	Meteorological models are in widespread use for weather forecasting. They typically have a horizontal spatial resolution of typically 2-20 km that describes weather processes e.g. the interaction between atmospheric airflows at high altitudes for geostrophic winds (12-20 km above ground level) and the underlying landscape contours, temperatures, ground surface properties, etc. Mesoscale models are implemented as computer programs, e.g. WRF, KAMM, MM5, Skyron. See e.g. http://wrf-model.org
Microscale model	Mathematical model with a horizontal spatial resolution of typically 1-1000 m that can predict the airflows at a given spot and height above ground level in the landscape for given wind speeds and wind directions as measured from a nearby meteorology mast. Examples, WAsP (including WAsP CFD), WindFarmer, WindPro + *CFD microscale models*.
MW	Megawatt. Unit for electrical power.
MWh	Megawatt hour. Unit for electrical energy transferred during a given time interval.
Power Curve	Table or graph showing the relationship between wind speed and power generation (in kW or MW).
Observational wind atlas	Wind atlas made solely on the basis of observations from meteorology stations, as explained in section 4.
PPA	Power purchasing agreement. Contract between a power producer (a wind farm owner) and an electricity offtaker, e.g. a power distribution company or a national integrated power company.
Reanalysis dataset	Database of historical weather patterns (winds, temperature, barometric pressure, precipitation) recorded at fixed time intervals at each intersection point on a regular grid of longitude and latitude circles as extrapolated by global weather forecasting models. The American MERRA and the European

	ERA databases, which are in the public domain, are often used for mesoscale wind resource modeling purposes. The databases CFSR and CFDDA are similarly used.
LIDAR	Doppler LIDAR (Light Imaging, Detection, And Ranging) is a remote sensing system that uses the Doppler effect to measure wind speed using reflections from a (conically rotating) laser beam on dust particles or aerosol at different heights.
Resolution	Resolution is in this paper used to apply to the grid spacing used in a mesoscale or microscale model. Mesoscale modeling resolution is typically 2-5 km, i.e. the speed and direction of the airflow is only simulated for discrete points 2-5 km apart.
RIX index	An indicator of the ruggedness of the terrain and at the same time a signal whether linearized flow models, such as *WAsP* can be expected to perform reasonably well in a particular location.
Roughness length	Measurement unit for *surface roughness* (see below), measured in m. The roughness length is the distance above the surface where the wind speed theoretically becomes zero. Typical roughness lengths vary from 0.0002m for water surfaces to 1.6m for large cityscapes. Open agricultural areas with few buildings typically have a roughness length around 0.03m.
Roughness rose	A table (or 360° graphic) showing the average surface roughness length for a number of compass sectors, normally twelve 30° sectors.
SODAR	Doppler SODAR (SOnic Detection And Ranging) is a remote sensing system that uses the Doppler effect to measure wind speed using reflections of sound impulses on turbulent air layers at different heights.
(Orographic) speedup effect	The acceleration of wind speeds on tops of rounded hills and ridges. There is a corresponding slowdown in terrain troughs.
Surface roughness	Surface roughness plays an important role in determining how an object will interact with its environment. Rough surfaces exhibit higher friction than smooth surfaces. In meteorology the surface roughness of the landscape determines how the wind is slowed down near ground level. Cities and forest areas have high surface roughness; grassland, snow and water surfaces have low surface roughness. Roughness is measured using the concept *roughness length*.
Topographical dataset	Gridded global elevation dataset usually derived from satellite radar observations. Many modelers use the SRTM (NASA Shuttle Radar Topography Mission) dataset or cleaned-up variants thereof. These datasets were originally compiled for every 3 arc seconds, (about 90m) globally though with some holes and errors in the original data. Most areas of the globe now have 30m datasets. Increasingly higher precision national aerial survey datasets are available.
Turbulence	Unsteady wind flows with chaotic changes in wind speed and wind direction.
(IEC) Type certification	A certificate issued by an accredited institute that states that a design of, say,

	a wind turbine, complies with standards, e.g. set out in IEC 61400.
TSO	Transmission systems operator. The company responsible for building, maintaining and operating the national electricity transmission grid.
Turbine class	Wind turbines are designed and *type certified* for different wind classes (I-IV A or B) under the IEC/ISO-61400 international standardization system, depending on the site mean wind speed, the expected 50-year extreme wind speed and the expected level of *turbulence* intensity.
Validation	Scientific method for confirming the validity of a hypothesis or modeling results. In the case of wind atlases observational validation is used, i.e. comparing observed mean wind speed and wind direction values over certain periods with the predictions made by a set of mathematical models.
Veer angle	The angle between the *geostrophic wind* direction and the wind direction near ground level.
Wake effect	(Array effect). The power generation loss due to upstream wind turbines shading downstream turbines from the wind and creating a *turbulent* wake. Park effects can be calculated (with some uncertainty) using conventional microscale wind resource modeling software.
WAsP	Wind Atlas Analysis and Application Program. WAsP is the de facto industry-standard mathematical model and software package for the siting of wind turbines and wind farms developed by DTU Wind Energy (formerly known as Risø). It is used for wind resource and energy yield assessments and is the calculation engine inside other widely used commercial wind farm planning software packages such as WindFarmer and WindPro. WAsP features two flow models. One model uses a linearized version of flow equations, which gives it very fast computation and *robust* results, i.e. most qualified wind consultants would obtain reasonably similar results using that same methodology. The latter property makes analyses run on this model more »bankable« than others. The second mode uses a CFD model configured for robust simulations, carried out by the user on a remote computer cluster. WAsP is not to be confused with the software WASP, Wien Automatic System Planning Package, from the IAEA, which is used for power generation plant portfolio planning and scheduling.
Wind atlas	Maps and datasets of expected wind speeds and wind directions for an area, usually a country, but the Global Wind Atlas (https://globalwindatlas.info/) offers worldwide coverage.
Wind obstacle	Building, tree or another structure located close to a point of wind measurement. Microscale models can estimate the obstacle effect on wind speeds. If wind obstacles are farther away, their wind shading effect is usually subsumed in the surface roughness assessment for that area, rather than taking the obstacle directly into account.
Wind rose	A table (or 360° graphic) showing the mean wind frequency, mean wind speed, and mean wind power for a number of compass sectors, normally

	twelve 30° sectors.
Wind shear (vertical)	Wind speed variation with height above ground level. The size of the effect depends on the surface roughness length of the landscape and boundary-layer stability.
WRF	Weather Research and Forecasting Model. Weather forecasting and mesoscale modeling software. Primary modeling framework used by main-stream mesoscale modeling vendors for wind energy purposes. Modeling is done on time series, typically hourly data for 10 years. The effort to develop WRF began in the latter part of the 1990's and was a collaborative partnership principally among the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (represented by the National Centers for Environmental Prediction (NCEP) and the (then) Forecast Systems Laboratory (FSL), the Air Force Weather Agency (AFWA), the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration (FAA).

1. INTRODUCTION

Most developing countries have only sparse local wind data. While this may be sufficient for regional weather forecasting, neither the data quality nor its geographic distribution give a sufficient basis for a bankable wind resource assessment required for modern wind farms. Large areas have no local wind measurements, and those that do usually have measurements taken at 10m a.g.l. (height above ground level). Such measurements are so heavily influenced by the presence of nearby *wind obstacles* that they are too inaccurate to use for wind power deployment.[8]

Mesoscale weather forecasting models are presently used to make wind forecasts for regions of several thousands of square kilometers. To cover a similar area with measurements would require so many stations that it would be prohibitively costly, and even if it were done, it would take many years to obtain reliable long-term climatological estimates. Mesoscale weather models can be useful tools to map the wind resource of a region based on historical weather data. However, mesoscale modeling cannot be used directly for the siting of wind turbines because the grid spacing of these models is too large.[9]

Modern high-quality wind atlases[10] have become important tools for government and electricity sector planners as well as for commercial wind farm developers. Scientifically validated wind resource mesoscale mapping combined with mesoscale-to-microscale wind resource mapping can help a cost-effective search for economically viable wind resources and can be used for public planning for the siting of wind power plants. [11]

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[8] Mean wind speeds can easily vary by 50-100% at distances of, say, 50m from a 10m tall meteorology mast, if it is not located in a completely exposed and level terrain with uniform surface roughness and far away from any wind obstacles, ridges or escarpments.

[9] Key concepts written in *italics* are explained in the section Acronyms, Abbreviations and Concepts above.

[10] For example, the Global Wind Atlas (https://globalwindatlas.info)

[11] Wind atlases are not a substitute for local measurements of at least a year within a wind farm site in order to have sufficient certainty to invest in a project safely, both in terms of the economics and the turbine technology to be used for any site. But a wind atlas is an excellent tool for searching for economically viable wind farm sites.

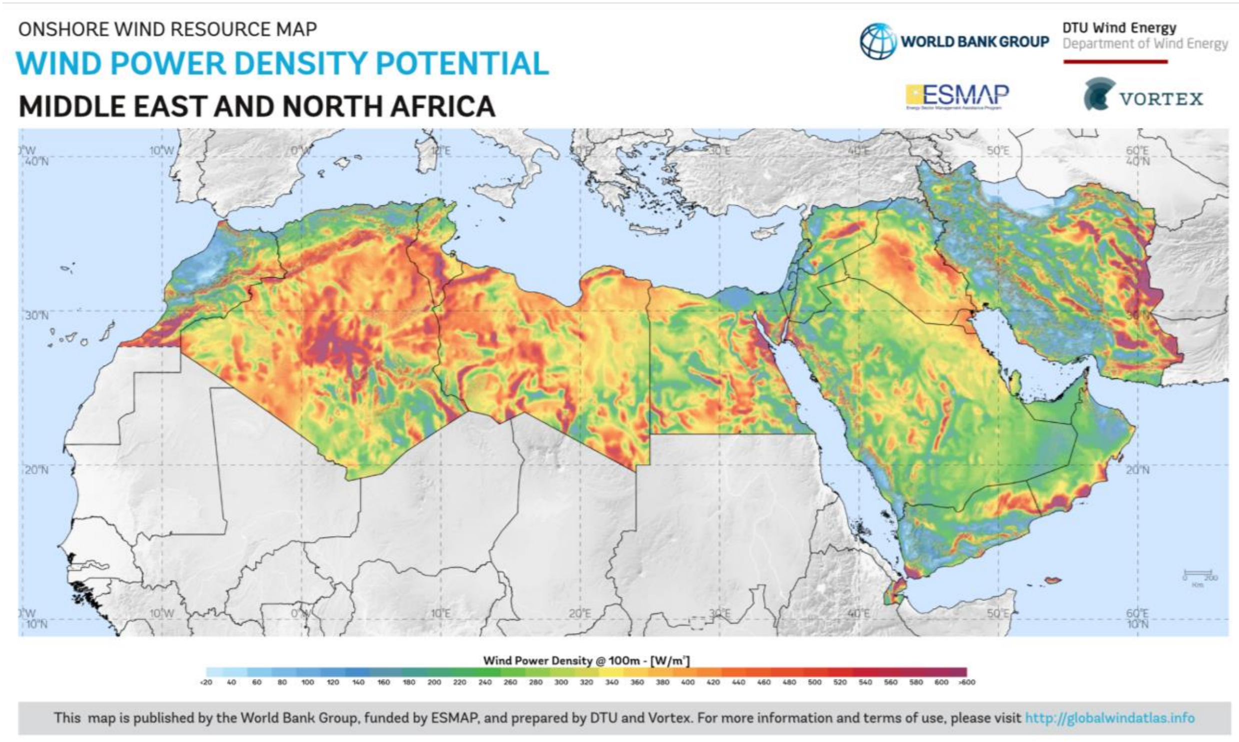


Figure 2. Map of wind power density potential (source: Global Wind Atlas)

1.1. PURPOSE OF THIS GUIDE

The purpose of this paper is to give guidance when either commissioning, validating or using mesoscale and mesoscale-to-microscale modeling studies of wind resources. The first objective is to provide *GIS* data that is useful for both searching for good wind resources and for public planning and policy purposes. The second objective is to map wind resources at the country level in order to provide preliminary input for site-specific wind resource assessment, (which is best carried out by commercial developers and their consultants).

The paper provides background information on how to obtain state-of-the-art, validated wind resource mapping (with a reasonable, well understood precision) of large land areas at a reasonable cost, with manageable amounts of output data, and with a long shelf life.

1.2. UNDERSTANDING THE PHASES IN BEST PRACTICE WIND RESOURCE MAPPING

A high-quality scientific-grade wind resource-mapping program requires three phases: [12]

1.2.1. Phase 1: Preliminary Mesoscale Mapping of the Wind Resource

This phase consists in having a team of experienced modelers do a mesoscale (typically 2-5 km resolution) preliminary wind resource map of the country or region.[13] Since this mesoscale modeling has already been

[12] (ESMAP 2016)

[13] It should be noted that there are economies of scale in mapping adjacent countries at the same time.

done for the entire globe in the Global Wind Atlas (GWA), https://globalwindatlas.info, most countries would probably prefer to skip this step and instead go directly to phase 2, setting up a national validation measurement program.

Mesoscale mapping is done on the basis of satellite data for topography and land cover, plus a dataset of preferably at least 10 years of historical weather data for the region obtained from the databases with so-called reanalysis data from one of the global (synoptic) weather models. The methodology is explained in section 4 and 5, but readers who are not wind power experts themselves will need to read section 2 and 3 to understand the concepts used.

The duration of this phase is typically 2-3 months for a national mapping program.

1.2.2. Phase 2: Validation Measurement Program

On the basis of the preliminary wind resource map the consultants who made the mapping can propose a number of sites in different, relatively high-wind locations[14] where the model will be validated using ground-based measurements from tall meteorology masts.

The primary criterion for selection of measurement sites is their suitability for validation purposes, not their suitability for wind farm development, though the two purposes can to a certain extent be combined within a validation measurement program.

Before starting the measurement program, a consultant will do a site assessment and provide a *microscale modeling* of the wind resource on each site, based on the mesoscale model output and local topography and land cover. The estimated wind resource will be compared with what is measured afterwards.

The validation measurements may either be done with conventional, tall meteorology masts or using remote sensing equipment, such as LIDAR.

In case meteorology masts are to be used, the consultant will need to obtain the necessary permits for the erection of meteorology masts and do a summary environmental and social brief for each site to check for any concerns. The consultant will then install (typically 80-90m) meteorology masts with high quality instrumentation on the selected sites and measure the wind climate for a period of 2 years. It is simpler to use remote sensing (LIDAR) equipment, since such measurement equipment is housed in a fairly small box that does not have any perceptible impact on the local environment and consequently does not require local permitting to be used. It is preferable that the measurements be simultaneously conducted from all measurement locations during a contiguous 24-month period.[15]

The consultants will then provide an analysis of the data collected and a set of wind resource estimates that can be compared with the modeling results in order to estimate the deviations between the modeling and the measurements. The mesoscale-modeling consultants should report on the possible bias in the modeling and the apparent reasons for any systematic deviations in the modeling compared to the measured data.

In case the Global Wind Atlas is used for the Phase 1 mesoscale modeling step, it may be advantageous to look to the established protocol for the validation of the Global Wind Atlas. A national validation

[14] For the purpose of finding wind power sites that are economic, it is important to validate the modeling particularly in areas with economically viable (high) wind speeds.

[15] If the measurements are staggered in time, then it is impossible to tell which part of the variations can be ascribed to geography and which are due to seasonal or inter-annual variations.

program can in this way both benefit from and contribute to the overall quality of the Global Wind Atlas.

1.2.3. Phase 3: Final Mesoscale and Microscale Modeling of the Wind Resource

In case a national mesoscale model was done in Phase 1, it may at this stage be revised, e.g. in case the previous step revealed systematic errors in the assignment of *surface roughness*; the horizontal or vertical resolution of the model or other modeling setup parameters may likewise be optimized.

It is <u>not</u> permissible to recalibrate the model to fit the simulated values with the measured data (e.g. using some type of regression analysis or similar techniques), since that will render it impossible to validate the model through subsequent measurements, and it will eliminate the possibility of obtaining any estimate of the uncertainty of the modeling. Recalibration will also give the model a short shelf life, since it will not be possible to incorporate new measurements into the modeling process.

In case a national mesoscale modeling was done, modelers will finally do a high-resolution (1000 to 100m) *microscale mapping* of the country or region, which can be used both for prospecting for good, windy sites and for public planning purposes as explained in the next subsection. The Global Wind Atlas already contains such a modeling, done at a 250m resolution.

It should be noted that construction of a wind farm requires well-documented, high-quality measurements from a nearby meteorology mast or remote-sensing equipment such as LIDAR for at least 12-24 months.

1.3. Target Groups and Utility of Data Outputs

The target group for the output data from *mesoscale (1-5 km resolution) wind modeling* consists of wind farm developers and their consultants. The data is provided in the form of so-called lib-files, which describe the characteristics of the local wind resource in a compact format, which is equivalent to the output one would have from a meteorology mast located in each particular grid node on a map. This type of *virtual meteorology mast* data is directly usable as input for the mainstream commercial *microscale wind resource modeling software* used to determine optimal siting of wind farms and wind turbines.

An important by-product of the mesoscale modeling, if it is done as a time-series modeling, is at set of *24x12 tables of the wind resource* (1-5 km resolution), which for each grid point for every month of the year shows the variation of the historical mean wind speed that falls within each of the 24 hours of the day. That type of table is particularly useful in order to find sites, which are load-following, i.e. where power generation most closely corresponds to hourly electricity demand throughout the year. This modeling has already been done in the Global Wind Atlas, which also (as of 2019) includes data for the variability of wind speeds over a 10-year historical period.

The 24x12 tables can also be used to ensure complementarity with the difference between hourly electricity demand and the hourly pattern of power generation from other non-dispatchable renewable energy sources, such as solar, run-of-the-river hydropower or large hydropower with dispatch tied to irrigation needs. These tables are useful both for the transmission systems operator and for government agencies responsible for planning, policies and incentives for localizing wind power so as to minimize cost and maximize the value of wind power in the grid.[16]

The target groups for the final maps from *microscale wind modeling (100m resolution)* outputs is much

[16] Generating this type of table requires the most recent generation of mesoscale models such as WRF, that can simulate hourly time series data over a period of several (typically 10-20) years.

wider:

Firstly, the data is useful for planners to include in a countrywide *GIS* (geographical information system) that includes layers with the transmission and distribution electricity grids, road network, waterways and lakes, population centers, and can include protected areas and other geographical properties, which are important for planning and permitting for efficient wind power development, as well as analyzing tradeoffs between several different technical, economic and non-economic criteria.

Secondly, microscale data can provide developers and their consultants with input for very preliminary gross wind power output calculations for potential wind farm locations.

1.4. Structure of This Paper

Following this introduction, **Section 2** explains those fundamentals of wind power meteorology, which are essential to understand the basics of the modeling methods, the output data and the maps provided in wind atlases, be they mesoscale or microscale. The section explains the basic physics of the spatial variation of wind resources in the landscape. This section is particularly useful for readers who are not already familiar with wind power generation, the technology of wind farms and the physics of the interaction between airflows and the landscape (boundary layer meteorology).

Section 3 explains how *observational wind atlases* can be built, using existing meteorology data from weather stations. The section shows how all the elements from section 2 fit together and how wind data from one location can be used to predict the wind climate in another nearby location.

Section 4 explains modern *mesoscale* wind resource modeling.

Section 5 describes the most useful outputs from the models, limits for the applicability of the analysis and how data can or cannot be used for different planning or resource exploration purposes. It also describes additional GIS layers, which are necessary or useful to combine with the data available from outputs or inputs to the modeling in order to help developers, environmental planners and electricity sector planners.

Section 6 explains how the output from mesoscale modeling is used for *microscale* modeling.

Section 7 explains the need for *validation* of modeling output and describes best practice and standards for bankable, scientific-grade ground-based wind climate measurements.

2. FUNDAMENTALS OF WIND POWER METEOROLOGY[17]

2.1. WIND SHEAR, SURFACE ROUGHNESS LENGTH AND THE ROUGHNESS ROSE

Airflows, like any fluid flow, interact mechanically with their environment. Close to a solid surface this friction interaction is strong, i.e. the flow is slowed down to zero, but this slowdown effect gradually declines with the distance from the surface depending on the properties of the surface and the fluid.

The variation of wind speed with *height above ground level* is referred to as vertical *wind shear*. In the description below neutral boundary-layer stability will be assumed.

The graph in Figure 3 shows typical wind speed variation with different heights above ground level in flat terrain in two different types of landscapes: Farmland (green) and desert (orange). Wind speeds are displayed horizontally, height is shown vertically. If the instantaneous wind speed in both cases measured at 80m height is 10.5m/s, then it will be only 9.1m/s at 20m height in the farmland, whereas it will be 10.2m/s at 20m height in the desert.[18]

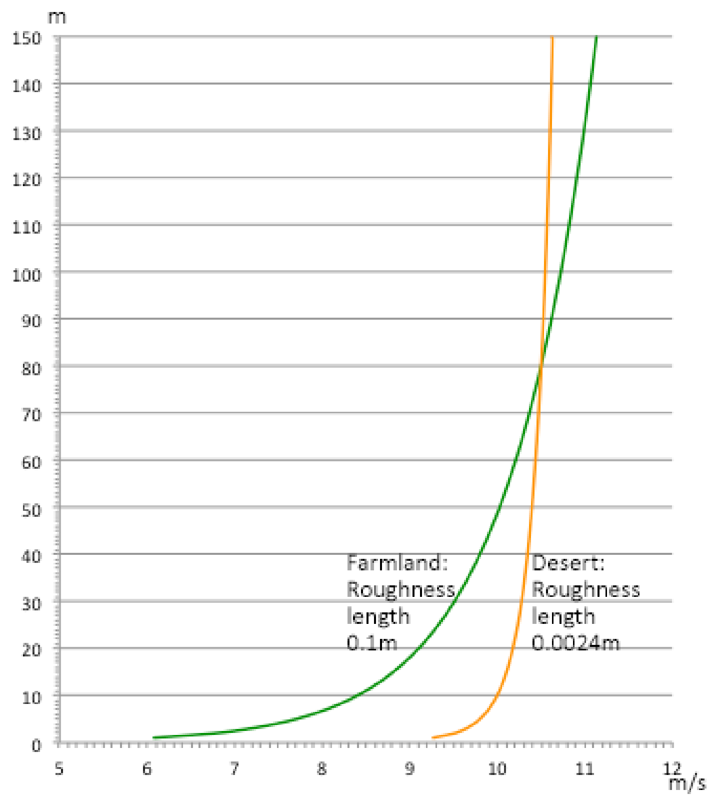


Figure 3. Vertical wind shear

How much the wind varies by height depends on the surface roughness in the upwind direction. The *roughness length* is a measure of roughness, which is associated with different types of landscapes. In this particular example, farmland is loosely defined as »agricultural land with some houses and 8m tall sheltering hedgerows with a horizontal distance of approx. 500m«. This roughness length is about 0.1m. In the case of deserts e.g. on the Red Sea coast in Egypt the typical roughness length is approximately 0.024m[19]

(The roughness length is actually the height above ground level where the wind speed theoretically becomes zero).

[17] A more in-depth introduction to wind power by this author may be found on the 256-page web site http://windpower.org/en/knowledge/windpower_wiki.html

[18] This slowdown near the surface is quite important, particularly in the farmland: Since the kinetic (mechanical) power of the wind varies with the third power of the wind speed, then in this case the amount of power in the wind at 20m height is only 65% of the power in the wind at 80m height.

[19] The surface roughness length of, say, a concrete airport runway is about 0.0024m.

The graph above shows how wind speeds vary when the wind is coming from *one* particular direction in the landscape with a certain surface roughness length. It should be kept in mind that surfaces and hence roughness lengths will normally vary irregularly across a landscape, so for any point in the landscape we can define a *roughness rose* (in analogy with a compass rose), where for every 30° sector we determine (normally a different) roughness length. Thus, wind shear in any point in the landscape will generally be different, depending upon which direction the wind comes from.

Two important conclusions emerge from this discussion of roughness and wind shear:

1. When we keep *wind shear* in mind, then it is meaningless to refer to, say the mean wind speed or the typical wind direction at a wind farm site without at the same time mentioning the height above ground level. Wind maps are therefore always done for specific heights above ground level, say 50m or 100m.
2. Most landscapes have differently shaped zones with very different roughnesses.[20] Wind speeds will therefore vary considerably from one location to the next, even within distances of a few meters. It is therefore impossible to refer to, say, a single mean wind speed at a certain height above ground level as being representative for one whole area unless one also qualifies that statement with the roughness length of the terrain surface.[21]

Wind modeling software can recalculate wind speeds across areas with different surface roughness lengths. Hence, wind speeds measured at a certain height a.g.l. at a point with a given surface roughness rose can be recalculated to wind speeds for nearby terrain with a

Surface Roughness Length Assessment

It is not a simple, straightforward exercise to assign surface roughness lengths to different types of landscapes so as to calculate the wind shear in the real world. Forests may e.g. be more or less dense, deciduous trees are denser in summer than in winter, snow cover may mean lower surface roughness length in winter.

360° photo panoramas, aerial photographs such as Google Earth or satellite imagery of land cover and land use are often used by consultants doing wind resource assessments for wind farms. This need for surface roughness assessment arises even if the actual wind shear has been measured on a wind farm site using one or more meteorology masts, since the wind measurements need to be recalculated to a standard roughness (explained in Figure 14).

If a forest is sufficiently dense, then the wind will so to speak skip over it, and the point where the wind speed theoretically becomes zero may be near the top of the trees instead of near ground level. This issue is not easily dealt with using satellite imagery only, but requires on-site inspection.

Atmospheric Stability

In reality wind shear will often vary between day and night, depending on local, boundary-layer stability: When the vertical temperature gradient is small (at night) there will be little mixing between airflows at different levels, so the horizontal »layers« of air will slide gently on top of one another as shown in Figure 3. When the temperature difference is large, e.g. when the ground is heated in tropical areas, then there will often be more vertical mixing of the air, more *turbulence*, and less difference between wind speeds at different heights above ground level.

[20] Water surfaces have a surface roughness length of some 0.0002m, villages and small towns a roughness length around 0.4m and large cities a roughness length of 1.6m.

[21] If we have e.g. measured a mean wind speed of 7.5 m/s in an area with a surface roughness length of 0.1m such as the farmland described above, then that will roughly correspond to a mean wind speed of 8.1 m/s in an open

2.2. Geostrophic Winds, Coriolis Effect, Veer Angles and the Wind Rose

At high altitudes some 11-20 km above ground level so-called *geostrophic winds* occur. These winds are part of the synoptic (large-scale, order of magnitude 100-1000 km) global weather patterns, and are only influenced marginally by the surface of the earth.

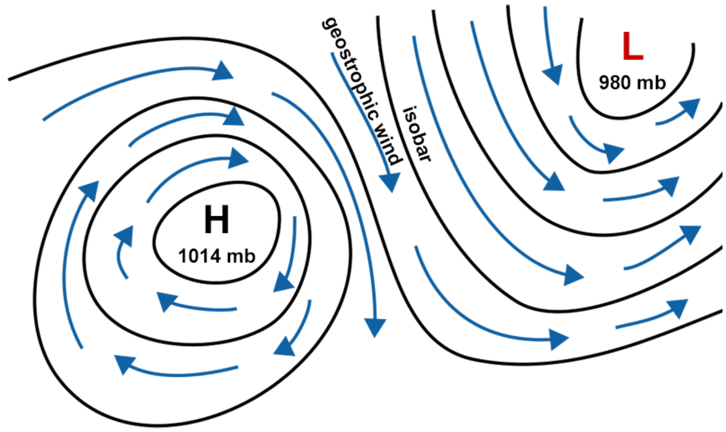


Figure 4. Geostrophic winds

But since the earth rotates relative to the geostrophic wind above, then the wind direction relative to the ground as seen from above will be turned towards the right in the Northern hemisphere and towards the left in the Southern hemisphere (how much depends on the latitude). This phenomenon is called the *Coriolis effect*. The corresponding force used for calculation purposes is called the *Coriolis force*.[22]

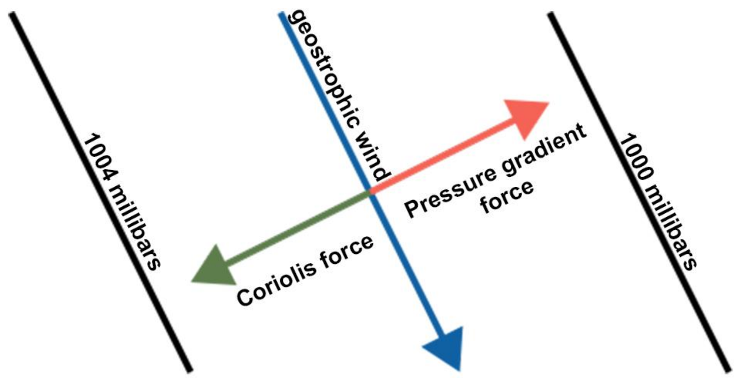


Figure 5. Pressure gradient force & Coriolis force

The interaction of the Coriolis force and the pressure gradient (the pressure difference between high- and low-pressure areas) means that geostrophic winds blow along *isobars*, as shown in Figure 4, (which represents a situation in the Northern hemisphere).[23]

The forces at work in this case are illustrated in the close-up in Figure 5, which shows how the Coriolis force counterbalances the pressure gradient force.

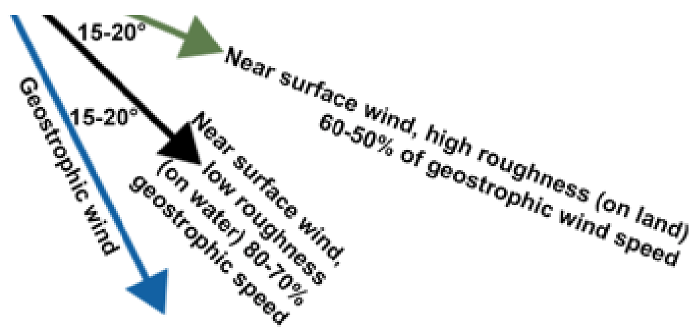


Figure 6. Veer angles and wind speeds seen from above

As we move down towards the surface of the earth the airflow will generally be more and more slowed down, the closer we get to the surface below. As shown in Figure 6, the wind direction

agricultural area without fences and hedgerows and very scattered buildings with a surface roughness length of 0.03m.

[22] Named after the French mathematician Gustave Gaspard Coriolis (1792-1843).

[23] Illustrations inspired by Environment and Climate Change Canada: National Marine Weather Guide.

near ground level will veer off from the direction of the geostrophic wind. This so-called *veer angle* will vary - not just with the height above ground level, but once again, how much it will veer off depends on how much the airflow is slowed down, and that in turn depends on the upstream *roughness* of the terrain, even up to 20 km away. Hence, wind directions in the landscape will differ from the directions in which clouds move at different heights in the atmosphere above, and they will differ depending on the roughness of the local terrain.

When planning a wind farm, it is extremely important to know the typical wind directions on the site, since wind turbines may be shading one another, and wind conditions across the site will vary due to roughness changes, wind obstacles and topography.

Wind modeling software can recalculate how wind directions change at different heights above ground level depending on the surface roughness of the terrain. Hence, wind directions measured at a certain height can be recalculated to wind directions for another roughness length, say 0.03m.

The typical wind directions for a given height above ground level are usually represented by a *wind rose*. It can be shown as a graphic similar to a compass as in Figure 7, or shown as a table of the mean wind frequencies, the mean wind speed, and the mean wind power in different directions (normally in 30° sectors).

Wind roses vary widely between different locations around the world. In some open areas the wind may be almost omnidirectional, in other areas such as mountain passes or along sea straits they may be almost unidirectional or have only a couple of typical directions. Wind roses may vary between the seasons and between day and night, hence one can draw wind roses both for an average year and for whatever period is useful.

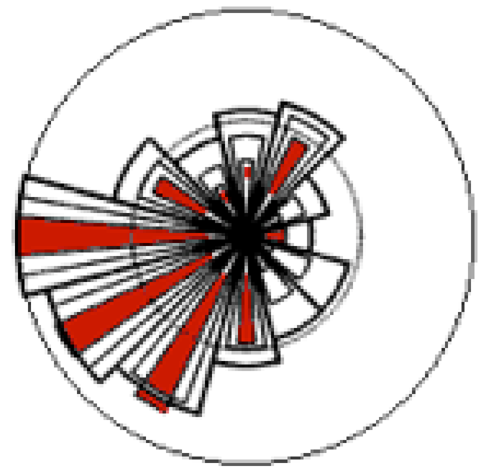


Figure 7. Wind rose

2.3. Orographic Speedup and Slowdown Effects, Complex Terrain

Orography deals with surfaces with varying *elevations*, such as a topographical mountain relief.

When the wind approaches a rounded hill or a ridge, the airflow becomes compressed and wind speeds are accelerated near the surface. This *orographic speedup effect* can be added onto the *wind shear* effect described above. The speedup effect of a rounded hill can be quite significant, as illustrated in Figure 8. It can even be so powerful, that the phenomenon of *inverse* wind shear occurs, i.e. that that in a certain interval of heights above ground level the wind speed actually *decreases* with height, since the acceleration effect declines quite rapidly with the distance from ground level. The phenomenon is difficult to

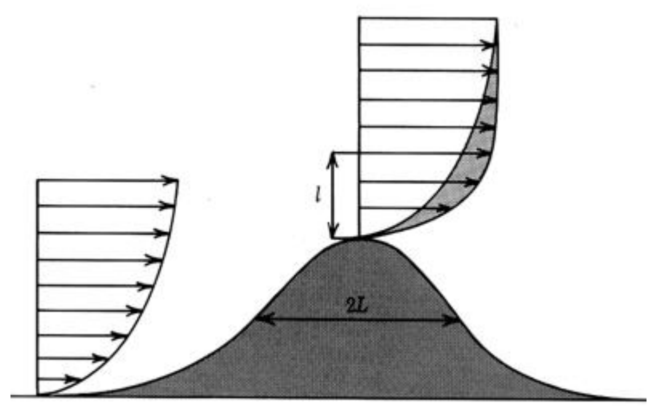


Figure 8. Orographic wind speedup across a hill (Source: DTU)

predict accurately, which is one of the reasons why wind measurement for wind power applications is always done at multiple heights above ground level.[24]

Conversely to the *speedup* effect on the upwind side of a hill, there is a *slowdown* for flow over terrain troughs.

It should be noted that this acceleration effect is very dependent on the precise shape of the terrain, and that it is difficult to model this phenomenon accurately, particularly if there are very steep slopes, escarpments and/or very rugged terrain surfaces upstream, which may create *turbulenc*e that may partly or fully negate the orographic speedup effect.

Wind modeling software can calculate the impact of slopes on wind speeds, though with some uncertainty, particularly for steep slopes and rugged terrain. Hence, wind directions and wind speeds measured at a certain height can be recalculated to what they would be in flat terrain and vice versa. When defining characteristic wind speeds for a larger area of, say, 2x2 km, it is most practical to compensate for orographic speedup effects, i.e. to eliminate them from the definition so as to get a more representative figure for the entire area.

The difficulties inherent in modeling speedup effects accurately mean that it is not advisable to use measurements taken in *complex terrain* i.e. hilly, rugged terrain as being representative for a larger area – or to use such data to *validate* wind modeling for a larger area. The uncertainty in recalculating the data between the simplified topography and roughness description in the mesoscale models and the complex terrain in the real world may simply be too large to give a conclusion with sufficient certainty.

Finally, steep slopes make the wind direction deviate from the horizontal plane. This creates problems for wind speed measurements, which can be biased when measuring on sites with steep inflow angles, particularly when measuring with low-quality instruments.[25]

Airflow over or around hills

Whether the wind will primarily flow over or around a hill or depends on the Froude number, a function of s*tability*, wind speed and the height of hill. Again, conditions may vary with the time of day and the season.

This phenomenon is also modelled in both mesoscale and microscale wind resource models.

2.4. Sheltering by Wind Obstacles

Obstacles to the wind such as buildings, trees, rock formations etc. can decrease wind speeds significantly downstream, and they usually create *turbulence* in their neighborhood. Figure 9 shows typical wind flows around an obstacle. The turbulent zone may extend to some three times the height of the obstacle. The turbulence is more pronounced behind the obstacle than in front of it.

The wind speed and turbulence effects of an obstacle are also important in the horizontal plane (sideways), as shown in the second part of Figure 9.

The impact of a wind obstacle varies with its *porosity*, which in the case of deciduous trees may vary between winter and summer. As trees grow, their wind shading effect will also change over time. It is very

[24] Severe wind shear increases tear and wear on wind turbines and can exceed their certified performance limits.

[25] Wind turbines are generally not *IEC type certified* to work with inflow angles that deviate more than 8° from the horizontal plane.

important to compensate for the effects of nearby obstacles close to meteorology measurement stations to get an accurate indication of the prevailing winds in the area. Since model calculations are far from perfect it is best to avoid measuring wind speeds near large obstacles, in any case.

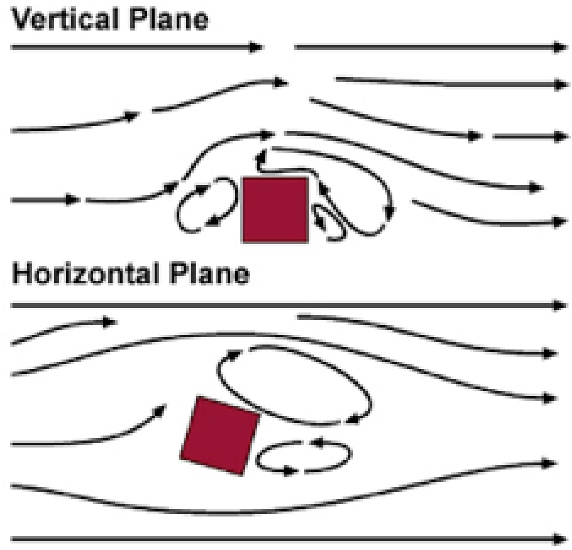


Figure 9. Airflows around obstacles

Whether a single building, a tree or a rock formation need to be taken into account in a microscale wind modeling setup depends on the obstacle size, its shape, its porosity as well as its proximity to the point where an accurate estimate of the wind speed is needed. Nearby wind turbines always need to be taken into account, but faraway objects can be subsumed in the assignment of roughness length to the general area.

The actual and calculated impact on wind speed will also depend significantly on the *turbulence intensity* of the wind. With high turbulence, there will be a significant mixing of the free wind with the sheltered wind, and the impact of obstacles on the wind speed will be less than with low-turbulence (laminar) airflows.[26]

Wind modeling software can calculate the impact of nearby wind obstacles, though with some uncertainty. When defining characteristic wind speeds for a larger area of, say, 2x2 km, it is most practical to eliminate the effects of local obstacles from the calculations (but they need to be included in the general surface roughness length estimates for the area). In this way we obtain a more representative figure for the entire area.

2.5. Wind Speeds and Wind Directions Defined for a Generalized Wind Climate

As we saw in sections 2.1 and 2.2 above, both wind speeds and wind directions even in a small zone of, say, 2x2 km, will vary not just with the height above ground level but also with the *roughness* of the terrain. In addition, wind speeds and wind directions will be influenced by *orographic speedup and slowdown effects* as well as by wind shade from obstacles as explained in sections 2.3 and 2.4.

[26] Note the similarity with the previous discussion of atmospheric stability in relation to *wind shear*.

If we want to describe the wind resource in general for a whole area of, say, 2x2 km or 5x5 km, then instead of referring to the actual wind speed and wind direction at a certain height above ground level at a very specific point within the area, it is more practical to *standardize the wind speed and wind direction at a certain height, assuming the whole area has* ***flat terrain***, ***no wind obstacles*** *and a given,* ***uniform roughness length*** *of, say, 0.03m*. The yellow boxes in the preceding sections explain how wind-modeling software can compensate for local variations in terrain and land cover

We will henceforth refer to this ***generalized wind climate*** definition, when we discuss wind resource data for a whole area (since actual winds vary from point to point).

This is a practical way of delivering wind reference data for a larger area, because this data can be used by *microscale wind resource models* to predict the wind speeds and directions at any particular point within in area, taking account of the very specific surroundings of each wind turbine or meteorology mast.

Why use Generalized Wind Climate Wind Speeds Instead of Actual Wind Speeds to Characterize an Area?

If we want to compare the power performance or pollution from cars, then it would obviously be a bad idea to do it while some of them are driving downhill and other are driving uphill. The surface roughness of the road for the test will also have an impact on what we measure. When these properties are measured for cars we therefore use the same set of *standard conditions* for all cars in order to be able to compare their performance.

If we want to compare characteristic wind speeds and wind directions at a certain height between two areas of, say 2x2 km each, then we likewise need to have the same *standard conditions,* e.g. the same surface roughness, since we know that high roughness slows the wind more than low roughness. We also need to include flat terrain in the definition, since we know that winds blowing over a hill will be accelerated and over a trough will be decelerated.

The typical standard conditions for explaining the wind forces at work in a given area are given in the definition of the generalized wind climate in the text to the left.

2.6. Interpreting Generalized Wind Climate Maps

The two maps in Figure 10 and Figure 11 below represent the estimated mean annual wind speeds in the Kingdom of Lesotho in a 2.5 km grid. The map to the left represents predicted wind speeds for the grid points as simulated by a mesoscale wind resource model, the map to the right represents the same data for a generalized wind climate.

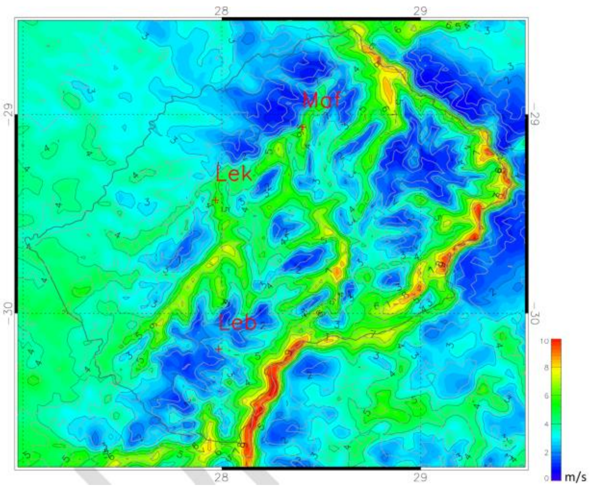


Figure 10. Simulated mean wind speed at 100m a.g.l. in Lesotho (Source: Risoe/DTU for ESMAP & IFC)

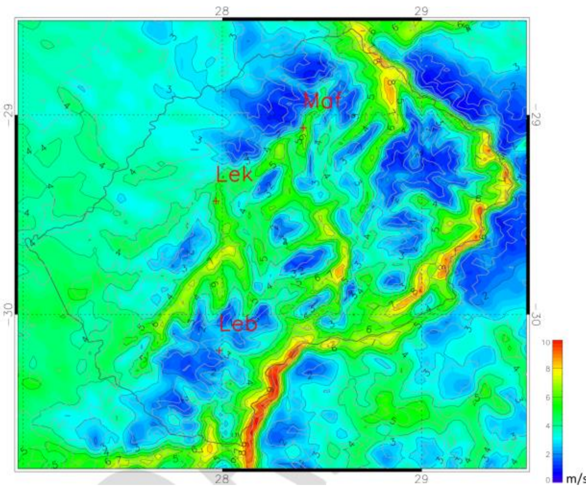


Figure 11. Generalized mean wind speed at 100m a.g.l. in Lesotho (Source: Risoe/DTU for ESMAP & IFC)

Although the two maps at first glance look very similar, the interpretations of the two maps are different.

In the case of the left map, (the simulated wind speeds) we see what the wind speeds are estimated to be, if the landscape corresponded to the simplified elevation and roughness description at the 2.5 km resolution of this mesoscale model. But the terrain conditions in relation to slopes and roughness may be very different in different points of the simulation grid.

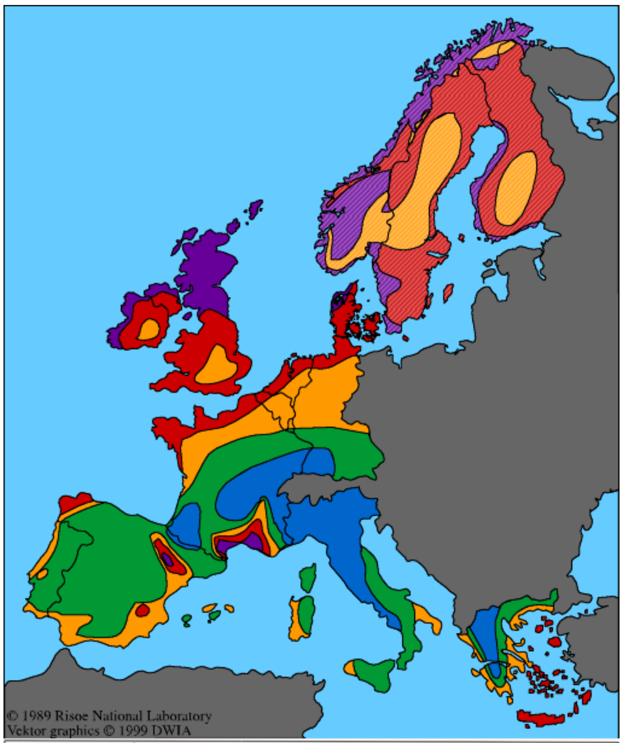
Two of the points on the map (marked »Leb« and »Lek«) actually have wind speeds, which are in the very high end of the range of wind speeds, despite the fact that they seemingly are located in low wind areas (the green-blue zones). This is possible because of slopes that accelerate the wind, but which are too small to be resolved in this coarse 2.5 km *mesoscale* resolution modeling. As we noted in section 2.3, we need to do *microscale* modeling (with 1-1000m resolution) to capture the local orographic wind speedup effects.

This example illustrates that there is very limited value in scouting for good, windy wind farm sites solely on the basis of the simulated wind speed values for areas as large as the grid size used in mesoscale modeling. The economically viable wind resource is systematically *larger* than what the mesoscale modeling grid indicates, simply because it does not capture terrain features that are smaller than the modeling resolution.

In the case of the right map we have therefore recalculated the wind speeds to a generalized wind climate, i.e. flat terrain and uniform roughness. The red areas now indicate those with *supernormal* wind speeds, generated by mesoscale-sized effects of the terrain such as barrier effects (from winds forced by a mountain range), gap flows (winds channeling through a gap in a mountain range) or low level jets (tunnel-like high speed winds similar to jet streams in the upper atmosphere). The most likely places to find very high wind speeds may therefore be located in these areas with supernormal wind speeds, though microscale modeling is obviously the only way to capture the local, microscale speedup effects from hills, since the two points on the map mentioned previously still no not appear to be particularly windy on the second map to the right.[27]

3. Observational Wind Atlases, WAsP Method

The development of modern wind atlases began in the 1980s. An important part of these methodologies were developed and assembled in connection with the European Wind Atlas,[28] which in several ways became a standard-setting methodology worldwide. The original European Wind Atlas map was derived from wind measurements before 1989 at 220 meteorological measurement stations in Europe. Figure 13 shows the *generalized wind climate* in Western Europe at 50m above ground level, transformed to flat terrain and a uniform roughness length of 0.03m.



Wind resources[1] at 50 metres above ground level for five different topographic conditions										
	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Figure 13. Generalized wind climate Europe 50m a.g.l. (Source: European Observatorial Wind Atlas DTU (1989))

Figure 12. Recent WRF mesoscale map, 11 km grid (Source: WindScout iOS app by CUBE® (2016))

[27] But there are other criteria that are important for the choice of wind farm sites, such as proximity to the electrical transmission grid, easy road transport (Lesotho is an extremely mountainous area), localization near an electrical load center, etc.

[28] (Petersen 1989)

What may be surprising is how well it actually represents what can be done with the most modern methods 25 years later, though clearly the resolution in the more recent mapping in Figure 12 is better. Actually, the two approaches may usefully be combined if there are already geographically fairly closely spaced meteorology observations of a reasonable quality available in the territory in question,[29] which is unfortunately rarely the case in developing countries.

Observational wind atlases have been developed for several countries around the world, mostly until around the early 2000s, when mesoscale wind modeling gradually took over the lead in doing national and regional wind atlases.

The technique used to produce these observational wind atlases was to do a thorough roughness rose assessment of the surroundings of existing or newly erected meteorology stations, a mapping and assessment of nearby wind obstacles and of orographic wind speedup effects, after which the wind data was processed using the standard microscale wind resource model software, WAsP, to recalculate the data to a well-defined *generalized wind climate*, as explained above.

Figure 14 shows the wind atlas methodology of WAsP. The left arrow pointing up shows how the meteorological sub-models are used to calculate the regional wind climatology from the raw data – the analysis part.

The model for mountainous terrain corresponds to section 2.4 on orographic speedup effects, the model for roughness of terrain corresponds to sections 2.1 and 2.2 on the influence of surface roughness on wind speeds and wind directions and the model for sheltering obstacles corresponds to section 2.4. The generalized wind climatology is explained in section 2.5.

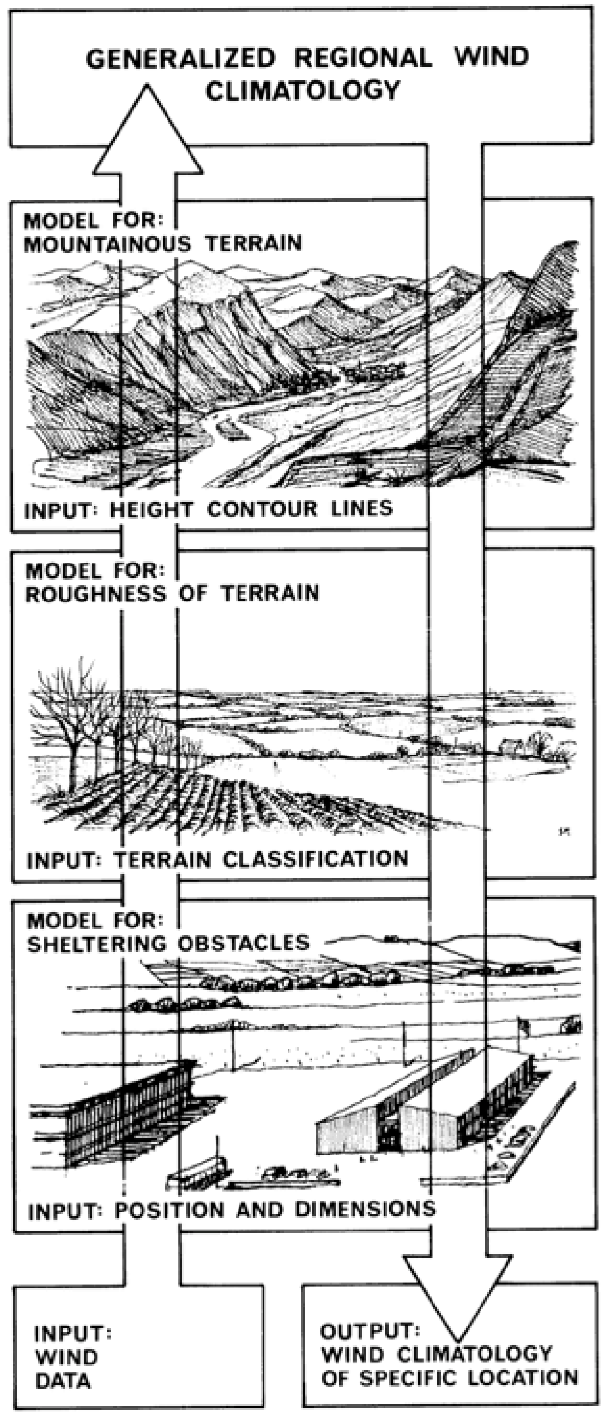


Figure 14. WAsP Method (Source: Risoe/DTU)

The arrow pointing downward to the right shows how in the reverse process – the application of wind

[29] This is e.g. the case in Egypt, for which both a regional and a national wind atlas were developed by Riso/DTU.

atlas data – the wind climate at any specific site may be calculated from the regional climatology.

There is actually no major difference between this modeling method and the way a developer would predict wind resources based on observations from a nearby wind measurement mast.

Looking at Figure 14 we can draw an important corollary:

Transforming data forward and back for the same position would obviously give the same result with the same parameters describing the landscape. Since each step in the modeling process has some uncertainty involved, it is clear that it is a very major advantage to measure wind or have wind data for a point where the surrounding terrain as much as possible resembles the other point where one wants to predict the wind resource, e.g. similar roughness etc. Hence, if one wants to *validate* a prediction made by a model for a certain general area, of some km^2, then it is best to do validation measurements in a point, which is highly representative of the average orography and roughness in the area.

4. Mesoscale Wind Resource Modeling

Modern mesoscale wind resource modeling took off in the mid 1990s, using numerical weather forecasting models with fluid dynamics and thermodynamics equations. These models describe the interaction between weather phenomena and their physical interaction with the surface of the earth at the mesoscale level. The models are generally run on supercomputers with, say, 5,000-10,000 processing cores if any reasonably sized area is to be covered. This is because the fluid dynamics equations are highly nonlinear, and the numerical solutions have to be found in small time steps analyzing weather patterns, including airflows in a very detailed 3-dimensional grid. The 3D grid represents not just the *orography* and the variations in *surface roughness* of the landscape, but also a large number of heights above ground level in order to account for phenomena such as *wind shear*.

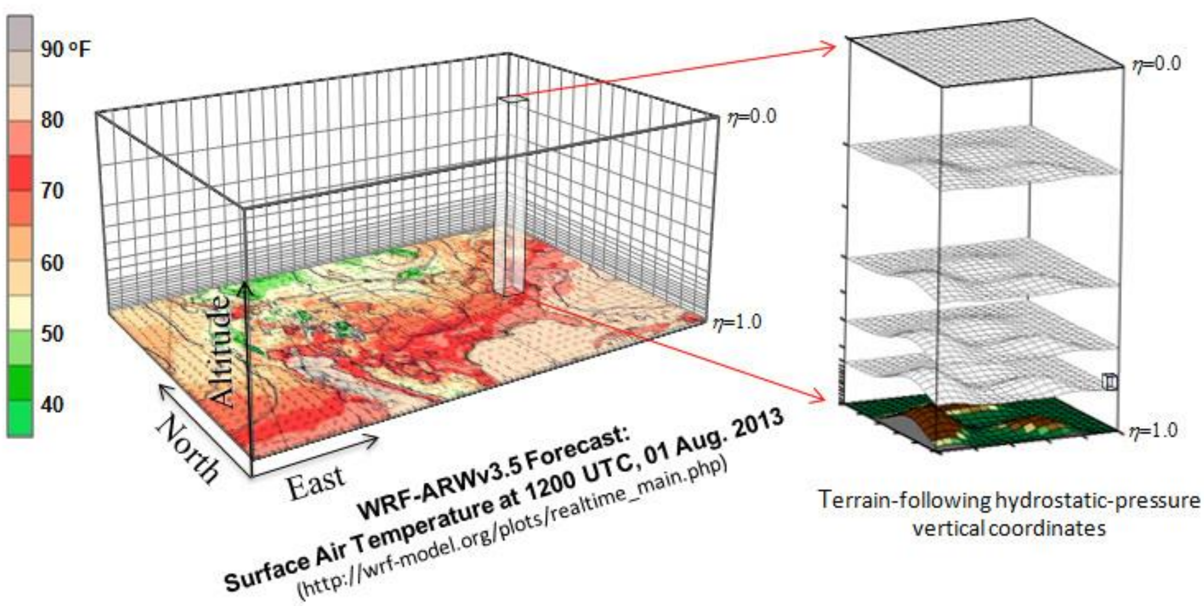


Figure 15. Terrain-following 3D zoomed grid of WRF Model (Source: University of Washington)

4.1. Choosing Model Resolution, Grid Spacing

The typical horizontal grid spacing used for mesoscale models is 2-20 km, but the models can also be run with a very fine grid spacing of, say, 300m. However, this is so computationally intensive, that it is only used for studying, say, air pollution in very small areas. Figure 16 shows a terrain-following zoomed grid, i.e. the grid points are denser vertically near the surface than higher up, since it is near the surface the interactions with the landscape are the strongest.

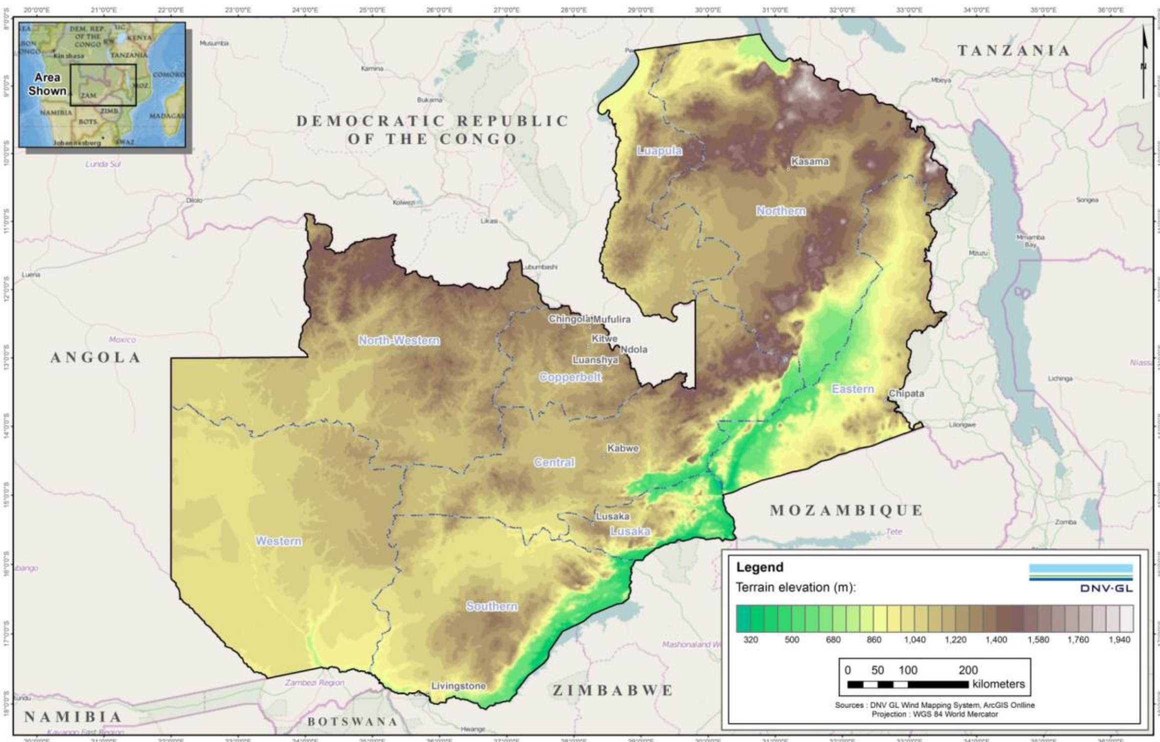


Figure 16. Model terrain elevation for Zambia (Source: DNV/GL for the World Bank ESMAP)

The vertical grid used for wind power applications typically has some 40-60 levels. This means that the number of nodes where the 3D grid lines intersect and where the motion of air packages are analyzed becomes extremely large for a countrywide or regional modeling run.

If we double the resolution from, say 4 km to 2 km, then the number of horizontal grid points becomes 2x2=4 times as large, but simultaneously the user of the model has to halve time step in the modeling, since air parcels will move from one cell to the next in half the previous time interval. Consequently a doubling of modeling resolution will require at least 2x2x2=8 times more computing time.[30]

It is important to understand that a horizontal resolution of, say, 2 km, can only resolve atmospheric weather phenomena that are about 5-7 times the size of the grid spacing and cannot resolve topographical features that are smaller than the grid spacing.

[30] Or at least increase the computing resources required 8 times, since the software architecture of the modern mesoscale models is structured so that several processes can run in parallel.

More detailed landscape features need to be modeled with a *microscale model* in order to be used for resource assessment for a wind farm, as explained later.

At this stage the question arises, how detailed a resolution would be optimal for simulation, given that there is a cost tradeoff between computing time and resolution?

There is not a simple answer to the question, much depends on the complexity of the terrain, i.e. the more complex the terrain, the more one is likely to benefit from a higher resolution. For completely flat terrain or for low islands spread across a large area there is no real benefit to a high resolution, indeed one may skip the mesoscale step altogether and directly downscale the meteorological reanalysis data to the surface the earth, as was done in the Global Wind Atlas.[31]

For large countries or regions it may be most cost effective to model the majority of the country with a fairly coarse resolution of, say, 5 km and use a higher resolution of 2 km for regions with more complex topography. Going lower than 2 km resolution may not yield better results, depending on the effective resolution of the input data, notably for surface roughness. 1 km tends to be the limit for conventional mesoscale wind resource modeling.

4.2. LAND SURFACE MODELING INPUT

Mesoscale wind resource modeling is based on building a 3D land surface model of the country in question and its surrounding areas. The total area that needs to be modeled is substantially larger that the country in question as explained in section 4.4 on the *nested domain* method.

4.2.1. Topography Data

The modelers normally use satellite topography data, which is available at a 90m resolution for most of the land area between 60°N and 56°S latitude (though with some voids filled out by computational methods). Increasingly 30m resolution data is available in the public domain for most of the same land area.[32] If national digital topography data is available with a better quality, that data can be used instead.

4.2.2. Land Cover Data and its Conversion to Surface Roughness Data

Land cover data is important for properly modeling *surface roughness*. If no better national data is available, modelers normally use satellite data, typically with a 1 km resolution.[33]

Conversion of land use to an appropriate *roughness length* is normally done through a table lookup mechanism in the modeling setup. There is not a simple and standardized, recognized method to do this; much depends on the modeler's experience and understanding of how the local land use is represented in the available datasets.

[31] Produced by DTU in 2015 and accessible online at globalwindatlas.com.

[32] The data can be downloaded from USGS, United States Geological Service. The NASA Shuttle Radar Topography Mission (SRTM) collected the data in 2000. It has since been subject to quality control and void filling. WiewFinder has a privately cleaned up version of the 90m SRTM dataset.

[33] Land cover data is typically provided by USGS/EROS (Center for Earth Resources Observation and Science), or by the European Space Agency, ESA, in the Corine (Coordination of Information on the Environment Land Cover, CLC) database, or the Modis (Moderate-resolution imaging spectroradiometer) land cover database.

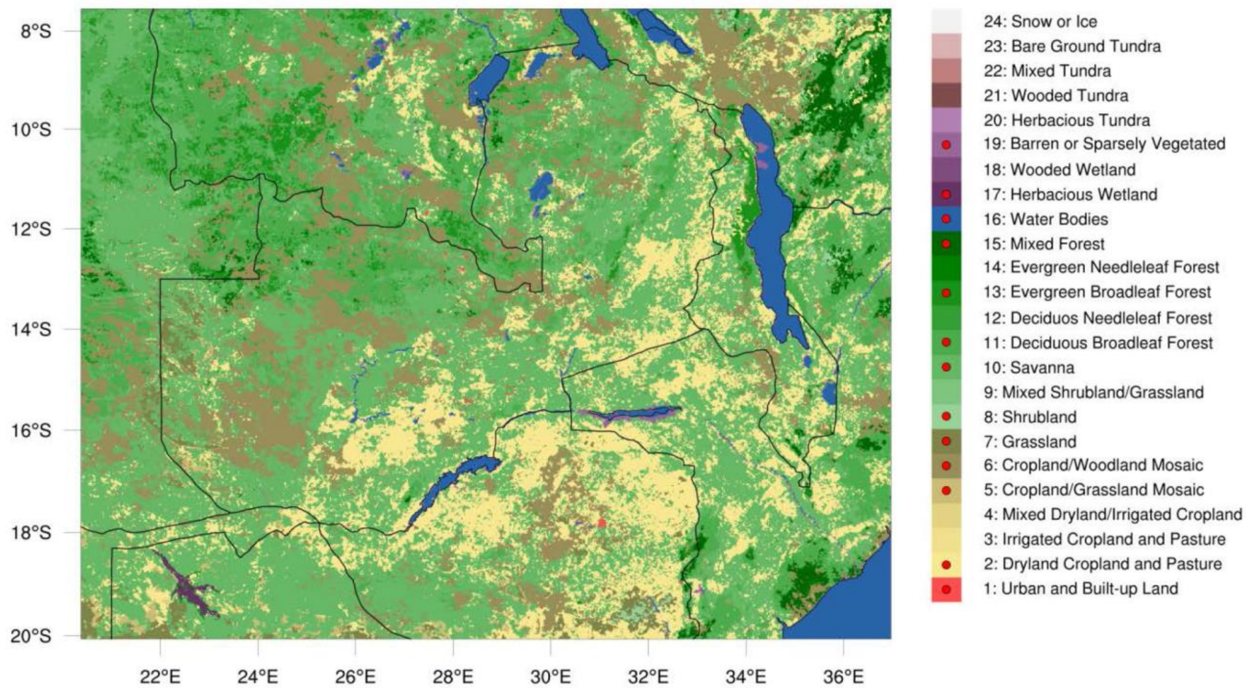


Figure 17. Land use types for Zambia (Source: DNV/GL for the World Bank ESMAP)

This is one of several areas where different modelers may have different opinions, and the task may be more or less complex depending on the land use types in the country in question.

It is recommended that the mesoscale modeling reporting contain a clear description of how surface roughness has been assigned to the land surface areas. This is because for certain areas the roughness description may be a source of systematic bias in the modeling results.

4.3. HINDCASTING USING REANALYSIS DATA

Mesoscale models work by producing a weather forecast, typically 24-120 hours ahead from a set of initial meteorological observations of barometric pressure, temperature, wind speed, wind direction etc. When used for analyzing wind resources the model is run using historical weather data, so called *reanalysis data* to initialize the model.

Input data used for global weather forecasting is measured several times daily at ground-based meteorology stations, weather balloons and satellites, typically hourly or with 6-hour intervals. The data is then recalculated to a uniform global grid with a resolution of about 50 km using so-called *data assimilation* techniques, since the observation points are not uniformly spaced around the globe. [34]

Reanalysis data describes large-scale (synoptic) weather phenomena such as high and low pressure areas and fronts at a scale of hundreds of km occurring in upper parts of the atmosphere. The mesoscale models simulate the interaction between these high altitude weather patterns and the landscape on the surface

[34] For example, the MERRA (Modern Era-Retrospective Analysis for Research and Applications) database from NASA; the ERA database from the European Center for Medium Range Weather Forecast (ECMWF); CFSR (Climate Forecasting System Reanalysis) and NCEP DOE2 databases from NOAA; CFDDA (Climate Four Dimensional Data Assimilation) database from NCAR.

of the earth, so as to get the weather forecast for smaller areas, typically with a resolution of 2-20 km.

4.4. Nested Domain Method

Mesoscale models are initially run at a coarse resolution in order to prepare data to use as input for the next level of simulations that has smaller grid spacing. Figure 18 shows an example for Nepal, where the simulation is done in three nested domains.

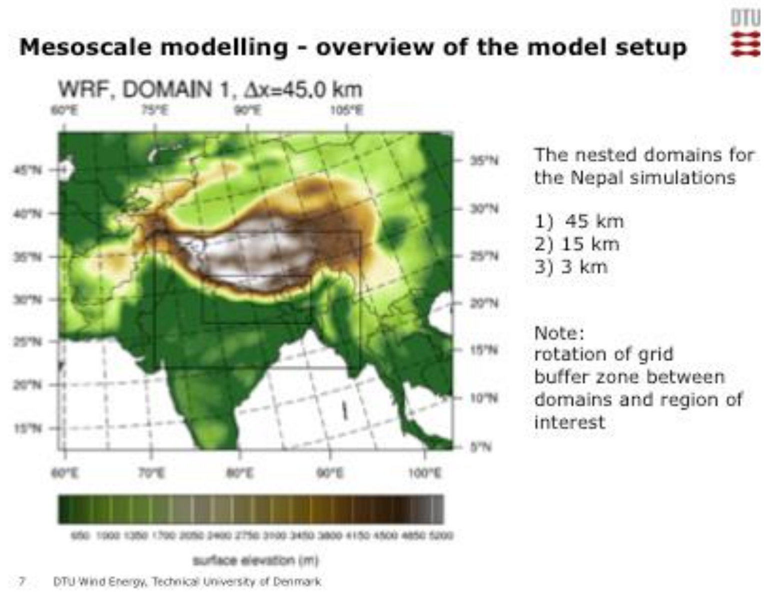


Figure 18. Nested domain set up example (Source: Risoe/DTU for the World Bank ESMAP Energy Resource Mapping Project for Nepal)

The outermost domain includes a much larger area than the country itself, since it should include all the regional weather patterns (in this case e.g. monsoons) that will ultimately affect the weather patterns within the country. Landscape features outside the country itself will also affect the initial conditions for the modeling within the densest grid. Another reason why the calculation domain has to be larger than the region of interest is that the model will be expected to perform poorly along the edges of the simulated area.

This is yet another example of the fact that the setup of a mesoscale models is not a straightforward process but requires a good understanding of the meteorology of the region in question. The optimal choice of modeling domain size and localization is not a simple task.

It is recommended that the modelers include a climatological description of the country and the surrounding region in their report of the mesoscale modeling.

4.5. Mesoscale Modeling Methods for Wind Resource Assessment

Mesoscale model types used for wind resource modeling can be categorized in two groups:

4.5.1. Time Series Modeling Technique (e.g. WRF)

Mesoscale modeling for wind resource assessment is today most often done by simulation of a (preferably long), historical *time series* with wind speeds and directions simulated on an hourly basis. This is normally the case when using the dominant model on the market today, WRF.

One advantage of the time series approach used for the WRF modeling is, that if the time period simulated is sufficiently long, say, 10 years, then it is probable that the mean simulation results reflect the long-term wind climate in the areas analyzed. However,

It is recommended that the modelers compare the 30-year means for the reanalysis data with the, say,

***10-year period selected for modeling to assess if the sample period is representative of a long-term (30-year) cyclical climate, and if not, analyze the possible biases in the results*.**

This may not be as straightforward as it seems, since the data assimilation procedures and data points used to compile the reanalysis meteorological data may have changed over time, although the institutions maintaining these databases recalculate the data to avoid breaks in the time series.

It is clear that the longer the period over which a simulation is carried out, the more certain is the mean result. Typically, most mesoscale wind resource modeling activities use a 10-year simulation period as a compromise between cost and benefits. Very short modeling periods, say 3 years, are very likely to give results that deviate from the long-term (30-year) mean climate.

It is recommended to use a time series simulation of at least 10 years in order to get a sufficiently reliable estimate of the mean wind resources.

Another advantage of the time series approach is that long time series can be used to generate a number of optional outputs:

1. Time series offer the possibility of estimating the periodic (inter-annual, monthly or daily) *variability* of wind power in the grid nodes.
2. Another option is to generate, say, 24 (hour) by 12 (month) matrices of expected power generation[35] in the grid nodes in order to characterize the typical variations in diurnal and seasonal variation in energy output.
3. Another possibility is to use the simulated wind data to construct an *extreme wind atlas*, showing the probable extreme wind speeds during a 50-year time period in the form of a *generalized wind climate*. [36] (Extreme winds are important for the choice of wind *turbine class* for a site.)

These issues are discussed further in Section 5.

The drawback with the time series approach is that it is computationally intensive / expensive. But one reason why the time series approach has been more and more feasible in recent years is of course the increasing processing power and relative price decline of each new generation of supercomputers.

4.5.2. Wind class[37] (Modeling Technique (e.g. KAMM/WAsP)

One way to reduce the computational requirements of mesoscale modeling dramatically is to simulate winds based on a number, say 100-150, representative historical meteorological situations and their frequency in the area in question. This technique, called statistical-dynamical downscaling, is used in e.g. the KAMM/WAsP model (combining the Karlsruhe Atmospheric Mesoscale Model, KAMM, with the microscale Wind Atlas Analysis and Application Program, WAsP).[38] This technique summarizes a number of

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[35] One would use a single hub height above ground level, say, 100m, and a power curve for one widely used wind turbine to generate the table, since the precision that can be achieved is limited anyway.

[36] This can be done post-processing the simulated results using the WAsP Engineering software package, see e.g. (X.G. Larsén 2013)

[37] (Badger et al. 2014) Wind class weather forecasting is a form of Monte Carlo analysis, where the same weather model is initialized using slightly different, probable initial conditions, thus generating a range of probable forecasts. This technique is used by major weather forecasting centers to assign a probability to various weather outcomes such as volume of precipitation.

[38] (Helmut P. Frank 2001)

steady states rather than simulating hour-to-hour weather development over multi-year periods.

4.5.3. Choice between Mesoscale Modeling Techniques

One major drawback of using the latter ensemble modeling technique is that one cannot get the time series outputs mentioned above. Experience with the WRF modeling framework [39] also seems to indicate that the WRF model is capable of capturing a number of meteorological phenomena that are not directly modeled in the KAMM/WAsP framework.

Risoe/DTU, one of the institutions that was the most active in developing and using the KAMM/WAsP model, and subsequently has been using the more recent WRF model, characterizes the difference between the two methods thus, analyzing the outcome for their South Africa modeling:[40] ***»KAMM/WAsP method, numerically very cheap, gives good results; WRF method, numerically very expensive, gives excellent results.«***

4.6. CHOICE OF STANDARD MESOSCALE MODEL

The mesoscale modeling frameworks most commonly used for wind resource assessments have been developed by the large meteorological institutions and the academic research community and are available in the public domain.[41] The features of these models tend to be well documented and have been peer-reviewed by other researchers.

At present, the WRF (Weather Research and Forecasting Model developed and maintained by NCAR, NOAA), for which the software and documentation is in the public domain as open source, is currently dominating the market for mainstream vendors of mesoscale modeling for wind resource assessment.

There are several advantages in adhering to the present de facto industry standard modeling framework, WRF. The large user community means that there is a considerable amount of user experience and peer reviewed literature about the properties of the model, and it tends to be accepted as the gold standard by wind power developers and other members of the wind industry community.

Some private vendors of mesoscale modeling services use so-called proprietary algorithms, which are kept as business secrets. Although they may claim that they have commercial success it is not recommended to use anything but the peer reviewed, publicly available mesoscale modeling frameworks.

It should be noted that the wording »modeling framework« indicates that models like WRF have many different options, which may include all sorts of more or less relevant meteorological features, (e.g. analysis of the spread and chemical reactions of pollutants), and there are quite a few wind power-relevant settings that can be tweaked by modelers. Several of meteorological phenomena are not resolved mathematically in the model equations, but depend on *parameterization*, i.e. settings that force the model behavior. The most suitable settings are to a large extent a matter of experience of the modelers, and their skills and quality control may vary.

It is recommended to require that the modelers document their model settings in their reporting, so as

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[39] The type of index that can be produced depends on the modeling techniques the vendor uses. Ensemble forecasts can e.g. be combined with the WRF modeling method to provide statistical metrics for the modeling uncertainty.

[40] (N.G. Mortensen 1995) (A.N. Hahmann 2014)

[41] e.g. WRF, KAMM/WAsP, MM5, NAM, Skyron.

to make the modeling results reproducible. Buying mesoscale modeling is to a large extent a matter of confidence in the modeling teams, their professional qualifications, experience and track record.

Asking around in the final user community is one way of ascertaining the modelers' qualifications; their peer-reviewed publications may be another source to inform the choice of vendor. Some modeling teams may be good at doing weather forecasting and handling mesoscale models, but experience shows that not all vendors have a good understanding of the needs and conventions of the wind industry and its associated investor and finance community.

4.7. CHOICE OF MESOSCALE MODELING HEIGHTS ABOVE GROUND LEVEL

As explained in section 4.1 mesoscale modeling of wind resources needs to include a large number of heights a.g.l. (typically 40-60) in order to represent the wind shear near ground level properly. Turbine manufacturers in particular are interested in having a very close vertical grid spacing near ground level, since the wind shear across the entire rotor surface is very important for the fatigue loads on the turbines,[42] the *turbine class*[43] needed for a site as well as the longevity of the turbine in a particular location.

With the fairly coarse grid size used for mesoscale modeling of an entire country of typically 2-5 km we cannot hope to achieve a high precision on local wind shear, so it is better to put a priority on modeling outputs for likely future hub heights for wind turbines in the area being modeled, taking a view to future developments of wind turbine sizes and possible improvements in logistics methods for transporting and erecting turbines. (In 2016 commercial wind turbine prototypes were already running with up to 165m rotor diameter and hub heights up to some 180m.)

It is consequently advisable to have the *top level* output data at no less than 200m. Since our surface roughness description in the mesoscale modeling is somewhat uncertain, the wind speeds modeled are more likely to be relatively more correct far from ground level than close to ground level, i.e. it is safer to extrapolate downward than upward from the simulated results. Another reason for simulating relatively high above ground level may in some places be to test for the possible presence of the meteorological phenomenon of low-level jet streams.

The *lowest level simulated* may be, say 10m or 20-25m, depending on local conditions and the likely types of turbines that may be installed. Generally speaking it is preferable to use the higher of the two levels due to the considerations above.

It is important to include a *primary validation height to be simulated* that as far as possible corresponds precisely to the top level anemometers on the meteorology masts used for validation purposes, as explained in section 7. In the case of the ESMAP studies 80m meteorology masts are used for model

[42] When a rotor blade on a wind turbine is in its uppermost position, where the wind speeds generally are the highest, then the thrust (the horizontal force acting towards the tower for an upwind turbine) is at its maximum. In the lowermost position the situation is the opposite, hence the forces that attempt to bend the rotor blades and the tower are very variable, and these fatigue loads may in some locations exceed the technical design limits for a particular turbine model.

[43] Wind turbines are designed and type certified for different wind classes (I-IV A or B) under the IEC/ISO-61400 international standardization system, depending on the expected 50-year extreme wind speed on the site and the expected level of turbulence intensity.

validation.[44]

The modeling heights above ground level used and published in the ESMAP studies are generally 20(/10)m, 50m, 80m, 100m and 200m above ground level for the reasons explained here.

4.8. Choice of Reference Surface Roughness Lengths for Modeling

The standard roughness lengths in ESMAP modeling studies are 0.000m 0.030m 0.100m 0.400m 1.500m. These values cover the gamut of roughness lengths from water surfaces to large cities. There is no practical reason to deviate from these values.

5. Mesoscale Modeling Reporting

5.1. Mesoscale Modeling Data Outputs

Appendix 1 contains recommended requirements for mesoscale modeling and reporting. This section 5 explains the reasoning behind these requirements in more detail.

Mesoscale wind resource modeling produces enormous amounts of output data from simulations, several terabytes, even for a moderately sized country of a few tens of thousands of square kilometers. This raises the question of which data to keep and how to post-process it into a practical format, and which data to keep for future analysis? The following discussion assumes that the modeling was done with a time series approach like WRF.

The simulated data for wind speeds and wind directions for each node in the grid is an enormous amount of data. These time series are generally speaking not useful for the typical user in the wind industry, who will be using the mesoscale data for microscale modeling of a specific wind farm site. The reason is that both wind speeds and wind directions will vary with height above ground level and with the roughness distribution of the surrounding terrain. There is no simple way for the user to convert this data to the microscale characteristics. Instead, most developers prefer to buy such historical time series for specific locations from vendors who specialize in this type of work.

Consequently, it is more practical to extract and summarize the most important information in the data and serve it in a format than can be used directly for microscale modeling of a wind farm site in the vicinity.

5.1.1. .lib Files With Generalized Wind Climates: Virtual Meteorology Mast Collection[45]

Section 2.6 explained why simulated wind speeds for a whole area of, say, 2x2 km are not a good guide to picking suitable sites for wind farms, since the *microscale* effects, e.g. of slopes that accelerate the wind are not taken into account in the mesoscale modeling, which so to speak »smooths« the terrain to fit with the modeling resolution and likewise averages out the roughness variations within the area.

However, we can normalize the simulated wind speeds and wind directions to a number of suitable *generalized wind climates* as explained in section 2.5. The advantage of doing this kind of post-processing is

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[44] In certain areas with very high lightning frequency it may be necessary to use the topmost level of the meteorology mats to place a horizontal boom with lightning rods in order to protect the measurement equipment below. In that case measurements have to be extrapolated to 80m for validation purposes.

[45] The layout of a .lib file is documented in Appendix 1.

that the result for each grid node can be stored in a small, compact file that summarizes the statistical wind speed distributions (compactly summarized as the two parameters describing the characteristic Weibull distribution) in a number (typically 12) directional sectors for (typically five) different heights above ground level, given a local roughness length of (typically five) values. We thus have 25 alternative descriptions of what the wind climate would be like close to each grid node, depending on the *microscale* local roughness and height above ground level.

This type of file (called a .lib-file, which was originally developed for the WAsP microscale modeling software) is thus in reality the *»climatological fingerprint«* for each particular node in the modeling grid, since it contains the wind characteristics in a compact format. In fact, it is also equivalent to a *virtual meteorology mast*, since it summarizes the wind speed data similar to what we would have done, if we had a real meteorology mast standing at this particular node in the grid.

A .lib file with a climatological fingerprint can be used as input to all mainstream microscale modeling software[46] in order to find the best estimate for nearby local wind speeds, preferably using more accurate input data for real terrain characteristics, notably in respect to roughness changes in the landscape.

In order for mesoscale modeling outputs to be compatible with mainstream microscale wind models, the vendor shall estimate Weibull frequency distribution parameters using the technique found in the European Wind Atlas, i.e. Weibull distributions must be energy-conserving.[47]

It should be noted that all nodes in the simulation grid are not created equal, in that some of the virtual meteorology masts represented by the .lib files should not be considered representative for the area as a whole. This is notably true for points, which represent dramatic changes in topography, e.g. an escarpment, which may not be properly resolved in the model's topography. In general, it is advisable to use a .lib file from a nearby location that roughly resembles the area to be modeled at the microscale level, and that the point from the .lib file is located on the same side of major mesoscale features as the area to be analyzed, taking into account the prevailing wind directions.

5.1.2. Summary Statistics Characterizing Each Mesoscale Node

In order to give the user an understanding of the landscape, it is recommended that at least the following statistics be available for each node in the simulation grid:

- ***Roughness length used for modeling in m***
- ***Elevation used for modeling in m***
- ***Land/water mask for cell, 1 land, 0 water***
- ***Mean annual air density for cell kg/m³***
- ***Quality/uncertainty index***[48] ***for mesoscale modeling (methodology to be proposed by the Vendors)***
- ***Inter-annual standard deviation of mean wind speed @ 100m based on at least 10 years of***

[46] e.g. WAsP, Wind Farmer, WindPro, etc.

[47] Technically, this means that the two Weibull parameters are determined by the requirements that: first the total wind power in the fitted Weibull distribution and the observed distribution are equal, and second the frequencies of occurrence of wind speeds higher than the observed average speed are the same for both distributions.

[48] As mentioned previously, Ensemble forecasts can be combined with the WRF modeling method to provide statistical metrics for the modeling uncertainty.

simulations[49]

- ***Inter-annual standard deviation of mean wind power @ 100m based on at least 10 years of simulations***

It is practical to provide each of these datasets as GIS layers that can be displayed using standard software. The user of the numerical wind atlas should be able to get readout of the data by clicking on or (ideally) hovering over a point on the map.

5.1.3. 24x12 Table of Hourly and Monthly Mean Power Generation

One of the advantages of the time series approach to mesoscale wind resource modeling is that with, say, 10 years of hourly wind data we can build a table of hourly and monthly mean power generation. This requires some post-processing of the simulated wind speeds, using them as input to a generic wind turbine specified by its *power curve*.[50]

It is recommended to provide 24x12 tables of the expected hourly and monthly wind power generation as a percentage of the mean annual energy production for a generic wind turbine, specified as the percentage of annual energy output within each hour of the day within each month.

Such tables give the possibility of optimizing the location of wind farms by finding sites that have microclimates that are load-following, i.e. sites where power generation tends to be highest when the demand for electricity is the highest. It is thus possible to analyze the tradeoff between the cost of energy per kWh and the value of the electricity in the grid, which is typically highest when demand is the highest. (Many countries have, »triple electricity tariffs« that vary with the time of day, particularly for industrial consumers (those with time-of-day metering).

Predicted hourly and monthly energy production as a percentage of mean annual energy production
Generic 3MW power curve at 100 m AGL

	Energy production [%]												
Hour	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
00:00	0.25	0.32	0.48	0.57	0.50	0.50	0.56	0.63	0.68	0.74	0.55	0.37	6.15
01:00	0.26	0.34	0.50	0.60	0.53	0.54	0.60	0.66	0.71	0.75	0.55	0.37	6.40
02:00	0.24	0.35	0.52	0.62	0.55	0.56	0.61	0.68	0.71	0.75	0.55	0.36	6.49
03:00	0.25	0.35	0.54	0.64	0.60	0.59	0.64	0.70	0.70	0.72	0.57	0.37	6.66
04:00	0.27	0.38	0.57	0.68	0.63	0.60	0.67	0.72	0.70	0.72	0.56	0.39	6.89
05:00	0.27	0.37	0.56	0.68	0.64	0.61	0.68	0.70	0.67	0.68	0.52	0.35	6.72
06:00	0.19	0.28	0.45	0.61	0.58	0.55	0.65	0.64	0.58	0.54	0.41	0.26	5.74
07:00	0.13	0.20	0.35	0.52	0.51	0.48	0.58	0.52	0.47	0.43	0.31	0.19	4.69
08:00	0.09	0.13	0.25	0.39	0.37	0.38	0.47	0.40	0.37	0.34	0.23	0.14	3.56
09:00	0.07	0.09	0.17	0.29	0.27	0.29	0.37	0.30	0.28	0.25	0.17	0.10	2.65
10:00	0.06	0.07	0.12	0.21	0.19	0.21	0.27	0.23	0.21	0.19	0.13	0.08	1.98
11:00	0.05	0.06	0.10	0.16	0.15	0.17	0.21	0.18	0.18	0.17	0.12	0.07	1.62
12:00	0.05	0.05	0.09	0.13	0.12	0.14	0.18	0.16	0.17	0.16	0.11	0.06	1.42
13:00	0.06	0.06	0.09	0.13	0.12	0.14	0.17	0.15	0.17	0.16	0.12	0.07	1.41
14:00	0.06	0.07	0.10	0.13	0.12	0.13	0.16	0.15	0.17	0.18	0.14	0.09	1.50
15:00	0.07	0.08	0.11	0.13	0.12	0.13	0.16	0.15	0.17	0.18	0.14	0.09	1.53
16:00	0.10	0.12	0.15	0.17	0.16	0.16	0.18	0.18	0.19	0.21	0.17	0.13	1.90
17:00	0.15	0.17	0.21	0.25	0.27	0.25	0.27	0.30	0.28	0.29	0.22	0.18	2.84
18:00	0.18	0.20	0.29	0.34	0.34	0.34	0.36	0.40	0.40	0.43	0.28	0.23	3.80
19:00	0.21	0.25	0.34	0.41	0.40	0.40	0.43	0.47	0.49	0.53	0.37	0.29	4.56
20:00	0.24	0.26	0.38	0.45	0.42	0.43	0.46	0.51	0.54	0.59	0.43	0.32	5.04
21:00	0.22	0.26	0.41	0.49	0.44	0.44	0.47	0.54	0.60	0.65	0.45	0.31	5.27
22:00	0.21	0.28	0.43	0.51	0.45	0.45	0.49	0.58	0.63	0.69	0.49	0.32	5.52
23:00	0.21	0.29	0.43	0.53	0.46	0.47	0.52	0.59	0.66	0.71	0.51	0.32	5.69
Total	3.85	5.05	7.61	9.64	8.93	8.95	10.14	10.51	10.71	11.05	8.08	5.46	100.00

Figure 19. 24x12 table of expected hourly and monthly power generation (Source: DNV/GL for the World Bank ESMAP)

Figure 19 shows an example of a 24x12 power generation table for a grid node in a mesoscale modeling of Zambia.

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[49] The reason why the mean wind speed or mean wind power themselves are not stated in relation to these two last items on the list is that wind speed varies with height above ground level. These statistics are only available when the mesoscale modeling uses the time series approach to modeling (such as WRF does).

[50] A power curve describes relationship between the instantaneous wind speed and the power generation of a specific model of a wind turbine for a given air density and a given turbulence intensity. Wind turbine manufacturers can provide (certified) power curves for their turbines.

5.2. Mesoscale Data To be Conserved

While the simulated results for wind speeds and wind directions will probably be of little use to the typical user of mesoscale wind resource modeling data as explained in section 5.1, the data can nevertheless be used for other purposes. One possibility mentioned above is to use the data as input for post-processing to provide an *extreme wind atlas* for the region being modeled.

It is fairly inexpensive to conserve the simulated wind data on a high-capacity disk storage drive in order to keep it for later research purposes, hence it is recommended to do so.

6. Microscale Wind Resource Modeling Using Mesoscale Data

Microscale wind resource modeling is concerned with estimating the wind resource at a certain height a.g.l. in a given location or area based on wind speed and direction data from a real or a virtual meteorology mast. The resolution for mapping an entire area may be in the range of 1-1000m.

The outputs of the mesoscale modeling explained in the previous two sections can thus be used as input in order to predict the wind climate in an area at a fairly high resolution. Such data can be used for preliminary siting of wind turbines and estimates of mean annual energy output from a wind farm.

6.1. How a Professional Wind Farm Developer or Consultant uses Mesoscale Data

Reading Figure 14 on page 26 from the top and downward we can see how we can use the *generalized wind climate* we obtained as (.lib file) output from the mesoscale model as input for a *microscale wind resource model* in order to predict the local wind speeds and directions by applying all the models for orographic speedup / slowdown, surface roughness changes and obstacle sheltering mentioned in section 2 of this paper.

One important reason why we – so to speak – »washed out« the local properties of the mesoscale simulation results by converting the data into a *generalized wind climate* is that once we start doing microscale modeling we will take local, small-scale terrain effects such as orographic speedup / slowdown into account in our modeling. If we worked directly on the basis of the simulated wind speed values from the mesoscale modeling, we would risk doing some »double counting« of the mesoscale and microscale effects, since our microscale modeling will in fact overlap with the mesoscale terrain description. In the microscale model we will typically model the terrain at a distance of several km around the wind farm depending on the local roughness and orography variations.

Another reason why we calculated the *generalized wind climate* in the previous step is that a professional developer or wind energy consultant doing a feasibility study for a wind farm site would look closely at (preferably) both aerial / satellite imagery and field observations on the site itself and its surroundings in order to do to a much more precise estimate of roughness variations in the surrounding terrain than what can be obtained from the very coarse 1-km resolution maps generated from automated satellite data collection.

The actual *roughness rose* on the terrain in the real landscape is quite likely to differ from the coarse mesoscale modeling description, thus the microscale model will need the information contained in the *generalized wind climate* in order to work with roughnesses that differ from what the mesoscale modeling is based on.[51]

When a consultant or a developer does a mesoscale mapping of a wind farm site, they will do the siting of wind turbines with a precision counted in meters and not kilometers. In addition, they will include a *park effect* (array effect) modeling, i.e. compensate for the power generation losses due to wind turbines shading one another (taking into account surface roughness changes and the wind frequency rose).

6.2. PRODUCING A COUNTRYWIDE MICROSCALE WIND RESOURCE MAP

6.2.1. Reducing the Volume of Microscale Data to the Most Useful Items

Global orography data is available with a resolution of 90m (3 arc seconds) and increasingly with a resolution of 30m (1 arc second). This is obviously a much better resolution than what is provided in the mesoscale modeling, which will require averaging (and possibly addition data smoothing of the input data to ensure that the computing algorithms can handle the data).

When doing microscale mapping for the area of an entire country it is not practically feasible to do accurate surface roughness assessment with a higher degree of accuracy than what can be obtained with automated assessment using satellite observational data with a 1 km resolution,[52] although some countries have a better mapping than this. In any case, the level of precision that can be obtained for a countrywide map is not at the level that a good, professional wind energy consultant can achieve, as explained in the previous section.

These considerations limit the value of producing extremely detailed microscale data.

Another important consideration is the volume of data that can be produced: When going from a 2x2 km mesoscale resolution to a 100x100m microscale resolution the number of grid points increases 400- fold. In order to keep the output data to a manageable volume and to retrieve data reasonably rapidly it may be useful to limit data collection to the following:

- ***Geographic location (decimal latitude, longitude)***
- ***Air density kg/m^3***
- ***Elevation m***
- ***Surface roughness length m***
- ***RIX index[53]***
- ***Quality/uncertainty index for microscale modeling***
  (methodology to be proposed by the Vendors and discussed between them and the buyer)

[51] In addition, the cartographical projections and resolutions used for the different data sources for orography, land cover, climate data, and the simulation grid may differ, which will mean that the basic data to a certain extent will be smoothed by averaging across grid boundaries.

[52] This may change in the future; since it is possible to estimate the porosity of e.g. forest foliage using laser (LIDAR) scanning from aircraft, while at the same time doing a topographical mapping of the surface. Methods to operationalize this in wind resource modeling are still in their research stage, however.

[53] RIX index defined as the percentage fraction of the terrain within a certain distance from a specific site, which is steeper than some critical slope, say 0.3. This index was proposed as a coarse measure of the extent of flow separation and thereby the extent to which the terrain violates the requirements of linearized flow models. RIX is worked out as an average for all sectors. (Wood 1995).

- ***12 sectorial Weibull distributions (A, k) @ 100m a.g.l.***
- ***12 sectorial wind frequencies @100m a.g.l.***

A few items require additional explanation:

The *RIX index* is an indicator of the ruggedness of the terrain and at the same time a signal whether the linearized flow model, WAsP, which is used for high-volume microscale (100m resolution) calculations when doing a national wind map can be expected to perform reasonably well in this particular location.

The final two data items can be used together with a (user selected) power curve for a wind turbine to calculate annual energy production for a given location. It is practical to automate this facility in the user interface to the database. In order to save on the data volume, only 100m height a.g.l. is included in the dataset.[54]

6.2.2. Quality Index

Quality indices in meteorology are well known from weather forecasts, where e.g. the probability of a certain amount of rain is expressed as a percentage. A quality index can be built in various ways, depending on the methods used by the modeling vendor. One way is to initialize the mesoscale model with slightly different parameters to see how that changes the forecast wind speed values. What is important is to have a signal about the probable reliability of the microscale estimates in different areas. The quality index thus serves as a warning that the resource estimate in a particular location may be highly uncertain, e.g. because of steep slopes, wind obstacles or complex terrain.

6.2.3. Modeling Scale Matters for the Size of the Apparently Commercially Viable Wind Resource

A countrywide microscale wind resource map at a resolution of e.g. 100 m will seemingly increase the wind resource dramatically compared to the apparent resource, which has been simulated in a mesoscale map at a resolution of, say 2 km. The reasons are firstly, that the terrain in the mesoscale modeling has been smoothed compared to the much more varied topography visible at a 100m resolution. The high-resolution microscale mapping will capture the orographic speedup and slowdown effects of smaller hills and ridges, which are below the mesoscale resolution.

Secondly, mesoscale modeling gives us the mean wind speed for a fairly large area of, say 2x2 km. But knowing the mean wind speed for such an area is not really that interesting, since we would not think of distributing wind turbines evenly across the landscape. We would only want to place turbines in the very windiest locations with reasonably low turbulence and reasonably horizontal airflows.

Figure 20, taken from the Global Wind Atlas,[55] illustrates how mapping resolution matters: Higher resolution mapping + only considering the windiest half of an area may increase the apparently available wind resource by 100%

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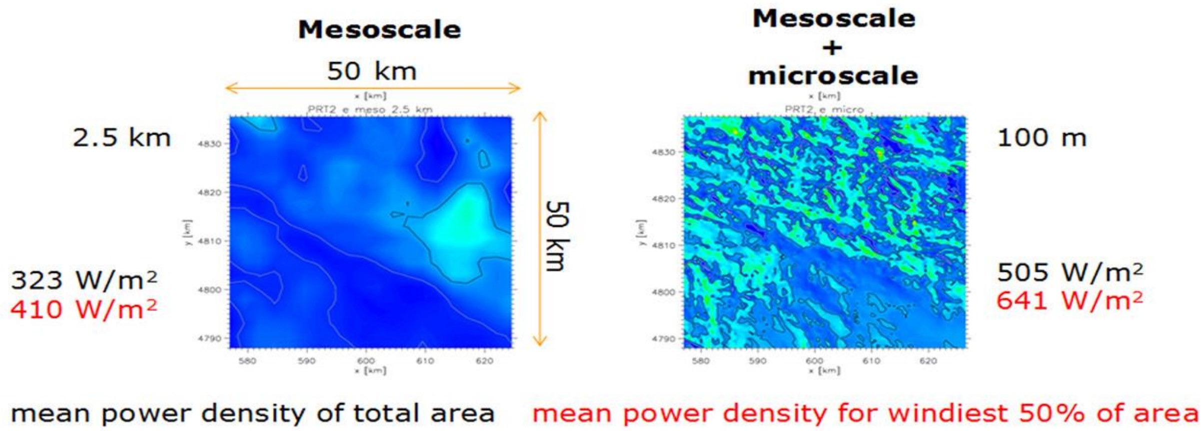
[54] A crude adjustment for other heights a.g.l. can be done using the average surface roughness and assuming a logarithmic wind profile. This is not the way things are done in a real mesoscale modeling of a site (wind directions will also change with height above ground level), and it is not recommended for assessing the output of a real wind farm on the site. Such calculations also require more precise siting than what can be done with the 100m resolution in this mapping.

[55] Produced by DTU for the IRENA Global Atlas: https://irena.masdar.ac.ae/gallery/



Wind power density calculated at 50 m above the surface for a 50 km x 50 km area at two different resolutions, (left) 2.5 km and (right) 100 m. The colour scale used in each map is the same. Dark blue is low values and bright green and yellow are high values. The mean power density for the area is given in black. The mean power density for the windiest 50% area is given in red.

Figure 20. Microscale mapping may increase the apparent wind resource in the windiest 50% of an area by 100%

6.2.4. Choice of Microscale Model used for National Wind Mapping

The most conventional choice for microscale modeling of a whole country is to use the WAsP microscale model. The primary reason for selecting this model is that it is conventionally used in the wind industry for bankers' wind project assessment. The model has been used and continuously developed for more than two decades, and its merits, biases and limitations are well known by professionals, and it is well documented in peer reviewed scientific papers. In addition, the model gives robust calculation results, i.e. the results are not overly sensitive to which (certified, well-trained) user is operating it.

The WAsP model is a linearized version of computationally much more complex microscale CFD (computational fluid dynamics) models, which can analyze complex terrain in much more aerodynamic detail than what the WAsP model does. (CFD models use essentially the same numerical methods that mesoscale models do). The feasibility of using microscale CFD modeling for countrywide microscale mapping are virtually non-existent at the present stage of modeling and computing technology, however, since even computing a single wind farm site requires using a supercomputer. An additional drawback to microscale CFD modeling is that the results are quite sensitive to the modeling setup by the user, i.e. the results cannot be characterized as being robust, and the possible biases and limitations are at present less well documented than what is the case for linearized microscale modeling

7. Validation of Mesoscale Wind Resource Modeling

Buying mesoscale wind resource modeling from a vendor is to a large extent a question of confidence. Even if the modeling framework has been peer reviewed and both the software and the input data are available in the public domain, there are many steps along the way, which require both theoretical understanding and practical experience from the modelers to get reliable results from the models. This is not just a question of pre-processing input data, selecting nested domains, resolutions, and model settings, but also selection of data processing techniques, (e.g. the initial time steps and external border regions in modeling runs need to be discarded to provide reliable resolutions of the weather phenomena within the area).

7.1. VALIDATION METHODOLOGY

In order to estimate the level of confidence with which mesoscale modeling results can be trusted it is important to test how the models perform compared to real world measurements of the wind climates, which were covered by the modeling.

Comparing real world wind climate measurements with modeling results is not quite as straightforward as it may seem at first thought.

Firstly, we need to compare likes with likes:

- The model universe is a simplified description of the real world with terrain elevations and surface roughness descriptions averaged and possibly additionally smoothed. Air density and atmospheric stability have been calculated in the modeling process, etc.
- The ground-based measurements are influenced by local variations in surface roughness, orographic speedup and slowdown effects, the presence of wind obstacles and variations in atmospheric stability between day and night and seasonally.

The data measured and the data modeled thus need to be converted to a common *generalized wind climate*, as explained previously, in order to be comparable.

This conversion requires using microscale wind modeling techniques as summarized in Figure 14 on p. 26. The tests we will be doing will therefore in reality be testing *both* the validity of the mesoscale modeling *and* the microscale modeling that has to be applied to the measured data. Since we really want to test the mesoscale modeling, then it is logically ideal, if we have to do as little transformation of the data as possible, hence, ***ideally, we would prefer to measure in a terrain that resembles the terrain of the mesoscale model as much as possible***.

The technology and methodology used for ground-based wind measurements for model validation are precisely the same as those used for doing a bankable[56] assessment of the long-term wind climate for a feasibility study for a future wind farm. The advice given below is therefore equally applicable, whether one is measuring for a future wind farm project on the site or for validating a mesoscale + microscale model.

Figure 21. Typical 80m meteorology mast used for wind resource validation (Source: ESMAP & IFC, Lesotho (2015))

[56] For example, an assessment that will be trusted by a bank to finance a wind farm project on the site where the meteorology mast is located.

7.2. METHODOLOGY FOR GROUND-BASED WIND RESOURCE MEASUREMENTS

This section describes the reasoning behind the technical requirements for ground-based wind measurements. Readers who consider writing their technical requirements for a wind measurement program can find a best practice set of requirements in Appendix 2.

Experienced wind energy consultants generally have a checklist for measurement site selection and wind farm site selection that goes beyond what is mentioned here. The following subsections explain the most important considerations for purposes of wind atlas validation measurements.

7.2.1. Choice of Equipment type: Tall Meteorology Masts Preferred, but LIDAR may be a Second Choice

Ground-based wind measurement for model validation purposes is usually done using tall meteorology masts with high-quality, high-precision, calibrated instrumentation with cup anemometers, as explained in more detail below.

7.2.1.1. Remote Sensing Alternative: LIDAR

Tall meteorology masts are relatively expensive and may be difficult to transport, so an alternative is sometimes to rent or buy modern, remote-sensing wind speed measurement such as *LIDAR* or (less frequently used) *SODAR*. This type of equipment is currently used both to study the detail of wind flows across complex sites and to measure wind resources above deeper waters offshore, where it impracticable or extremely expensive to install meteorology masts.

LIDAR works by bouncing focused laser beams off dust particles or aerosols in the atmosphere in a number of different directions and 10-12 different heights measuring the Doppler effect (change in frequency) of the wave reflections so as to estimate wind speeds and directions.

SODAR works by bouncing sound impulses off turbulent air layers at different heights in different directions.

LIDAR equipment can measure wind speed and direction at 10-12 heights simultaneously, typically from 10 or 40m and up to some 200-300m a.g.l. [57] The equipment is in itself quite expensive to purchase, so it may only make economic sense to rent for relatively short measurement programs of, say around 12 months, otherwise meteorology masts or purchase of the equipment may be less expensive.

LIDAR is usually preferred over SODAR, since SODAR is sensitive to echoes from nearby surfaces, ambient noise, rain, snow, low humidity and thermally well-mixed atmospheric situations, and may not be environmentally acceptable with nearby residences due to its emission of audible pings.

LIDAR uses infrared laser beams and is thus less intrusive, but it may not yield valid data during low-visibility (fog or snow) periods. If fog is correlated with low wind speeds, as is often the case, consultants have to be careful how the missing data gaps are filled. [58]

Temperature, barometric pressure and humidity have to be measured at the same points in time, which is often done within the LIDAR unit itself. It should be noted that this type of remote sensing equipment

[57] This is true for Continuous Wave Doppler LIDAR. Pulsed Doppler LIDAR may measure at up to 10 km distance (N.D. Kelly 2007). The latter type of LIDAR is heavy, about 250 kg and takes up about 1 m^3 of space. They consume 500-1600W of power. They are generally not relevant for the use discussed here.

[58] Some guidance to trace weather conditions can be obtained by having an anemometer near the LIDAR unit. Webcams have also been used on several sites.

cannot measure turbulence directly, although there are methods to derive turbulence data indirectly from LIDAR data.

7.2.1.2. Remote sensing is best for studying high-altitude wind phenomena, less so for low-level validation

There are a number of counterarguments to using this remote sensing equipment for typical validation purposes - other than their somewhat lower measurement precision:

Firstly, it may be necessary to introduce an additional layer of uncertainty by being forced to do airflow modeling of the specific site where the unit is placed in order to obtain correct wind speed readings from the instrument itself. The reason is that the instrument cannot measure the correct horizontal wind speed vector directly if the wind flow is not homogenous, i.e. unless the terrain is flat and there are no wind obstacles nearby and the wind flow is horizontal in all directions, otherwise the site airflow needs to be modeled to obtain the correct readings. This introduces another layer of modeling of top of the two layers we already have to deal with to do our comparisons for validation. [59] It should be noted that a few LIDAR models have built-in software that automatically and reliably *can* compensate for non-horizontal airflow situations such as they occur in complex terrain or near wind obstacles.

Secondly, LIDAR/SODAR equipment is expensive and needs to be guarded since it is placed on the ground and prone to theft and vandalism. It needs power from the grid or generation equipment such as fuel cells to operate. (LIDAR units typically need some 70-100W of continuous power supply).

7.2.1.3. When to use LIDAR for Wind Atlas Validation

There may be occasions where the use of remote sensing equipment can be economic, technically necessary and/or practical:

This is e.g. the case when it may be useful to test for the presence of so-called low-level jets, e.g. barrier jets, which may form upstream of a mountain range oriented parallel to the range, or a valley-exit jet, above the intersection of a valley and its adjacent plain. These phenomena occur mostly above the 80m level of typical meteorology masts.

There may also be important logistical and cost considerations, since the equipment itself is quite small (less than 60 cm in all three dimensions) and lightweight (<60 kg). [60]

Finally, LIDAR units have the great advantage of being highly mobile and easy and inexpensive to install quickly. It may be very valuable to have one (or preferably more) LIDAR units available after a validation campaign ends, since they can be used for two different purposes:

- If a validation site is also intended for a future wind farm, then LIDARs are often used for ***site calibration***, i.e. to determine how the wind speed varies between the different proposed turbine locations across the site, especially if the terrain is complex (hilly). In this case *it is necessary that the original meteorology mast or LIDAR used for the validation phase remain in place beyond the, say, 24 months of the validation campaign and keeps measuring while the mobile LIDAR is*

[59] The problem may e.g. occur if the LIDAR is placed near the top of a hill. The LIDAR essentially scans the wind speeds around a horizontal disk at each measurement height, where the airflow will have a positive inflow angle in the upwind part and a negative inflow angle in the downwind direction. The component of the wind vector along the beam is reduced in both cases leading to a reduction in the apparent wind speed. See e.g. (M. Harris 2010)

[60] See the specifications for LIDAR units from e.g. Leosphere Windcube or ZephIR.

deployed on different parts of the site for, say, a few months at a time. (The duration depends on the seasonal variability of local wind speeds and directions). The measurement readings from the mobile LIDAR can then, say, after 3 months, directly be used to determine the wind speed where the mobile LIDAR is placed *relative* to the original, stationary reference mast (or LIDAR). This makes it possible to generate a full, synthetic time series of 27 months of wind speeds and directions for each location where the mobile LIDAR is placed, thus giving the wind farm developer and his or her financier much lower wind resource risk than if only microscale modeling (with unknown risk) is used to estimate wind speeds across the site.

- A mobile LIDAR unit can also be used for ***site exploration***, i.e. to find new, possible wind farm locations in the neighborhood of an *existing* mast or LIDAR that *keeps measuring concurrently with the use of the mobile LIDAR.* The sites used for validation purposed are preferably completely flat, open terrain, whereas ideal wind farm locations are often located on ridges of rounded hills nearby, where one can take advantage of the *orographic (hill) speedup effect* mentioned in section 2.3. Once again, the measurements of the mobile LIDAR unit can be used to generate a full, synthetic time series of wind speeds and directions of whatever time length the stationary reference mast (or LIDAR) has been measuring with (almost) as much certainty as if one had had two years of measurements on the site itself. Note, however, that this way of extrapolating concurrent measurements from one location to another can only be done within a relatively short distance where the same microclimate prevails. The »relatively short« distance limit can be up to 50-100 km in flat terrain, whereas it may only be a few km in mountainous terrain.

The two examples above demonstrate the importance of leaving the original measurement equipment in place and to keep measuring, even if the site used for validation is not in itself suitable for building a wind farm.

7.2.2. Site Selection, Validation-Climatic Considerations and Weather-related Risks

The primary consideration when selecting a number of sites for validating a mesoscale wind atlas is to have the diverse microclimate types in the country or region represented. There may also be considerations from the vendors of testing the modeling for specific mesoscale features such as gap flows, low level jets, etc. Since the mesoscale modeling is undertaken to serve as a guide for commercially viable wind resources, we are primarily interested in general areas with higher wind speeds, which may be suitable for wind farms, whereas the accuracy of the mapping of low-wind areas is less important.

It is usually not advisable to specifically target the very best wind farms sites, since the very orographic speedup effects that make them attractive for wind farms make the conversion of the measurements to a standard wind climate more uncertain, as explained in the next section. However, it is possible to make a compromise and combine the search for wind farm sites with validation measurements, as explained in subsection 7.2.5.

Some sites may be prone to heavy icing on guy wires, masts and instruments, or extreme winds that may make a meteorology mast collapse. It is best to demand that the mast structure be certified by an independent third party for its survivability in the local climate conditions, and that the vendor of meteorology measurement services does a prior due diligence on the site for climatic risks as well as for the proper dimensioning of the mast for these conditions. It is usually possible to take out insurance for extreme climate events.

Finally, some sites may be prone to icing on the measurement instruments. If this is a frequent occurrence, then heated versions of measurement instruments are required. This means that additional power is needed either from larger solar panels (which may be subject to icing and reduced efficiency themselves) or from diesel gensets or fuel cells, which raises its own logistical and operational challenges.

7.2.3. Site Selection and Microscale Modeling Uncertainty: Choose Flat, Simple, Exposed Terrain

Ground-based wind measurements are inherently uncertain, and there are multiple sources of uncertainty:

In order to minimize the uncertainties in the microscale modeling, we would prefer to measure on sites with *flat terrain* around the meteorology mast, so that there is no need to do corrections for orographic speedup or slowdown effects. The effects of escarpments and very rugged terrain are notably difficult to model accurately; hence we will prefer terrain characterized by a low *RIX-index*. We would also as far as possible like to avoid any major nearby terrain features, which are below the horizontal resolution used in the mesoscale modeling. Likewise, it is best to avoid the sheltering effect of nearby *wind obstacles* such as large trees, buildings etc. There are other known shortcomings of linearized flow models, e.g. these models can only »see« upwind at any point in time, hence they will ignore the effect of, say, a hill at a direction perpendicular to the upwind direction or downstream of the meteorology mast position. This latter problem and a number of the other issues can be (at least partially) averted by using *microscale CFD modeling* rather than microscale linearized flow models, though the reservations mentioned in the *Acronyms, Abbreviations and Concepts* section of this paper still apply.

7.2.4. Site Selection and Site Security

Figure 22. 80m meteorology mast with anti-climb protection (Source: ESMAP & IFC, (2015))

Meteorology masts may be subject of theft or vandalism. This is particularly the case in remote regions, hence it is often preferable to site them near populated areas, where it may also be possible to have locals check visually that the equipment appears to be in place and in operation.

Anti-climb devices such as barbed wires, fencing etc. may discourage theft or vandalism, but may not be sufficient to prevent it. If a mast can be co-located with a guarded meteorology station or have its own guarding (with a requisite shed etc. for the guard as protection against the elements), such a solution may be preferred or necessary.

Solar panels are objects that attract thieves, the same goes for copper wires used for earth connection for the lightning protection, and mast are sensitive to tampering with e.g. guy wires.

7.2.5. Site Selection and its Suitability for Wind Farm Development, Environmental & Social Study Brief

Although the primary aim of model validation means that measurement sites are usually selected on the basis of the criteria mentioned previously, some measurement programs may wish to use the data for finding good wind farm sites directly on the basis of the site measurements. This can be taken into consideration when selecting sites and when locating the meteorology mast within the general site itself.

When looking for potential wind farm sites a number of additional criteria will enter the selection process, e.g. proximity to the electrical grid.

In addition, it is worth being conscious of the fact that high quality wind resource data is very scarce, particularly in developing countries (and a reason for doing the resource mapping per se), hence there is a high probability that the wind data collected will be used for a feasibility study for a nearby wind farm, even if it is not the aim of the measurement program.

Whether a site is to be used for wind farm development or not, it may be a good idea to do a preliminary layout of a wind farm and a summary calculation of energy production as part of the reporting required for the site selection process.

The reason for this requirement is that it is far easier for non-experts to understand the size of the wind resource when translating it into probable energy production rather than raw wind distribution figures.

If a site is likely to be used for wind farm development, this puts an additional obligation on the site selection. Wind farms have much more impact on the local environment than meteorology masts have.

The World Bank has established a set of environmental and social safeguards in order to ensure sustainable development. The International Finance Corporation, IFC, similarly has set IFC Performance Standards on Environmental and Social Sustainability. These standards can be useful to apply to wind measurement projects.

Normally, the planting of a tall meteorology mast on a site has minimal impact on the environment. Generally, it is less intrusive than a telecommunications mast or a mast for an electrical transmission line, since the whole structure is very slender and is often not even visible at a distance. Consequently, in most jurisdictions only a short environmental brief of a few pages will suffice to obtain the needed permits from the national and local environmental authorities. The fact that the masts are 80-90m, however, means that they generally have to be delivered painted red-white and equipped with low intensity aircraft warning lights, and they cannot be erected in inflight corridors close to airfields.

7.2.6. Site Selection and Logistics Considerations

A meteorology mast can generally be shipped in a single 20-ft container. The measurement consultant running the mast installation program can generally do the verification of road conditions.

If a site is being considered for a wind farm, it is best practice to do a logistics study in advance of final site selection in order to ensure that the generally very large and heavy wind turbine equipment can be transported to the site. This usually involves hiring a logistics (road haulage) firm that can drive from the nearest port and document and do cost estimates for overcoming whatever obstacles may occur on the way to the site, be it narrow road bends, road signs, underpasses, electrical wiring, bridge load limits, inclines, long and wide load transport legal restrictions etc.

7.2.7. Duration of Measurement Program: Preferably at least 24 Months – and Leave Mast in Place

Wind speeds vary from year to year in any given location, and it is indeed one of the purposes of the mesoscale modeling to estimate the variability of the wind resources in different areas within the geographical modeling domain. If we measure less than 12 months on a site, measurements will be biased compared to the long-term mean, simply because wind speeds almost everywhere are seasonal. Measuring for 12 months may (if we are unlucky) give results which are 20% away from the true long-term wean wind speeds. The annual standard deviation of wind speeds is often around 5-8% . Measuring for 24 months will reduce the year-to-year uncertainty, but of course not eliminate it.

The preferred strategy is to leave the meteorology mast in place, in principle indefinitely, in order to be able to do a (statistically speaking) stronger validation after having measured for several years. If the instrumentation and the structure are maintained correctly such long-terms measurements are also extremely valuable for later use to recalibrate nearby on-site <u>concurrent</u> measurements for a nearby wind farm. In fact, the value of such reference data to increase precision of long-term estimates for wind resources nearby can cut development time and/or reduce risk of wind power projects <u>more</u> than additional years of on-site measurements would. This should be kept in mind at the planning phase, since resources need to be allocated for continued maintenance. Section 7.2.1 explains how concurrent measurements from exiting masts are used to develop wind farms in other locations than the site used for validation.

> ***Why keep measuring after two years?***
>
> The standard way the wind industry attempts to correct wind measurements for year-to-year variations is to use long-term measurements from a nearby meteorology station to recalibrate the measured data to an average wind year. Particularly in developing countries this technique is fraught with difficulties, however. Usually there are no nearby meteorology stations, and »nearby« in highly complex terrain such as mountain regions quite literally means within a few km, at the most. (Wind climates may be very different on two different sides of a mountain range). For this type of reference measurement it is less critical if the local measurements are highly accurate, what matters are the year-to-year variations. Another difficulty may be that instruments are poorly maintained locally. Anemometer bearings wear down over time, and low-cost anemometers do not even have ball bearings. Other difficulties may be that the reference mast has been moved or that it is very short and surrounded by wind-shading trees or bushes that have grown or been removed, thus introducing spurious changes in the measured values.

7.2.8. Data Validation, Data Communications Strategy, Operation and Maintenance, Spare parts

Any measurement equipment, even high-quality instruments are prone to fail. Equipment such as solar panels used to power the instruments may be stolen or vandalized. Data loggers may stall and stop functioning temporarily, etc.

It is essential to get a complete dataset from a meteorology mast with as high a data recovery rate as possible, at least 95% of data for the 8760h of a year should be available and valid, and the number of consecutive days of measurements lost should be kept as low as possible, preferably kept to only a handful of days during a year.

In order to be able to do unscheduled service calls at a meteorology mast it is essential to transmit data on a daily basis, preferably through automatic upload to a central database via the internet. This can be done cheaply by using cellular data communication, if there is reliable GSM coverage on the site. If there is no such coverage, satellite communication is a more expensive option, though still affordable compared to the overall price of a properly equipped meteorology mast and its operation and maintenance. Standard software should be run automatically on a daily basis to check for missing or erroneous data and calibration drift of the instruments.

In case communications with a mast is lost, it is essential that a service technician can be available to be at the mast within at the most a few days. It is also essential that spare parts be available, e.g. extra anemometers and wind vanes and at least one data logger per country.

Missing data from short periods can be reconstructed using data from other anemometers at the same or different levels, but if there is a failure of the data logger (or its power supply) no data will be collected.

If a meteorology mast is particularly remotely located it is an advantage to have extra redundancy of instruments, e.g. to measure wind at all levels with two anemometers, on a boom on either side of the mast, like the configuration at the top level of the mast as shown in section 7.2.11.

Meteorology masts typically require scheduled maintenance every 3 months. Such maintenance consists of visual inspection of the mast to check that all instruments seem to be operating, that booms are not sagging, i.e. that anemometers and wind vanes are completely vertically adjusted. Such checks will also include a verification of the data logger settings, notably the clock setting of the logger. (It is preferred to use data loggers, which at least daily synchronize with a time-server on the internet). Finally, guy wire tensioning should be checked and adjusted in accordance with the mast manufacturer's specifications.

7.2.9. Meteorology Mast Height: 80m or More Preferred (Best: Wind Turbine Hub Height)

The impact of microscale effects such as surface roughness changes, orographic speedup or slowdown effects and local wind obstacles generally decrease significantly by height above ground level, as illustrated in section 2. In order to improve the quality and statistical strength of validation measurements it is therefore valuable to use as tall masts as economically feasible to validation measurements.

Meteorology masts come in two types:

1. *Tubular towers* supported by guy wires that can be raised without cranes using a winch system. Heights for such masts are limited to some 40-50m. They are the least expensive to buy and erect, but they have the important drawback that it is not possible to exchange the instruments for repairs (e.g. for recalibration, which needs to be done every 2 years) without taking the mast down again, which in itself is costly. For all practical purposes their technical and economic longevity may be considered some two years.
2. *Narrow, low porosity lattice towers* supported by guy wires, that can be erected without external cranes, but using a climbing winch for hoisting addition tower sections on top of the tower as it is being erected. Such towers are climbable, and instruments can be replaced without taking the tower down. They can have a certified technical and economic longevity of 25 years, if properly installed with adequate foundations and regular maintenance (correct guy wire tensioning). Typical height for this type of tower is 60-90m. For economic/technical tradeoff reasons, generally 80m is the preferred height for this type of tower.

Since both types of towers use guy wires, they require reasonably flat terrain for a footprint slightly larger than the height of the tower. Otherwise guy wires of different lengths may pose stability problems.

7.2.10. Instrumentation Required: First Class Anemometers and Wind Vanes

Meteorology masts used for wind resource assessment require high-quality, high-precision calibrated scientific-class instruments, which are mounted in accordance with industry standards.

For anemometers and wind vanes this means that the instruments have to comply with the latest edition of the IEC/ISO-61400-12 standard and the MEASNET recommendations, and the instruments have to be classified as First Class instruments. [61] They have to be calibrated in accordance with the MEASNET recommendations by a laboratory authorized to do so by a recognized accreditation body). It is recommended only to allow First Class instruments equivalent to WINDSENSOR (formerly RISO), VECTOR, THIES First Class, or THIES First Class Advanced[62]. It is required that any alternative instruments' classification meets or exceeds these instruments for both class A and class B classification.

The cost savings by ordering cheaper instruments are too small to consider, given the data quality problems that may arise otherwise, and taking into account the overall costs for a properly executed measurement program. If these standards are adhered to and – equally important – the instruments are mounted correctly, then the uncertainty on the wind speed measurements can be kept within a range of about 1-2% in flat terrain. In complex terrain the uncertainties may be up to 8%. For complex terrain is of special importance to choose equipment with low uncertainty.

The major problems with lower quality anemometers is that they usually do not measure the horizontal wind vector correctly if the wind flow is non-horizontal, the instruments may be subject to over-speeding, which biases their measurements, and their (lack of) bearings may mean that they have an overall poor performance.

Wind vanes shall be calibrated by an accredited laboratory and, even more importantly, be correctly north aligned. It is very important to document during the installation of the wind vane if the vane has been aligned to true or to magnetic north as the difference between both can be up to 30° depending on where the mast is installed. The dead band of the wind vane should be facing the mast.[63]An additional advantage by buying high-quality instruments is that they are built to last, and it is economic to refurbish them with new bearings and recalibrate them again after 2 years. (It is generally most economic to buy another set of instruments (or have the exchanged by the vendor with equivalently refurbished instruments) when they are to be refurbished and recalibrated for the first time. This way the exchange of instruments can be done most economically during a single service visit to a mast.

A final note on this issue: When bankers decide on the uncertainty of the wind energy yield of a project, they tend to be quite conservative, and will often downgrade a project to be financed of the basis of P90 rather than P95 yields. Using less than top quality instrumentation mounted in accordance with IEA standards and MEASNET recommendations will cost developers millions over the lifetime of a project, compared to the extra cost of such instruments which runs into a few thousand dollars.

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[61] The most important reference documents are: (IEA 2000), (Measnet 2016), (Measnet Undated), (IEC, International Standard u.d.)

[62] The word "advanced" is not part of the classification name; in this case it refers to the addition of a horizontal shield that ensures proper performance of the instrument for non-horizontal wind inflow angles.

[63] These details may seem highly technical, but they are key to getting accurate wind measurements. Wind measurement projects may be useless, unless this best practice is followed.

7.2.11. Instrument Mounting Requirements

Wind speeds are measured at multiple heights in order to measure *wind shear* and its variation with *atmospheric stability*. Wind directions are usually measured at two heights for the same reasons, as is air temperature. Finally, instrumentations should include high-quality sensors for barometric pressure and humidity near hub height.

It is just as important that instrumentation is mounted in accordance with the IEC-61400-12 standard as having the recommended instruments. Only a single brand and model of instruments should be mounted in the same vertical column in order to measure wind shear correctly. It is best practice to use <u>two</u> brands of anemometers when measuring at the top level of the mast in order to hedge against any systematic problems with one brand. Booms must be mounted perpendicularly to the expected prevailing wind direction on the site. The minimum distances and clearances for the mounting of instruments required in the IEC-61400-12-1 standard must be met or exceeded.

The final two sentences refer to the fact that the impact of the shading effects of the meteorology mast and instrument mounting booms on measurements may be quite significant. Depending on the porosity of the lattice tower the boom lengths requires are considerable (up to some eight times the width of the mast) as are the mounting clearances for anemometers vertically (fifteen times the boom diameter). In addition, booms need to be sufficiently rigid to avoid vibrations, instruments must be aligned perfectly vertically, vertical distances between booms / instruments or aviation lights mounted on the mast must exceed 2m.

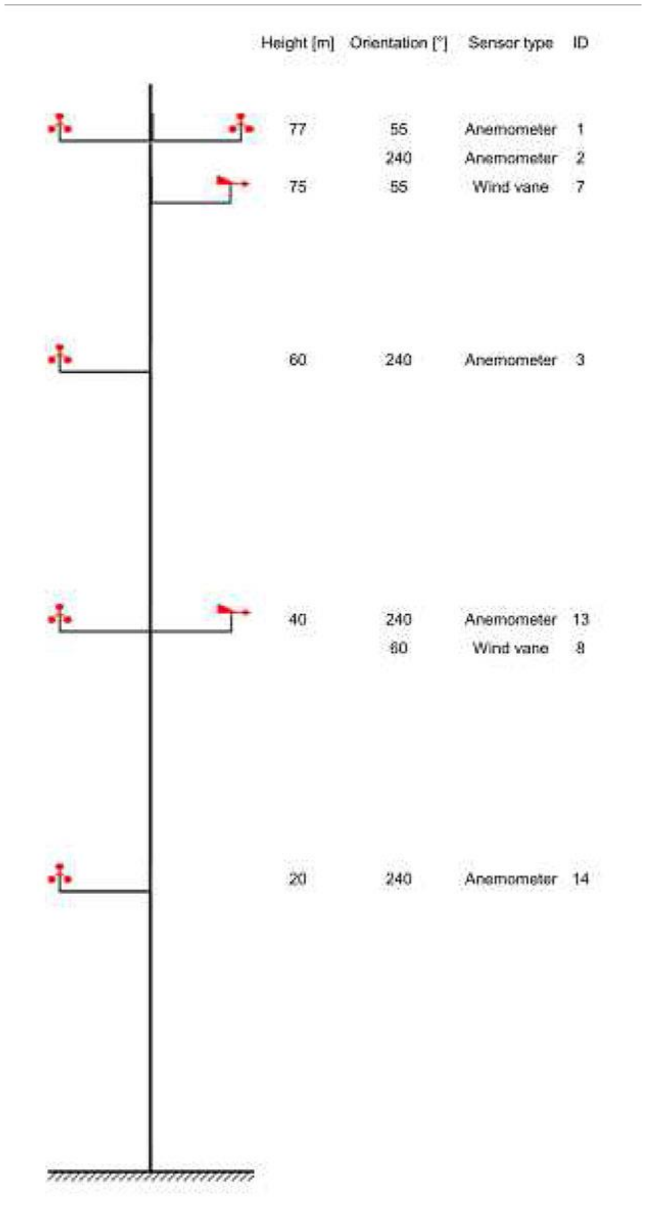

Figure 23. Typical measurements heights on 80m mast (Version with special lighting protection at 80m) (Source: 3E Wind Consultants)

7.2.12. Measurement Program Documentation Requirements

Experience shows, that one of the biggest problems in wind measurement programs is inadequate documentation. Without proper documentation data collection can be worthless.

It is oftentimes seen that even the precise geographical location of where measurements were taken are missing from the documentation of a measurement program, or even that all documents are missing except the data files themselves, which makes the data useless.

7.3. Wind Resource Measurement Reporting

It may be useful to have a first set of reports from each site after 12 months, to check that the measurement program is being operated satisfactorily. Since the format of the reporting done after 24 months will be identical, the added cost of also doing a 12-month report should be moderate.

7.4. Mesoscale Model Validation Reporting

It is useful to have a thorough analysis of the deviations between what was measured and what was modeled.

7.5. Mesoscale Modeling Adjustments

The validation of mesoscale modeling may reveal weaknesses in the modeling setup that lead to biased results. It may also be the case that the 10-year period deviates from the 30 year mean climate, and that the modeling needs to be readjusted accordingly. At this stage it is permissible and desirable that the consultants do whatever modifications, (say, adjustment of surface roughness lookup tables), that may improve the quality of the mesoscale modeling, but as mentioned in section 1.2.3, but ***it is not permissible to recalibrate the model to fit with the measured data (e.g. using some type of regression analysis or similar techniques), since that will render it impossible to validate the model through subsequent measurements, and it will eliminate the possibility of obtaining any estimate of the uncertainty of the modeling. Recalibration will also give the model a short shelf life.***

The final mesoscale modeling outputs for the countrywide wind atlas can then be produced, as well as the (100m) *microscale modeling* outlined in section 6.

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