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Published in:
Proceedings of Wind Power Shanghai 2007

Publication date:
2007

Document Version
Publisher's PDF, also known as Version of record

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Citation (APA):
Hansen, J. C., Mortensen, N. G., Badger, J., Clausen, N-E., & Hummelshøj, P. (2007). Opportunities for wind resource assessment using both numerical and observational wind atlases - modelling, verification and application. In Proceedings of Wind Power Shanghai 2007 (pp. 320-330). Shanghai: Chinese Renewable Energy Industry Association.

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Opportunities for wind resource assessment using both numerical and observational wind atlases - modelling, verification and application

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Abstract This paper presents an updated state-of-the-art recommended approach to wind resource assessment, which employs both mesoscale modelling, measurements and microscale modelling. Results of such an approach are primarily a Numerical Wind Atlas and an Observational Wind Atlas, which have been compared and verified using measurements. The application in wind farm project planning and preparation is discussed with an emphasis on application of the Numerical Wind Atlas.

Keywords Wind resource assessment, wind atlas, measurements, wind farm, project planning, energy production estimation, mesoscale modelling, microscale modelling

Introduction

The wind atlas methodology was developed in the 80's and used initially for creation of the European Wind Atlas [1]. The wind resource assessment started the work to develop the microscale flow model, WAsP, conceived and developed at Risø National Laboratory [2]. WAsP did what we now call an observational wind atlas as described below. During the 90's techniques to employ mesoscale models were developed, which made it possible to model larger domains, mesoscale effects, and long-term wind climates [3]. Recently, the techniques have been combined for development of wind atlases in countries with scarcity of measurement stations and consistent verification against comparable values has proven effective. This paper is a brief overview of the updated state-of-the-art of the wind atlas methodology for wind resource assessment as illustrated in Figure 1.

Mesoscale	Pre-processing Wind classes Terrain elevation Terrain roughness Input specifications Model setup	Modelling KAMM WRF MC2 MM5 etc.	Post-processing Predicted wind climate Regional wind climate Predicted wind resource for selected terrain site coordinates	Numerical WA Mesoscale maps Database WAsP *.LIB files Uncertainties Parameters
Measurements	Met. stations Siting Design Construction Installation Operation	Wind data Data collection Quality control Wind database Wind statistics Observed wind climate	Verification Meso- and microscale results vs. measured data Adjust model and model parameters to fit data Satellite imagery (offshore sites only)	Applications Best practices Courses and training Microscale flow model Wind farm wake model ⇒ Wind farm AEP
Microscale	Pre-processing Wind speed distributions Wind direction distribution Terrain elevation Terrain roughness Sheltering obstacles	Modelling WAsP MS-Micro CFD-models etc.	Post-processing Regional wind climate Predicted wind climate Predicted wind resource for selected terrain site coordinates	Observational WA Microscale maps Database WAsP *.LIB files Uncertainties Parameters

Figure 1. Wind atlas methodologies use wind measurements, as well as microscale and mesoscale modelling for wind resource assessment and siting.

Observational wind atlas

As the name implies, an *observational wind atlas* is based on observed wind climates from a dense network of meteorological stations. The observed wind climates contain the wind speed and direction distributions derived from long-term time-series of wind speed and direction measurements at the meteorological stations.

The observed wind climates are thus representative for specific locations and heights above ground level, so in order to be able to predict the wind climate at a given wind turbine or wind farm site the observed wind climates must be transformed into generalised *regional wind climates*. This may be done using the wind atlas methodology of the European Wind Atlas [1], see Figure 2.

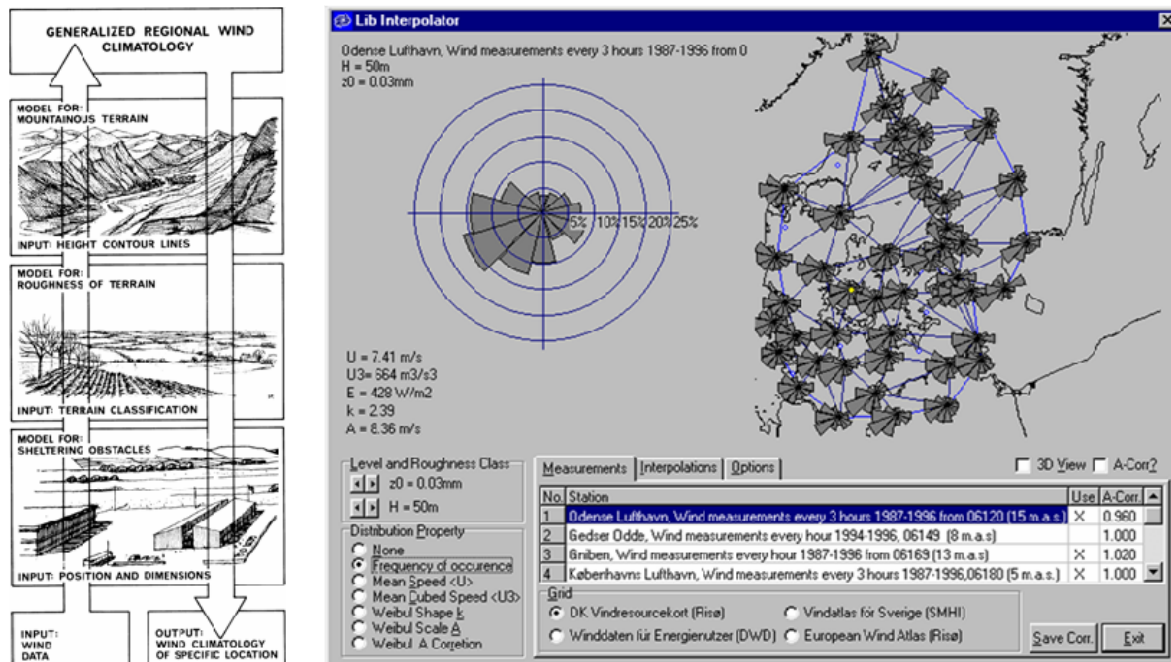


Figure 2. The wind atlas methodology (left) and the observational Wind Atlas for Denmark (right). The wind roses are located at the positions of the meteorological stations used for the atlas.

Employing detailed descriptions of terrain elevation, land-use and the occurrence of sheltering obstacles around each meteorological station, the observed wind climate is transformed into what would have been measured at the location of the station if the surroundings were completely flat, featureless and with a homogeneous surface and the measurements had been taken at 10, 25, 50, 100 and 200 m a.g.l. Through this transformation procedure, the observed wind climate is freed from the influence of local topography to become *regionally representative*.

The results in an observational wind atlas are given in the form of detailed statistics of the generalized wind speed and direction distributions for the locations of the meteorological stations. These data sets can then be used as inputs to the application process, whereby the same models are used in reverse to transform the regional wind climate to the *predicted wind climate* at any specific site and height. For this procedure to be applicable to all sites, the density of meteorological stations must be high, say, from one station per 100-10000 km² for national and regional applications to one station per 1-10 km² for detailed wind farm work.

Mesoscale numerical wind atlas methodology

Numerical wind atlas methodologies have been devised to solve the issue of insufficient wind measurements, which render wind resource mapping efforts through observational methodologies problematic. One such methodology is the KAMM/WAsP method developed at Risø National Laboratory [3]. In this methodology an approach called statistical-dynamical downscaling is used [4]. The basis for the method is that there is a robust relationship between meteorological situations at the large-scale and meteorological situations at the small-scale. Information about the large-scale meteorological situation is freely available from the NCEP/NCAR reanalysis data-set, see [5]. This data-set has been created by assimilating measurement data from around the globe in a consistent fashion from 1948 to the present day. Typically, a 30-year period of NCEP/NCAR data is used to create approximately 150 different large-scale wind situations, called wind classes, that represent the large-scale wind climate. In order to make these wind classes meaningful at a smaller scale, a mesoscale model is used to find out how the large-scale wind forcing is modified by regional scale topography. Therefore for each wind class a mesoscale model simulation is performed using the Karlsruhe Atmospheric Mesoscale Model [6]. Typically the domain size is 500 km × 500 km in the horizontal, 6 km in the vertical. Figure 3 shows a schematic diagram illustrating how the mesoscale modelling results are combined to give wind climates in the numerical wind atlas system.

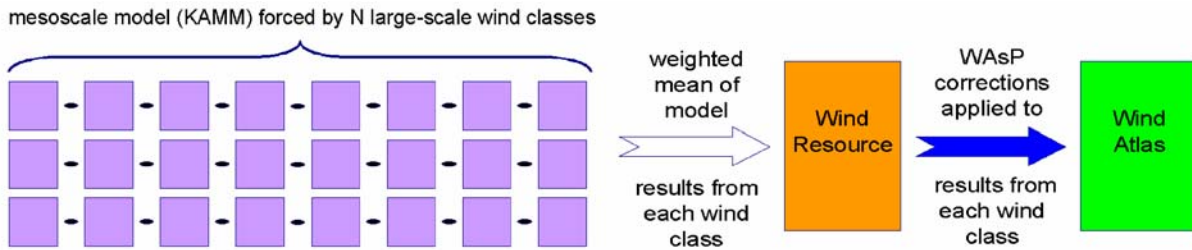


Figure 3: Schematic showing the numerical wind atlas methodology. The mesoscale model, KAMM, is used to create a wind map for N, typically 150, different atmospheric conditions, called wind classes, representing the climate of the region. The results are combined by taking into account the frequency of occurrence of each wind class, to create a wind resource map. The wind maps can be also transformed to standard conditions to create a wind atlas map.

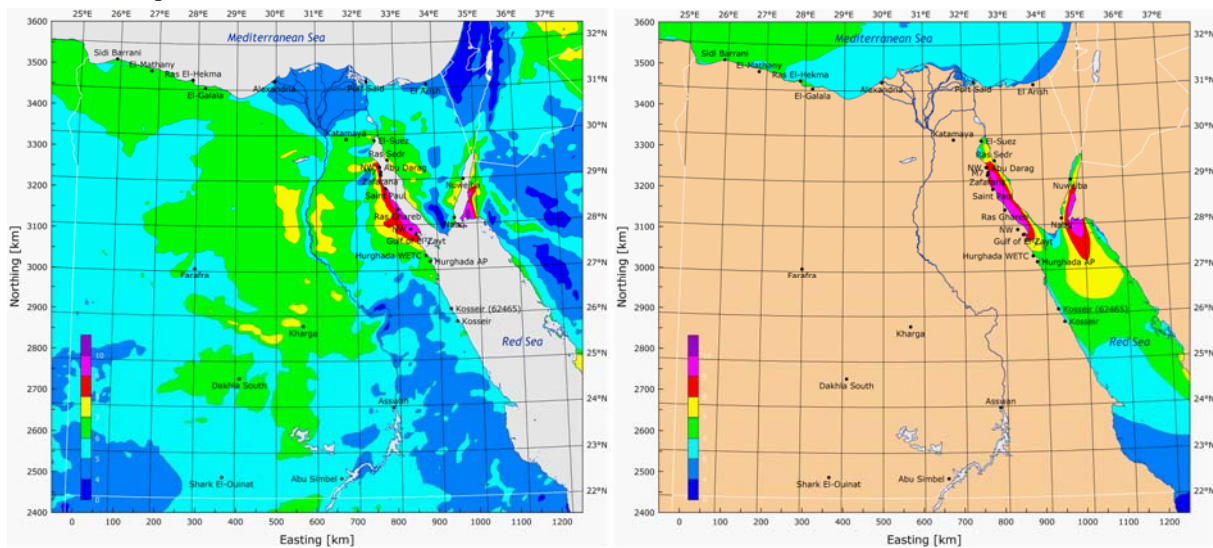


Figure 4: The wind resource map for Egypt giving the wind at 50 m above ground level for land and offshore areas at 7.5 km resolution. Four smaller domains covering different areas of interest were also used to create specific wind resource maps at higher resolution (5km).

The results of the mesoscale numerical wind atlas can be given in the form of maps of wind climate for conditions as they are represented in the mesoscale modelling, and as maps of wind climate for generalized conditions. For generalized conditions a conversion is carried out to give the wind for flat terrain and homogeneous roughness. Figure 4 shows the wind resource map for Egypt, taken from [7]. The results can also be given in the form of detailed statistics giving the generalized wind speed and direction distributions for any location within the calculation domain for a set of standard heights above ground level. This information is given in a file format that is directly compatible with the WAsP software [2].

Verification

The value of a wind resource assessment is increased significantly if it can be shown to be a true reflection of the actual wind resource. The process of verification aims to evaluate the uncertainty of an estimate of wind resource, whether based on the observational wind atlas or the mesoscale numerical wind atlas methodologies. Central to the verification process is the principle that a proper comparison of wind characteristics is being made. As examples: just as it makes little sense to compare a mean wind measured at 25 m a.g.l. with a mean wind measured at 80 m a.g.l., even at the same location, *without* accounting for a vertical wind profile, it makes little sense to compare a mean wind measured at a lakeside with a mean wind measured in a semi-urban area, *without* accounting for the effect of surface roughness. Similarly for measurements made on top of a hill the orographic speed up effects must be accounted for. Accounting for these kinds of effects is the backbone of the wind atlas methodology and the models within the WAsP software [2]. Therefore only wind climates transformed to standard conditions can be compared, i.e. winds at standard heights over flat terrain with a single homogenous surface roughness.

This principle *must* also be used when comparing mesoscale modelling results to measurements, because the spatial representation of the terrain in the model is impacted by the spatial resolution, even at high resolutions. Roughness conditions varying on a scale smaller than the grid scale will not be represented. Sharp or steep surface elevation features will tend to be smoothed and rounded by the grid scale representation. Therefore the

wind climate given by a particular grid cell of a model cannot be directly compared to a measured wind in the vicinity of the same grid cell. The necessary step is to transform the model winds to standard conditions to account for the effects of the roughness and orography as represented in the mesoscale model to provide the winds for mean flat terrain with a single homogenous surface roughness.

A number of high quality and well distributed wind measurement stations are still needed to validate the model output as described above in a given geographical area. A chain of carefully executed and well documented activities are needed to provide these locally measured data. The same careful approach is needed regarding the use and interpretation of externally measured wind data.

Figure 5(a) shows the wind speed distribution derived from the KAMM/WAsP numerical Wind Atlas for Egypt [7] for Dakhla (South), where a wind measurement station is also located. Figure 5(b) shows the generalized wind speed distribution derived from the wind measurements. Comparison of wind speed and direction distributions derived from both numerical wind atlases and measurement is a fundamental part of the verification and quality assessment of a numerical wind atlas study. By comparing wind climates based on modelling and measurements for several wind measurement stations, an assessment of the uncertainty of the modelling based estimate can be made. Figure 5(c) shows modelling- and measurement-derived generalized mean wind speeds for measurement stations in the Western Desert region of Egypt. For this region the mean absolute error on the wind speed was found to be 3.1 % [7].

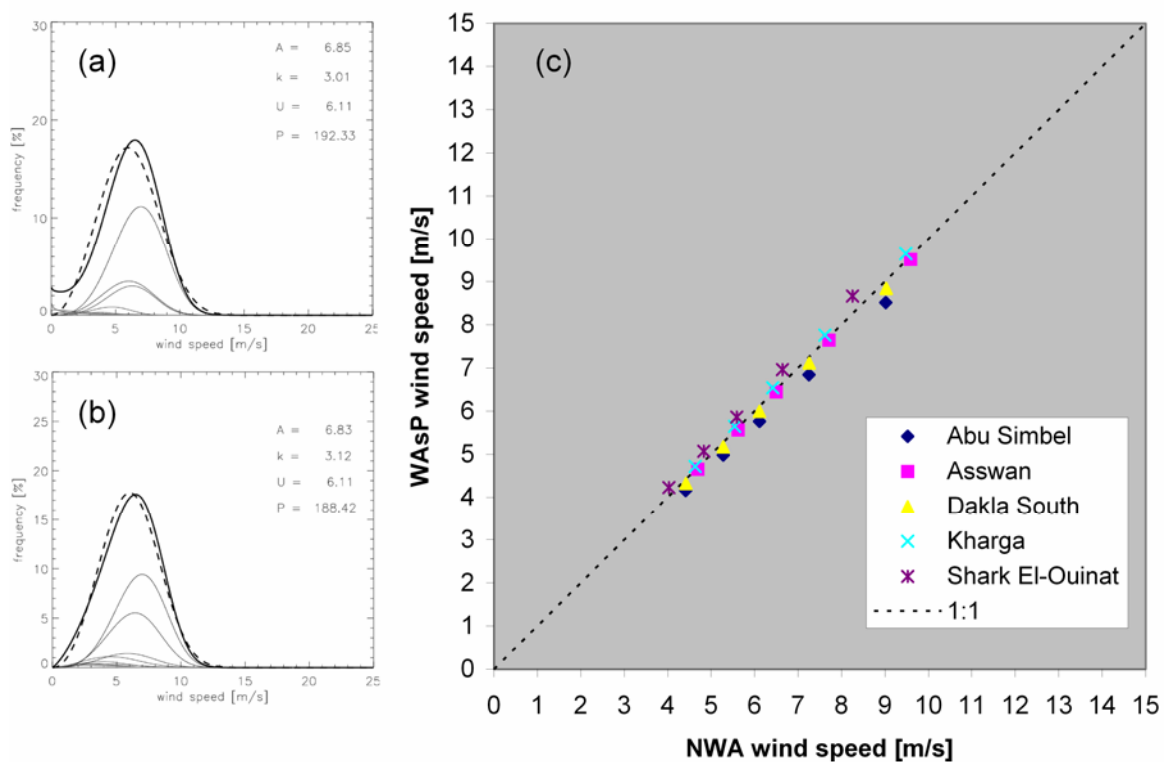


Figure 5: The generalized wind speed distributions for Dakhla (South), Egypt, from (a) the numerical wind atlas (b) from observations. In (c) a scatter plot showing the mean generalized wind speed at different heights derived from observations (y-axis) and from the numerical wind atlas (x-axis) is given for 5 wind measurement stations. The generalized conditions are flat terrain with 0.03 m roughness. In (a) and (b) the bold solid line shows the distribution for all sectors, based on summing the sectorwise distributions (fine solid lines). The dashed line shows the best fit of the Weibull distribution using the all sector mean wind speed and mean cube of wind speed.

Application in wind farm projects

Wind resource assessment is applied for determination of wind conditions and energy production estimation for many purposes, including physical planning (national, regional or local), wind farm siting, project development, wind farm layout design, micrositing and wind farm performance verification.

The various purposes require coverage and modelling of different size geographical domains and different levels of accuracy. However, the extended wind atlas method employing both the numerical wind atlas method and the observational wind atlas method verified against measurements offer opportunities to serve all purposes; basically by applying the same methodology just through employing higher or lower resolution of data and modelling together with well planned dedicated measurement programmes. Implementation may then be planned

with a successive refinement of resolution for the regions and areas of interest for wind farm development. An overview of the extended wind atlas approach applied for the different purposes is given in Table 1, indicating the model type, scale, resolution and data needed as well as typical uncertainty level to be expected.

	National planning	Regional planning	Wind farm siting	Wind farm layout and micro siting
Model – type	Mesoscale	Mesoscale	Meso+Microscale	Meso+Microscale
Domain size	~500-1000 km	~100-500 km	~20-100 km	10-20 km
Map resolution	5-10 km	1-5 km	10-100 m	1-10 m
Wind data	NCEP/NCAR	NCEP/NCAR	NCEP/NCAR+ met stations	Dedicated met stations
Verification	Repr. met stations	Repr. met stations	Dedicated met stations	Dedicated met stations
Uncertainty on mean wind speed	10-30%	10-20%	5-15%	1-5%

Table 1 Brief overview of model type, domain size, map resolution, wind data needed and uncertainty level to be expected for the various purposes for which wind resource assessment is made using the wind atlas method.

Figure 6 is an illustration from a location at the Gulf of Suez in Egypt, showing how mesoscale and microscale models resolve different features of the terrain and how they are useful in the different phases of planning and project preparation as indicated in Table 1. Furthermore, it is seen that mesoscale modelling has to be employed in order to enable assessment of the validity of the assumptions used for microscale modelling. In Figure 6 it is seen that the wind farm site may include an area with a large regional wind climate gradient, which would violate the microscale modelling assumption that the regional wind climate is approximately constant over the microscale modelling domain. The mesoscale modelling may be used to identify locations with large gradients and thus locations where an extended measurement programme will be advisable in order to avoid gross errors in wind resource assessment.

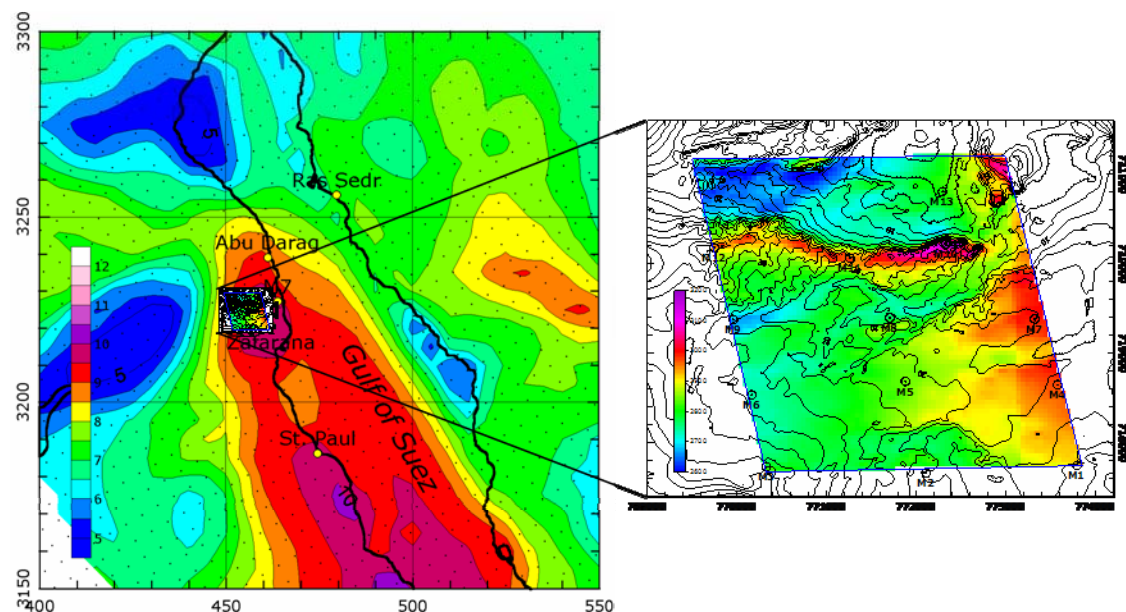


Figure 6 Mesoscale and microscale maps giving the mean annual wind speed as calculated by KAMM and WAsP, respectively, from Wind Atlas for Egypt [7]. Note that color scale are different in the two maps.

The terrain features that influence the wind flow close to the ground – and thereby determine how the regional wind climate is transformed into the site-specific wind resource – are often categorized in three broad classes:

- The geometry of the terrain surface (elevation, slope, complexity, ruggedness, etc.)
- The surface characteristics of the terrain (land use or roughness length)
- Near-by sheltering obstacles (houses, trees, shelter belts, etc.)

As an example, the detail in the elevation description influences the modelling of the wind flow and thereby the estimation of the annual energy production (AEP). In microscale modelling an increase in height contour

intervals from 2 to 10 m has been found to increase the contribution to uncertainties in AEP estimates by more than 5% - even in terrain with relatively little complexity or ruggedness. In more rugged, complex and mountainous terrain the uncertainty increases and the dependency on accuracy and resolution of terrain data increases. To test uncertainties associated with microscale and mesoscale flow modelling as well as with terrain data it is generally recommended to carry out

- model parameter studies and adaptation of models to local conditions
- sensitivity analyses, site calibration and verification against measurements

Other aspects to be considered are

- wind climate variability within the time-frame of the data collection and the planned projects
- inter-annual variations, long-term averages and climate change
- man-made large-scale effects on wind climate by changes in terrain and flow conditions due to the utilization of the land, especially building of new large wind farms and urbanisation

In general inter-annual variations relative to long-term averages are often seen to be of the order of 10% on mean wind speed. Wind climate variability differ however in different climate zones. For a site in the Wind Atlas for the Gulf of Suez, 1991-2001, the AEP of a wind turbine has been calculated to have an inter-annual variation of the yearly production as low as about $\pm 12\%$ from the long-term average during the 11-year period.

Longer-term wind data series that may be used to assess inter-annual variation and long-term averages are available from the NCEP/NCAR reanalysis data set, but any such dataset must be used with care in a wind power context. Global climate change modelling, rather than NCEP/NCAR reanalysis, may be valuable in the evaluation of impacts of global climate change on wind farm AEP – see e.g. [8].

Regarding man-made large-scale effects on wind climate, it should be noticed that the uncertainty due to any new large wind farm may be significant for its surroundings. Exact quantification is difficult, but up to 20% loss in energy production has been seen. This aspect is presently a subject for research, in particular related to off-shore applications. Results of this research will be relevant for all large wind farm projects and thereby also in planning phases when assessing the potential energy production from wind and the economics.

All in all it may be concluded that the mesoscale numerical wind atlas in combination with observational wind atlases offer new opportunities for doing planning on a large scale even with a limited availability of wind data from meteorological measurement stations. At wind farm sites and in project preparation it provides a consistent basis for verification of model results against each other and against measurements when employing the wind atlas method and together it may be applied with a view to reducing uncertainties. Evidently techniques may be improved through a continued research effort making use of the ever increasing computing power of new computers and new measurement technologies, mapping techniques and satellite imagery.

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