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# A DETAILED AND VERIFIED WIND RESOURCE ATLAS FOR DENMARK

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ABSTRACT: A detailed and reliable wind resource atlas covering the entire land area of Denmark has been established. Key words of the methodology are wind atlas analysis, interpolation of wind atlas data sets, automated generation of digital terrain descriptions and modelling of local wind climates. The atlas contains wind speed and direction distributions, as well as mean energy densities of the wind, for 12 sectors and four heights above ground level: 25, 45, 70 and 100 m. The spatial resolution is 200 meters in the horizontal. The atlas has been verified by comparison with actual wind turbine power productions from over 1200 turbines. More than 80% of these turbines were predicted to within 10%. The atlas will become available on CD-ROM and on the Internet.
Keywords: Wind Atlas, Terrain, Resource Mapping.

## 1. INTRODUCTION

Information on the actual wind resources of a region or an entire country is a prerequisite for the optimal utilisation of wind energy on a large scale. In the past, this information was often given as the wind resource potential, e.g. in the form of a 'wind atlas'. The wind atlas, however, does not provide directly the detailed information required for planning purposes and siting of large wind farms; it only forms the necessary basis for more detailed resource assessments. The purpose of the present work has been to establish a methodology whereby a detailed and reliable 'wind resource atlas' can be constructed for a not-too-complex terrain, and the approach is illustrated and verified by a new wind resource atlas for Denmark.

The methodology can be described briefly as follows: Wind data from existing meteorological stations are first analysed using the wind atlas methodology, in order to determine the regional or site-independent wind climate at each station. The regional wind climate over Denmark can then be described and stations to be included in the analysis selected. Based on these stations, the regional wind climate (wind potential) can be mapped. An interpolation procedure for points between stations is also developed. The wind potential map is verified using measured power production figures from a large number of wind turbines. The actual wind climate and wind resources all over Denmark can now be modelled using the verified wind potential data as well as digital terrain descriptions of the entire country. Finally, these results are used to map the wind resources of Denmark.

## 2. DANISH WIND-MONITORING STATIONS

The meteorological basis for the wind resource atlas for Denmark is wind atlas data sets for about 24 stations, carefully chosen to represent all regions of Denmark, Fig. 1.

From each station, continuous wind speed and direction measurements in the period 1987–96 have been analysed. The observation intervals range from 10 minutes to 3 hours, but the averaging period for wind speed is 10 min. for all the stations. Wind directions are instantaneous readings or averaged over 10 min. The wind measurements describe the local or site-specific wind climate at each station – where wind climate is taken here to mean the frequency distributions of wind speed in a number of sectors (here 12) and the frequency distribution of wind direction in the same sectors (the wind rose). The wind atlas data sets, on the other hand, contain the regional or site-independent wind climate estimates, derived from the measurements using the wind atlas methodology.

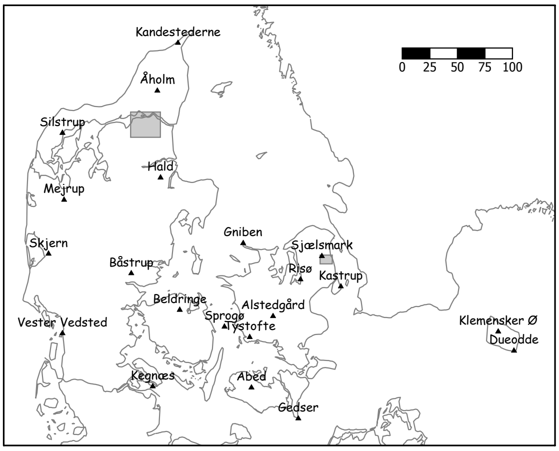


**Figure 1.** The Danish meteorological stations chosen for the wind atlas analysis. The stations are run by the Danish Meteorological Institute and Risø National Laboratory.

## 3. WIND ATLAS ANALYSES

The wind atlas methodology has been applied for the analysis of the wind measurements from the meteorological stations. This comprehensive set of models for the horizontal and vertical extrapolation of meteorological data and the estimation of wind resources was developed for the analysis presented in the European Wind Atlas [8, 5]. The actual implementation of the models is the Wind Atlas Analysis and Application Program (WAsP). The models take into account the effect of different surface conditions, sheltering effects due to buildings and other obstacles, and the modification of the wind imposed by the specific variations of the height of ground around the meteorological station in question. The analyses result in regional (site-independent) wind climates for the met. stations. The application part of the methodology is a procedure in which a regional wind climatology is used as input to the same models to produce site-specific wind climatologies and, given the power curve of a wind turbine, production estimates [8].

Accurate descriptions of each meteorological station and its surroundings were collected from maps and during field trips. The descriptions include details of the terrain roughness (water areas, forests etc.), of nearby sheltering obstacles (such as buildings) and of the terrain altitude variations (orography). Regional wind climatologies were subsequently calculated for the 24 wind atlas stations [4].

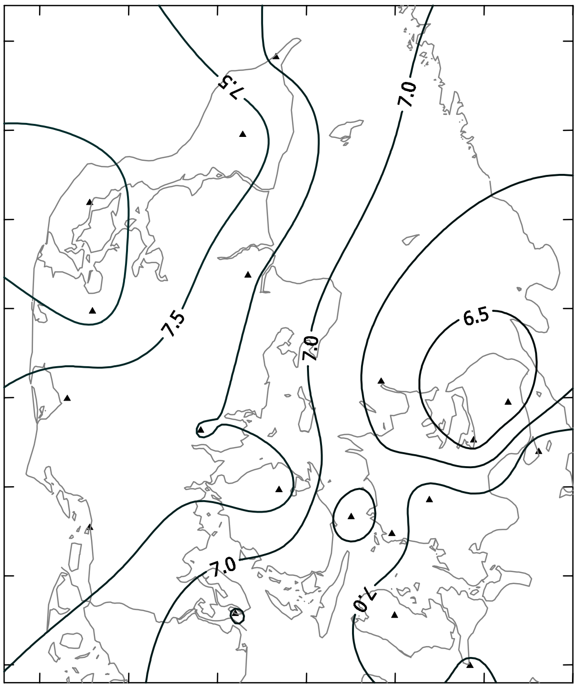


**Figure 2.** Mean wind speed 50 m a.g.l. in $ms^{-1}$ over a flat, uniform surface with $z_0 = 0.03$ m. The wind speed contour interval is 0.25 $ms^{-1}$. Distance between tick marks is 50 km.

## 4. REGIONAL WIND CLIMATE OF DENMARK

The collection of wind atlas data sets is a representation of the regional wind climate over Denmark. As an example, Fig. 2 shows the variation of the mean wind speed 50 meters above ground level over a flat, uniform surface with a roughness length $z_0$ of 0.03 m.

One meteorological station only, Bønsvig Strand in Fig. 1, was excluded from further analysis because the wind atlas data sets did not compare well with those of the neighbouring stations. Predictions based on data from this station also turned out to be very low when compared to power production data from near-by wind turbines.

The mean wind speed shown in Fig. 2 vary from about 8 $ms^{-1}$ in the NW part of Denmark to 6 $ms^{-1}$ in NE Zealand. It thus decreases from NW towards SE to a minimum around the Great Belt region and north Zealand, where after it increases towards the Baltic Sea. This picture of the magnitude and variation of the regional wind climate over Denmark is largely supported by similar data from Sweden [2] and Germany [7].

In order to be able to calculate the regional wind climate (not just the mean wind speed) for any place in Denmark, a continuous 'wind atlas surface' must be derived by spatial interpolation procedures for both the wind speed and direction distributions.

## 5. INTERPOLATION OF WIND ATLAS DATA

The starting point of any WAsP prediction is the Wind Atlas file describing the regional wind climate. Mapping the wind resource over a country will involve several regions and in order to avoid discontinuities we have to develop an interpolation routine. Setting up an interpolation scheme involves arbitrary choices, so perhaps it is worthwhile to review the objectives. We decide that:

- the interpolation must match the statistics of the measuring stations exactly
- the interpolation must be local, i.e. with emphasis on data from nearby stations
- the interpolation must work with an irregular mesh of data
- the interpolation must be as smooth as possible

The interpolation method implicitly assumes that the available data are of high quality and obtained in compatible sample periods, i.e. it does not intend to smooth extreme values or identify global trends in the data set. Corrections of the reference Wind Atlas files are best done from within the WAsP program, i.e. by improved description of the surface roughness and obstacle configuration around the measuring sites.

Wind Atlas files contain wind roses and probability distributions for wind speeds in each sector. The wind speed distributions are approximated by Weibull distributions, and the moments of the wind-speed distributions $\langle u \rangle$ and $\langle u^3 \rangle$ may be found from the Weibull parameters $A$ and $k$ and vice versa. These transformations allow us to interpolate directional distributions and the moments in the total wind-speed distribution independently.

The measuring stations are organised in a grid of triangles with local co-ordinate systems. The first step in the interpolation scheme is to identify the local triangle where the directional distributions and direction-independent $\langle u \rangle$ and $\langle u^3 \rangle$ statistics are known at the corners. The interpolation of $\langle u \rangle$ and $\langle u^3 \rangle$ is based on third-order Bézier polynomia which also require gradients at the measuring points in the corners the triangles. The common gradients ensure continuity between neighbouring Bézier patches and these gradients are settled by an algorithm which minimise the curvature of the interpolation surface. Directional interpolation is made by linear interpolation of Fourier transformations of the three reference distributions relative to a 'typical' wind rose orientation. This orientation is determined as the maximum of the Fourier spline rather than the maximum of the original wind-rose which has a crude directional resolution. Both shape and orientation are smoothly interpolated by this method.

The measuring stations were placed at inland locations and the interpolation grid does not cover all coastal areas. Straightforward extrapolation by the third-order Bézier patches produce large excursions so an alternative method have to be developed. The extrapolation method operates with values and gradients at two reference stations only.

The two reference stations and the interpolation point fix a second-order Bézier *curve*. This curve is formally interpreted as a third-order Bézier curve, with along-curve nodal gradients determined by projection. The parameters predicted by the extrapolation routine is a smooth extension of the interpolation surfaces and far-field extrapolation becomes more linear. The Bézier patches are defined only once whereas a new extrapolation has to be defined for every extrapolation point. Therefore extrapolation is computationally less efficient than interpolation.

The interpolation procedures have been implemented in a program which makes it possible to predict the wind atlas data sets for any site in Denmark. For the purpose of calculating the wind resource map, a number of stations in Germany and Sweden, where similar data exist, were included in the final analysis.

## 6. MODELLING OF LOCAL WIND CLIMATES

The site-specific wind climate of any place in Denmark can now be estimated using the application part of the WAsP program. The regional wind climate for a given site can be found using the interpolation procedures described above or the simpler one described below in Section 6.1. To account for the influences of local topography we further need digital terrain descriptions of the surrounding terrain. For an area of 43,000 $km^2$, it is not feasible to establish these 'by hand' – as was done in the analyses of the 24 meteorological stations – so an alternative approach had to be developed.

For the flow modelling, we have used a vector map of Denmark prepared by the National Survey and Cadastre. This map database contains height contour lines with 5-m vertical contour intervals for the entire country. The map has been established by hand digitisation as well as vectorisation of scanned contour map sheets. This database was reformatted into WAsP map files for direct application with the WAsP orographic flow model.

To account for the effects of the terrain roughness and roughness changes, a digital roughness map have been established from the land-use classification apparent in standard topographical maps. Map sheets with a scale of 1:50,000 were scanned and six layers of land use extracted: water areas, forests, cities and towns, tree groups, shelter belts and single houses. These layers were subsequently transformed into vector maps and analysed with respect to surface roughness.

Large water bodies, forests and cities are described as polygons and were simply assigned a roughness length. Small towns and forests, as well as tree groups, shelter belts and single houses were recorded and counted in sub-areas of 1 by 1 $km^2$. This registration was then used to assign 'background' roughness lengths for each of the sub-areas.

The polygons and background roughnesses were finally merged into several digital roughness maps in WAsP map format covering the entire country. Since the digital maps do not contain information on the size and height of single objects, modelling of the shelter effects from houses and shelter belts had to be abandoned. This is a minor problem, since most of the wind turbines are sited in the open landscape. The sheltering obstacles are therefore only treated as roughness elements in the analyses.

### 6.1 Modelling considerations

In the modelling of site-specific wind climates, two approaches have been tried. One is to employ the wind atlas data sets from one station located centrally in Denmark (here Beldringe on the island of Funen) together with a site-specific correction based on previously measured power productions from a large number (~200) of wind turbines. This approach is feasible in Denmark, because of the large number of turbine installations. The second, and presumably more correct approach, is the one outlined above, where the 'local' regional wind climate is determined from the three nearest met. stations. However, since we verify the methodology against actual wind turbine productions and we further aim at establishing a wind resource map suitable for production estimations, it is not obvious which approach will provide the most accurate results. The experience obtained so far suggests that accurate results may be obtained using the former, simple approach; whereas the second approach seems to be very sensitive to especially the measured wind roses at the reference stations. The results reported below are based on the former, simple approach.

## 7. VERIFICATION OF THE METHODOLOGY

In order to verify the regional wind climate interpolations, the digital terrain maps and the methodology in general, we have compared predictions of wind turbine power productions with actually measured productions. For this purpose, more than 1200 wind turbines all over Denmark were selected. The selection criteria included availability and quality of production data, minimum size of wind turbine (75 kW) and documentation of turbine history and performance. The power curves for the different turbine types were extensively checked and production data were further referenced to a normal wind year. For turbines in wind farms a simplified park efficiency correction was applied, based on the actual efficiencies of a number of wind farms.

Since there are several more or less 'unknowns' in the final modelling and verification process, this was done by iteration. In this process, errors in the different input data files were identified and corrected and the interpretation and transformation of land-use data to roughness maps were calibrated and made consistent. The main results of the verification are shown in the table below.

**Table 1**. Distribution of verification wind turbines according to prediction error, expressed here as $P_e/P_m$ in [%].

| $P_e/P_m \times 100$ [%] | Number of WT | [%] |
|---|---|---|
| 90 – 110 | 979 | 81 |
| > 110 | 93 | 8 |
| < 90 | 137 | 11 |
| Total | 1209 | 100 |

The estimated power productions, $P_e$, from more than 80% of the 1200+ control turbines thus fall within ±10% of the measured productions, $P_m$. For about 25 turbines, the difference between predicted and measured production is larger than 20%. These 'out-liers', which are located randomly all over Denmark, can in most cases be explained by severe local shelter effects not accounted for in the modelling, by errors in the digital terrain height map or by errors in the production data.

## 8. WIND RESOURCE MAP OF DENMARK

The wind resources over the land area of Denmark can now be estimated in the following way: the actual wind resource in grid points with a regular spacing of 200 m are calculated by the WAsP program for several heights above the ground surface: 25, 45, 70 and 100 m. Inputs are the wind atlas climatology from Beldringe and the WAsP terrain descriptions derived from existing databases of terrain orography and land-use. For each calculation point, the program uses terrain height information to at least 5 km from the site and a roughness map covering an area with a radius of at least 20 km. The wind climate and power production estimates are corrected as described above (6.1). The wind resource atlas (database) contains information on the wind speed and direction distributions in 12 sectors, as well as the mean energy density. As an example, Fig. 3 shows an energy density map of the southern part of the municipality of Aalborg in Jutland.

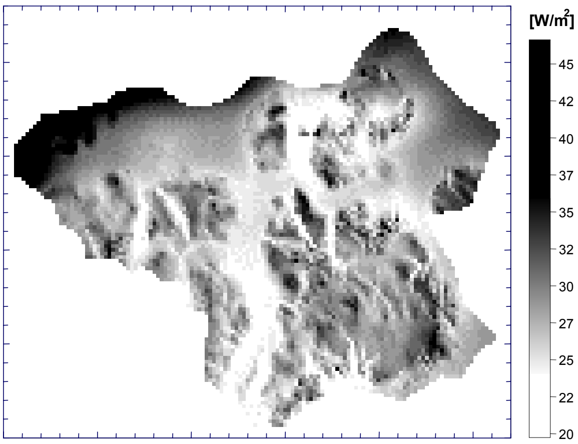


**Figure 3**. Mean wind energy density in $Wm^{-2}$ 45 m a.g.l. over the southern part of the municipality of Aalborg, Jutland, see Fig. 1. Results are shown with a horizontal resolution of 200 m. Distance between tick marks is 1 km.

Given a specific power curve, it is also possible to display directly the estimated power production for an area, an example of this is given in Fig. 4.

The wind resource atlas for Denmark is not published (yet) as a paper map. The results will be stored and distributed on a CD-ROM, together with software for retrieval, display, printing and export of the data to several common file formats. In addition, the CD-ROM contains a number of actual or generalised wind turbine power curves, in order for the user to be able to estimate actual power productions. An Internet version of the resource map is also in the making and will be made available at www.emd.dk.

## 9. CONCLUSIONS

The wind resource atlas for Denmark provides a detailed, reliable and coherent database of the variation and magnitude of the wind resource over Denmark. It can be used by planners on all levels of society to ensure a systematic and efficient planning process, whereby the available sites are used efficiently to optimise the power production. The export facility makes it straightforward to e.g. establish layers in common GIS-systems for certain heights and turbine types. However, given the detail and flexibility of the outputs, also private persons, organisations and wind turbine manufacturers may use the atlas for preliminary siting and power production estimation. Final siting, layout considerations and project feasibility, however, should not be based solely on the wind resource atlas.

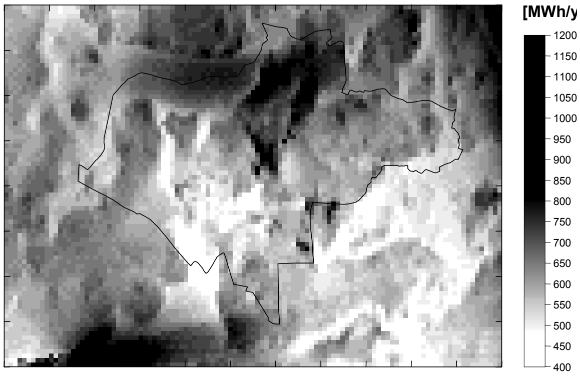


**Figure 4**. Expected mean power production from a 600-kW wind turbine with a hub height of 40.5 m in the municipality (full line) of Birkerød, Zealand, see Fig. 1. Results are shown with a resolution of 100 m.

The methodology can be used to establish similar wind resource atlases for other regions where reliable wind climatologies and topographical databases exist, and where the terrain in general is not too complex. In mountainous regions, or regions with a more complex wind climatology, the regional wind climate should be determined using meso-scale models [1, 6].

## ACKNOWLEDGEMENTS

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