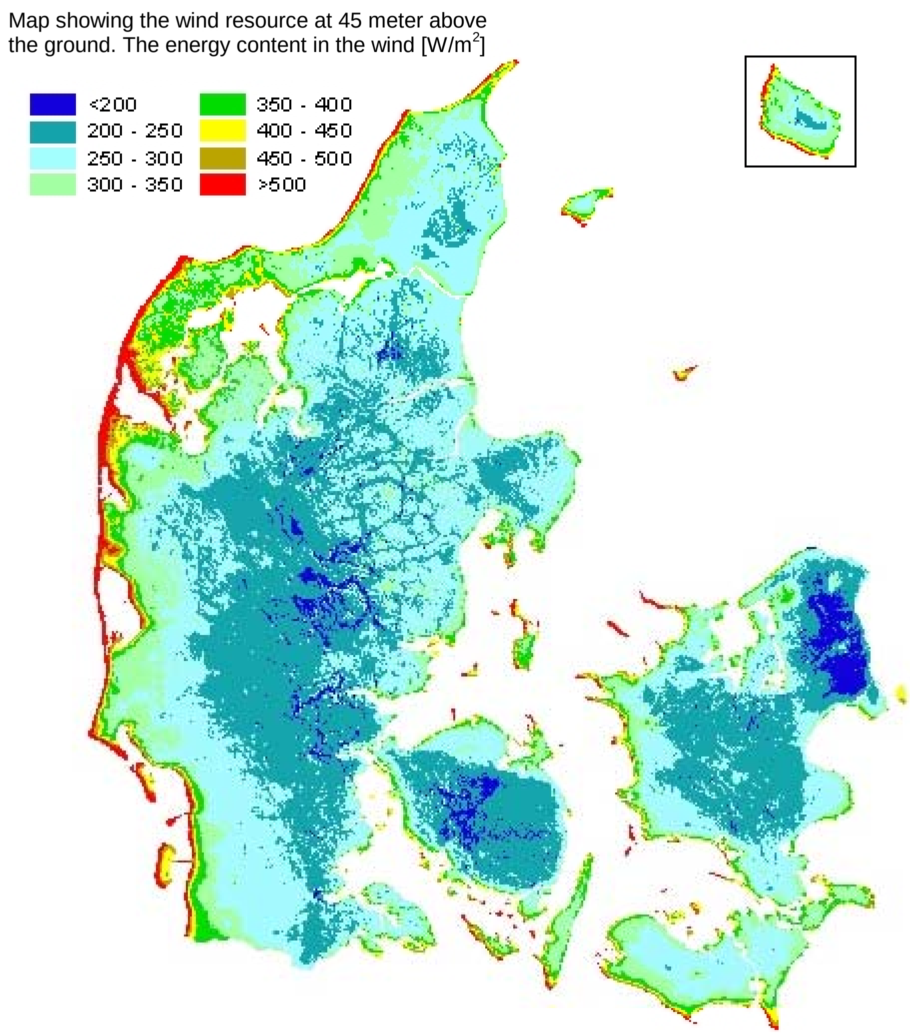
Danish Wind Resource Map

with data export to GIS-format



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Introduction

In 1999 Energi- og Miljødata (EMD) and Risø National Laboratory completed a detailed mapping of the Danish Wind Resource. The analysis was performed using a 200x200 m^2 quadratic calculation grid. The calculations were verified using production data from more than 1200 existing wind turbines. These existing turbines are fairly equally distributed around the country. This new and detailed analysis is reported in [1], and the data can be downloaded from www.emd.dk. Due to the increasing demand for detailed planning and projecting, different parties – especially local counties and municipalities – have expressed a need for transferring the data to common GIS-formats. This task has now been completed with the release of the computer program '*Resource Mapper 1.2'*.

The project was funded with support from the Danish Energy Agency through the *Udviklingsprogram for Vedvarende Energi (the Development Program for Renewable Energy)*, UVE j.nr 51171/00-004. All data are calculated using the EMD software WindPRO (www.emd.dk/windpro) and the software from Risø WAsP (www.wasp.dk).

The program '*Resource Mapper 1.2'* is a program for presentation of the Dnaish Wind Resource Map and for data export to GIS-format. The program is a freeware and can be downloaded from www.emd.dk. On this site, also some pre-calculated GIS-maps and wind resource map are available.

The GIS-format

EMD has completed a transfer of the wind resource map data to ArcView GIS-format (ESRI shape file format). The data are saved as raster files, where each 200x200 m^2 quadrant is saved as an individual polygon with the appropriate database set.

The program '*Resource Mapper*' offers the possibility to save either counties or municipalities as individual shape files or to use specific coordinates as input (UTM or geographical). Some pre-calculated shapefiles are available from www.emd.dk/windres. The export to local coordinate systems, e.g. the Danish System 34/45 has not been implemented, but this option is available using a number of external conversion programs, e.g. using one from Informi GIS [2].

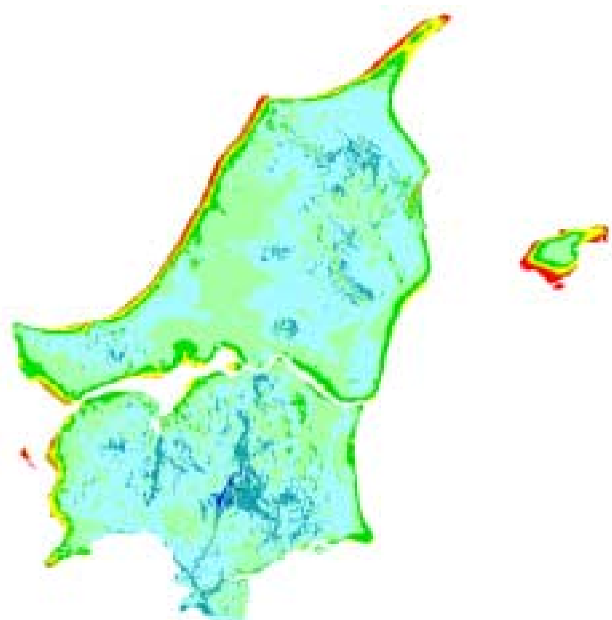


Figure 1: The Wind Resource in the northern Jutland.

Each GIS-export results in three files: a shape file (*.shp), an index file (*.shx) and a database file (*.dbf). It is possible to download a free viewer (ArcExplorer) in order to view the shape files [3].

Hub Heights Included in the Calculation

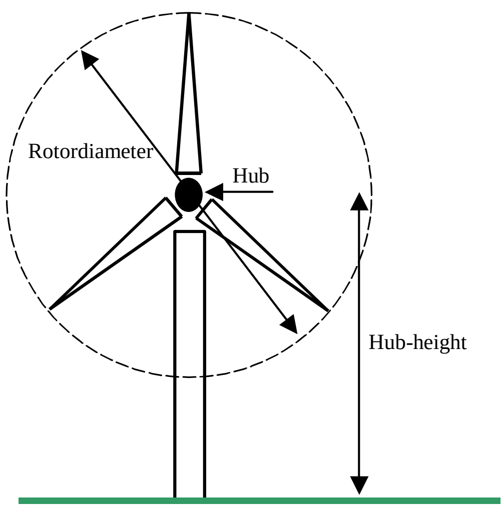


Figure 2: Sketch of a turbine with the main parameters..

The calculations are performed in four different hub heights in order to estimate the wind resource for different turbine sizes. These heights are 25 m, 45 m, 70 m og 100 m respectively. The heights approximately correspond to the typical turbine sizes not erected earlier, the ones erected today and finally the ones expected to be erected in the next few years.

- Hub height 25 meters: Turbines with a rated power <250 kW. (An earlier wind resource map of Denmark was calculated using this height)
- Hub height 45 meters: Turbines with rated power approximately 600-1000 kW – rotor diameter approximately 40-55 meter
- Hub height 70 meters: Turbines with rated power approximately 1500-2000 kW – rotor diameter approximately 70 meter
- Hub height 100 meters: Turbines with rated power >3-4000 kW (not of current interest)

For planning purposes preferably use the calculated hub heights which correspond to turbine size which is planned within the area of interest.

The Calculated Parameters

Belonging to each polygon, four numbers of different parameters are calculated and saved in the corresponding data file. For each polygon four hub heights are calculated resulting in 16 data sets for each polygon. The saved parameters and their origin are briefly explained below:

1. *The Weibull distribution parameters (A og k) for describing the distribution of the 10-minute mean wind speed (U_{10})*

   The Weibull-distribution is used in connection with wind resource assessment as a parametric description of the distribution of the 10-minute mean wind speed, U_{10}. U_{10} is known as a stochastic variable. A stochastic variable is an uncertain parameter, where the actual value of the parameter able to be determined is determined using probabilities or distributions (of probabilities). The distribution parameters of a Weibull distribution are given by twp parameters A og k. These parameters describe the shape of the Weibull distribution. Using these two parameters, the probability of exceeding the 10-minute mean wind in a certain 10 minutes period may be calculated. The distribution and density functions of the Weibull distribution are:

   Distribution function: $$F(U_{10}) = 1 - \exp\left(-\left(\frac{U_{10}}{A}\right)^k\right) \qquad (1)$$

   Density function: $$f(U_{10}) = \frac{k}{A}\left(\frac{U_{10}}{A}\right)^{k-1} \exp\left(-\left(\frac{U_{10}}{A}\right)^k\right) \qquad (2)$$

   Example: A site on the Danish island of Bornholm with the Weibull parameters A=9.10 m/s and k=1.93. Using the distribution function for calculating the probability of exceeding 20 m/s gives:

$$F(20) = 1 - \exp\left(-\left(\frac{20}{9.10}\right)^{1.93}\right) = 0.9896 \tag{3}$$

I.e. in a random 10-minute period we have approximately 1% probability that the mean wind exceed 20 m/s. This corresponds to approximately 90 hours on a yearly basis. In Figure 1 the density function is shown.

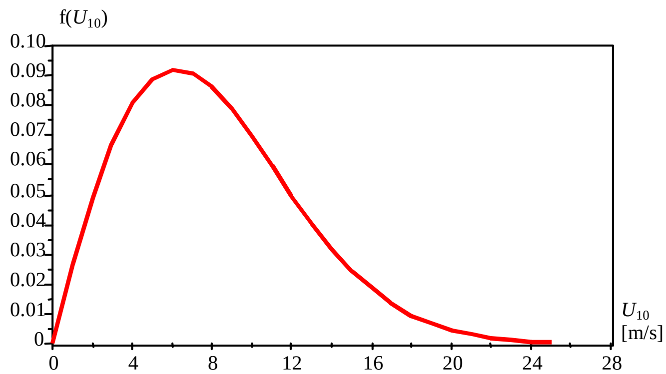


Figure 3: The Distribution of Mean Wind Speeds for A=9.1 og k=1.93.

2. *The site specific 10-minute mean wind speed*

The mean of the 10-minute mean wind speed (or the expected of the mean wind speed) on a given site can be calculated from the Weibull parameters *A* and *k*. Furthermore, other statistical parameters can be counted from *A* and *k*. Here, only the variance and the statistical *n*-th order moment is given. A description of the other statistical parameters may be found in the European Wind Atlas [4, p. 582]. The relationship between the Weibull *A* og *k* parameters and the mean (μ) and variance (σ^2) of the distribution are:

Mean [m/s]: $$\mu_{U10} = E[U_{10}] = A \cdot \Gamma(1 + 1/k) \tag{4}$$

Variance [(m/s)^2]: $$\sigma_{U10}^2 = E\left[(U_{10} - \mu_{U10})^2\right] = A^2\left[\Gamma(1 + 2/k) - \Gamma^2(1 + 1/k)\right] \tag{5}$$

The n-th order moment of the Weibull distribution is:

The *n*-th order moment [(m/s)^n]: $$E\left[(U_{10})^n\right] = A^n \Gamma(1 + n/k) \tag{6}$$

where E(X^n) is the *n*-te order moment (se below), Γ(·) is the gamma distribution, (*A*, *k*) is distribution parameters for the Weibull distribution The *n*-te order moment for a stochastic variable, *X*, is in general calculated as:

$$E(X^n) = \int_{-\infty}^{\infty} x^n f(x) dx \tag{7}$$

The equations (4) and (6) as a function of *A* and *k* is found by completing the integration in (7) using analytical methods.

Example: The mean value and the variance is calculated using the above equations. Using the site on Bornholm with the Weibull parameters *A*=9.10 m/s and *k*=1.93:

$$\mu_{U10} = 9.10 \cdot \Gamma(1 + 1/1.93) = 8.07 \text{ m/s} \tag{8}$$

$$\sigma^2_{U10} = 9.10^2 \left[\Gamma(1+2/1.93) - \Gamma^2(1+1/1.93)\right] = 18.98\,(\text{m/s})^2 \tag{9}$$

3. *The energy content in the wind – mean power per m² rotor*

The flow of kinetic energy (power) in the wind, which per unit time flows through an area of 1 square meter, is a good measure of the potential energy production of a wind turbine. In principle the energy content in the wind should be calculated from the instantaneous wind speeds, i.e. the turbulence of the wind should be included. However, according to the European Wind Atlas [4, p. 97] it is reasonable to use the 10-minute wind speed instead when calculating. This is due to the fact that the power curves from the wind turbines always are related to the 10-minute mean wind speed. Considering the energy of the wind as the amount of kinetic energy that flows through an 1 m^2 area per unit time, E_U [W/m^2], see also [4, p. 99] or [5, p. 31]:

$$E_U(U_{10}) = 0.5\,\rho\,(U_{10})^3 \tag{10}$$

where U_{10} is the 10 minute mean wind speed and ρ is the density of the air (~1.225 kg/m^3). As we want the average energy content of the entire year, we need including the contributions from every 10-minute wind speeds. These contents are included in the equation below:

$$\begin{aligned} E_W &= \int_0^\infty E_U(U_{10})\,f(U_{10})\,dU_{10} \\ &= 0.5\rho\int_0^\infty (U_{10})^3\,f(U_{10})\,dU_{10} \\ &= 0.5\rho A^3\Gamma(1+3/k) \end{aligned} \tag{11}$$

It should be noted, that the energy content must be corrected for the geographical position of the wind turbine. This is due to the fact, that the wind resource map is calculated using a set of wind statistics from a specific site on Fyn. This correction is given by the regional correction factors (see the description and map on page 6). When the regional correction factors, *LK*, are used the wind energy is given by:

$$\begin{aligned} E_{W,SITE} &= LK \cdot E_W \\ &= LK \cdot 0.5\rho A^3\Gamma(1+3/k) \end{aligned} \tag{12}$$

Example: The site on Bornholm the energy content in the wind is calculated as:

$$E_{W,SITE} = 1.01 \cdot 0.5 \cdot 1.225 \cdot 9.1^3\,\Gamma(1+3/1.93) = 644\ \text{W/m}^2 \tag{13}$$

4. *The energy content in the wind – average energy per year per m² rotor*

The average energy content in the wind per year per m^2 rotor area [kWh/(år m^2)] is easily calculated by using equation (12) and multiplying with the amount of hours per year.

$$E_{YEAR,SITE} = LK \cdot E_W \cdot 8760/1000 \tag{14}$$

Using the Map for Wind Resource Planning Purposes

When using the wind resource map for planning purposes, typically one parameter is only selected for the planning. It is recommended, that the energy content in the wind is used as this descriptive parameter, because it is essential for the production and thus for the economics in a wind turbine power plant. A typical wind turbine may utilize approximately 33% of the energy in the wind. In the above equations, there are two parameters describing this energy content (12) and (14), and in principle, it does not matter which one to use. However, the (12) is mostly often used in Danish and foreign wind resource maps and due to this it is recommended to use (12) for planning purposes.

Other parameters than the wind flow are of major importance for the planning and projecting of wind turbines, e.g. noise calculations and shadow impact. For a specific site, these can be calculated using WindPRO and isolines may be exported to GIS-format. The use of WindPRO requires a licence to the program. A demoversion is included on the CD from EMD or can alternatively be downloaded from the internet (www.emd.dk).

Analysis Background

Wind Data and Regional Correction Factor

The wind resource map is based on wind statistics from Beldringe on Fyn. In order to include the geographic variation of the mean wind speed (the variation in the geostrophic wind) a set of regional correction factors is used. These corrections were developed by EMD/Intercon in 1992 and are used for correction of the energy production. The use of the curves assures, that the calculated energy production (using the Beldringe wind statistics) for a specific turbine on a specific site is in agreement with the experience/expected on site. The correction factors are shown in the Figure 4. The regional correction factors are included in the output data.

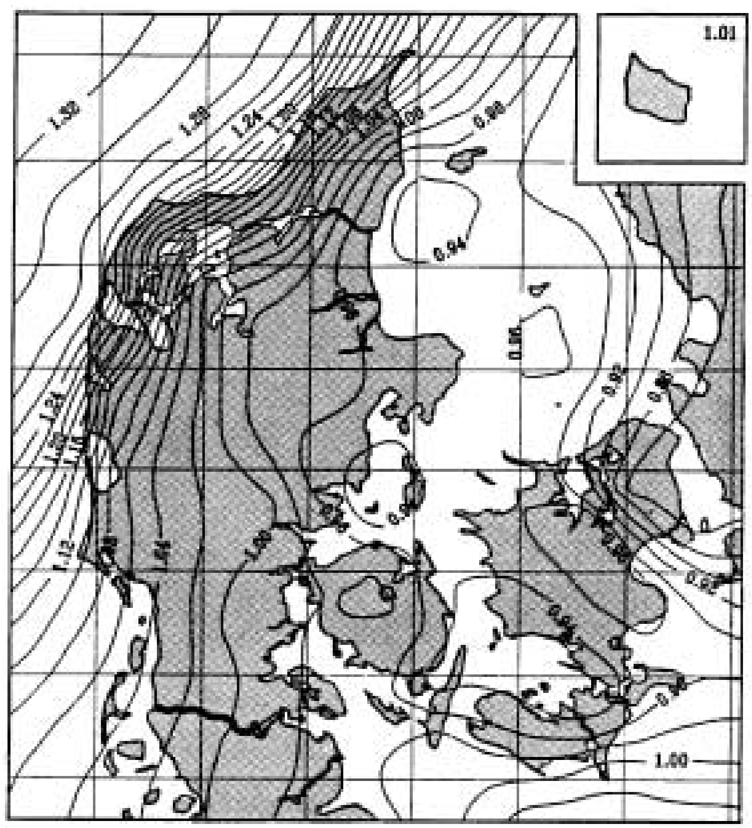


Figure 4: Regional Correction Factors for Denmark.

If the site specific mean wind speed is calculated based on the Weibull *A* and *k* parameters, see equation (4), then consistency between the energy production and the mean wind speed is not assured, see equation (10) og (12). The reason for this is, that the energy production is calculated using the regional correction factors while the *A* and *k* parameters are derived from the wind statistics from Beldringe. In order to obtain an agreement between the mean wind and the energy production, an empirical equation was derived. The empirical correction equation which included in the calculations are:

$$\mu_{U10,korr} = 3.7 + 0.0032[-1156.25 + 312.5 \cdot \mu_{U10}] \cdot LK$$

where $\mu_{U10korr}$ is the corrected wind speed
μ_{U10} is the original wind speed
LK is the regional correction factor

All wind speed data exported to GIS format is corrected with this factor.

Roughness, Hills and Local Sheltering Objects

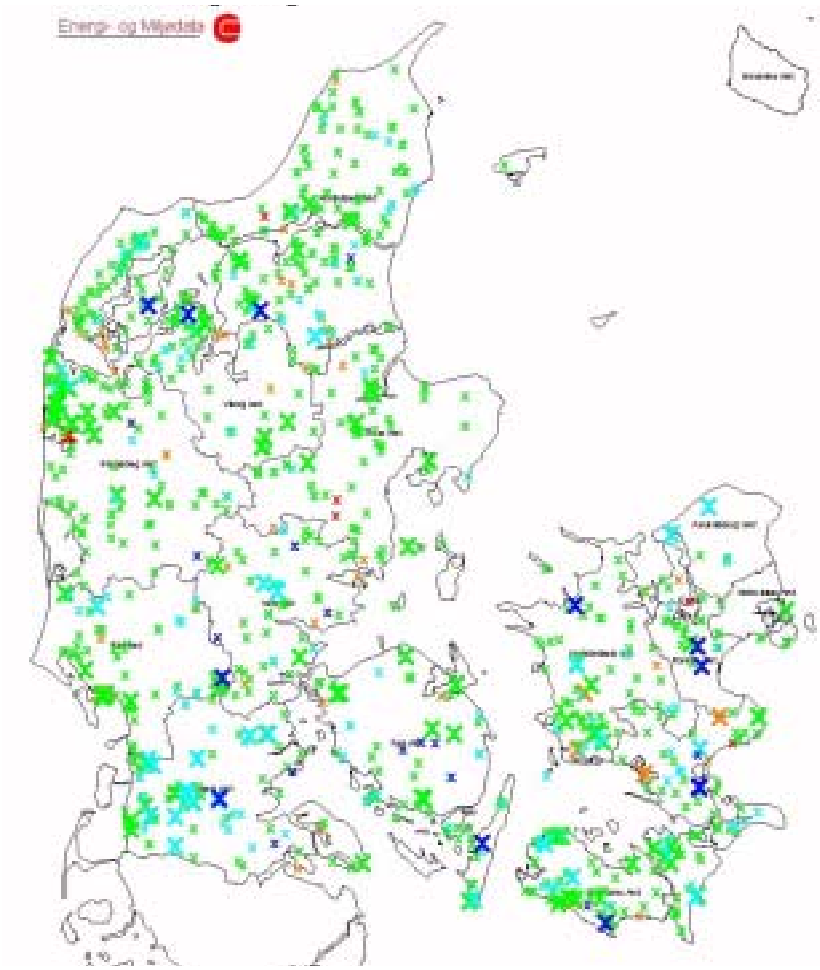
The Kort og Matrikelstyrelsens (the Danish Ordinance Survey) 2 cm maps (1:50.000) were scanned in 6 layers. These layers were vectorized afterwards. The layers have been transferred to roughness maps – please order the final report of the project for further details [1]. The digitalized data are then transferred to different layers in WindPRO depending on the type of object included:

1. Water (large and small polygons)
2. Forests (large and small polygons)
3. Cities (large and small polygons)
4. Groups of trees (points)
5. Wind breakers (lines)
6. Detached buildings – the black layer (polygons)

The height contour for every 5 meters line is used. The height contour lines originate from the Kort og Matrikelstyrelsen (Danish Ordinance Survey). Local sheltering objects are not included in the calculation, which may limit the use of the map for small turbines.

Verification

The data behind the wind resource map is verified through energy production calculations, using data from more than 1200 actual turbines. More than 80% of the turbines are found to produce within ±10% of the amount predicted using the wind resource map. The map, see Figure 5, shows an overview of the turbines included in the verification.



Legend:

- X Godhed < 80
- X Godhed < 90
- X Godhed 90-110
- X Godhed >110
- X Godhed >120

The *godhed* is an uncertainty parameter (in %). The *godhed* is the ratio between the actual measured energy production (wind index corrected) and the energy production predicted using the wind resource map.

The size of the X is scaled to correspond to the size of the turbine.

A small X = ~75 kW
A large X = ~600 kW

Figure 5: Verification of the Wind Resource Map using the 1268 turbines situated in Denmark.

Limitations and Comments

The wind resource map is developed as a guidance tool for general planning and projecting only. Investments in wind power should be based on a detailed and site-specific analysis, i.e. this wind resource map is not sufficient for this purpose.

The map does not cover offshore sitings – even if the possibility for showing offshore areas exists. Some errors have been found where roughness-maps are connected outside onshore positions. The current versions of the calculation engines used do not handle this roughness change in a consistent manner, resulting in calculation errors over open seas.

When wind turbines are placed in areas with forests, high vegetations or houses then the velocity profile should in general be 'risen' the number of meters, corresponding to the height of the objects. A rule of thumb is to subtract 66%-100% of the object height from the hub height of the nacelle in order to get a reasonable result (dependent on the character of the objects).

Please note that the map overestimates the wind energy in areas with fjords or large lakes.

Local objects with sheltering effects are not taken into account. Here local objects are larger sheltering objects (buildings, forests and other objects with a height exceeding approx. 25% of the hub height) within approximately 1000 meters of the site. The existence of such objects causes a reduction in the wind energy/production as compared with the prediction from the current wind resource map. This effect is increasing important for small turbines with a low hub height.

Sites near excavations or steep slopes may experience special conditions. These are also not included in the wind resource map.

A few errors were detected in the digital height contours used when calculating the map. The precise extent of these errors is not known, but it is our belief that these errors are rare. However, for precaution reasons, possible errors should be accounted for in hilly area.

Data Source and Program Development

The program for presentation of the wind resource map is coded by Michael Frederiksen with support from Jens Villadsen and Jan Lauridsen, Energi- og Miljødata. The GIS-implementation, upgrading to version 1.2 and this note by Morten Lybech Thøgersen, Energi- og Miljødata.

The data source is developed by Per Nielsen and Lars Bo Albinus, Energi- og Miljødata with support from The Department of Wind Energy at Risø National Laboratory (Lars Landberg and Niels Gylling Mortensen).

The Danish Wind Resource Map is made by Risø and Energi- og Miljødata 1998/99 and is partly funded by the Danish Energy Agency, under the UVE-program (j.nr.: 51171/97-0002). The GIS-export facilities are made in 2000/2001 and are also funded from the Energy Agency (UVE j.nr. 51171/00-0004).

Annex A The Content in the GIS Database File (ArcView Shape File Format)

As a part of the shape file structure, a database file (*.dbf) is saved containing data belonging to each polygon in the shape file (*.shp). In the database file the centre coordinate for each polygon is saved as well as the description of the wind climate in the chosen of the four pre-calculated hub-.heights: 25, 45, 70 og 100 meter. If the user has selected 'Production' as an option, then a further column is added to the file. An example of a database file with all chosen hub heights are shown below:

Column no.	Name in the database file	Unit	Comment
1	UTM_Exx or LATTITUDE	[m]	* UTM-coordinate (east) xx denote the UTM-zone number Alternative is latitude (if chosen)
2	UTM_Nxx or LONGITUDE	[m]	* UTM-koordinate (north) xx denote UTM-zone number Alternative is longitude (if chosen)
3	25WEIA	[m/s]	25 meter height: Weibull A-parameter
4	25WEIK	-	25 meter height:: Weibull k-parameter
5	25MEANW	[m/s]	** 25 meter height: Mean wind speed
6	25KWHYR	[kWh/(m^2·yr)]	** 25 meter height: Energy content in wind pr. m^2 per yr
7	25W/M2	[W/m^2]	** 25 meter height: Energy content in the wind per m^2
8	45WEIA	[m/s]	45 meter height: Weibull A-parameter
9	45WEIK	-	45 meter height:: Weibull k-parameter
10	45MEANW	[m/s]	** 45 meter height: Mean wind speed
11	45KWHYR	[kWh/(m^2·yr)]	** 45 meter height: Energy content in wind pr. m^2 per yr
12	45W/M2	[W/m^2]	** 45 meter height: Energy content in the wind per m^2
13	70WEIA	[m/s]	70 meter height: Weibull A-parameter
14	70WEIK	-	70 meter height:: Weibull k-parameter
15	70MEANW	[m/s]	** 70 meter height: Mean wind speed
16	70KWHYR	[kWh/(m^2·yr)]	** 70 meter height: Energy content in wind pr. m^2 per yr
17	70W/M2	[W/m^2]	** 70 meter height: Energy content in the wind per m^2
18	100WEIA	[m/s]	100 meter height: Weibull A-parameter
19	100WEIK	-	100 meter height:: Weibull k-parameter
20	100MEANW	[m/s]	** 100 meter height: Mean wind speed
21	100KWHYR	[kWh/(m^2·yr)]	** 100 meter height: Energy content in wind pr. m^2 per yr
22	100W/M	[W/m^2]	** 100 meter height: Energy content in the wind per m^2
23	UTM_ZONE	-	UTM zone for the site
24	PRODUKTI	[MWh/yr]	*** User defined

Table 1: Example of content in the database file (.dbf).*

*) UTM co-ordinates for Denmark is zone 32 except Bornholm which is in the UTM zone 33.

**) The parameters are corrected with the regional correction factors, see page 6.

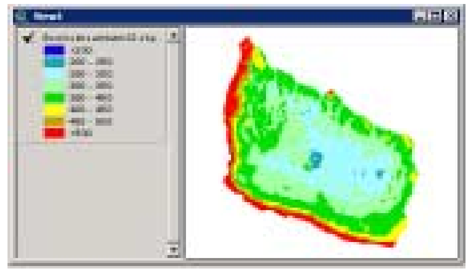
***) Option: If other data are calculated with the program then this column is used. Typically this column contains the energy production for a specific turbine (if selected).

Annex B Reducing the Number of Polygon

Subsequently, a procedure for reducing the 200x200 m^2 raster grid into a grid with larger irregular polygons is described. The procedure makes use of merging polygons with homogeneous properties (e.g. intervals of the energy in the wind). The procedure described below is valid for and requires ArcView GIS 3.2a. Please consult the ArcView user guide for further information [6].

1. Add a shapefile with the corresponding data (e.g. BornholmsAmt.shp)
   (Commands: File → New Project. New → View → Add Theme)

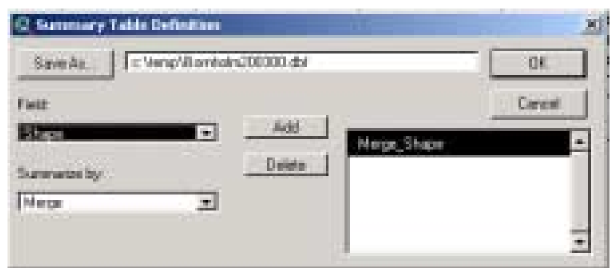
2. Choose a suitable graduation for the information wanted.
   (Command: Theme → Edit Legend → choose: Legend Type = Graduated Color and Classification field = Database field (see Table 1), here: 45W/M2. The result is shown to the right.



3. Choose which calculation interval to use (here between 200 and 300 W/m^2)
   (Command: Theme → Query → enter the criterion → New Set)

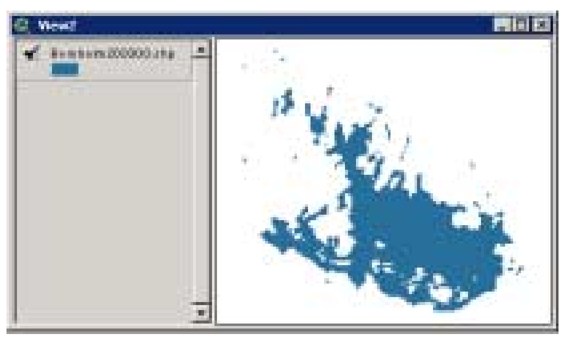
4. Choose the database window (attribute table). Mark the column where the properties are uniform – use [UTM_ZONE]. (Command: Theme → Table → Mark the column header [UTM_ZONE].

5. Click the summation icon  and add the information as indicated to the right. Remember to include a proper filename.



6. Add the file as a new view in ArcView. The energy content for the polygon shown is now between 200 og 300 W/m^2 and the polygons are merged.

7. If other intervals are needed, then repeat step (3)-(6).



Annex C Stepwise Guide in Using the Program Resource_Mapper ver. 1.2

Installation
Installed the program on your hard disk by running the *setup.exe file* and follow the guidelines appearing on the screen. It is possible to use the Kort og Matrikelstyrelsen's (the Danish Ordinance Survey) digital maps in an IT-format together with Resource_Mapper. If the program is on a CD-rom (as an alternative to downloading it from the internet), then other software is included on the CD-rom which may require a licence from EMD.

Choose the area of interest
Please choose the area of interest: All of Denmark (somewhat time consuming), a county, a municipality or an UTM-limitation. It is possible to calculate a wind resource map by selecting and calculating one area at the time.

Choose the hub-height

Choose the parameter(s) of interest
Please note, that W/m^2 and kWh/m^2/år is the amount of energy flowing through one square meter in the chosen hub height. A wind turbine utilizes approximately 1/3 part of this. If 'Production' is chosen, then the type of turbine requires input: rated power of the generator: range 150 - 2000 kW, rotor diameter: 20 - 90 m, power control: stall or pitch, generator principle: fixed (1 generator) or variable (2 generators). The production is calculated using the method by Helge Petersen [7]. This empirical method is based on the analysis of a large number of power curves. This method has – in several cases – proven more precise than a measured power curve. However when calculating pitch controlled turbines, the background data is sparse. Thus for pitch controlled turbines no discrepancy between one or two generators is found. It is only possible to select turbines within the limits that the method is judge to cover, i.e. from approximately 0.30 to 0.60 kW/m^2 rotor area. It is possible to select the number of colours, the starting and ending values of the desired presentation interval. A small hint: It is possible to make the lower interval transparent/blank. This feature may be utilized in order to emphasize areas that are completely unfit for deployment of wind power.

Background map
It is possible to show the wind resource map on top of a KMS-map. This option requires access to the Kort og Matrikelstyrelsen's (the Danish Ordinance Survey) CD-ROM maps (see www.kms.dk). Only the IT-format is supported (the 'red' CD-ROM maps).

Map scale
When using the KMS-background maps, one may use a random map scale among those present on the CD-rom. When no background is use then a freely chosen zoom factor is used.

Calculation
When all required specifications are set, then click the button 'Calculate'. When the calculation is finished and the map appears, then a new area may be chosen if no parameters are changed. If some parameters are required to change (e.g. the hub height) then the preceding calculation must be erased before the new calculation can start (click 'Delete').

Save
It is possible to save the results as either *.BMP, *.JPG and *.BMI format. BMP is the most common windows picture format, and may be read from virtually almost every program. JPG is a picture format with compression and therefore the size of the file is only a fraction of that of the BMP-files. The BMI format is used directly by WindPRO (see www.emd.dk). When using the BMI-files in WindPRO it is possible to use a wind resource map as the background map when planning wind turbines in an area or optimising the power production in a wind farm. It is possible to save the screen display or multiple screens. Please note, when saving multiple screens the origin is the one in the upper left corner, i.e. the map should be placed so the upper left corner of the required save area also is placed accordingly on the screen.

Problems with part of the maps have been experienced if no KMS-maps are shown as background maps.

Export to GIS
Click this button in order to export the chosen area to a ArcView shape file (a shape file, an index file and a database file). Before calculating the coordinate system and hub heights to export must be chosen. It is not necessary to have completed a calculation first. The exported arameters are described in, see Table 1. If ‘Production’ is chosen, an extra column/field is inserted in the database file. Production data from the turbines is saved in this column (unit: [MWh/yr]). Please note, that export of large areas require minimum 128 Mb ram and also a large amount of virtual memory.

A little help for calculating a wind resource map of Denmark
When calculating a map of Denmark with a resonable resolution, please follow this receipt: Use a screen resolution equal to 1280x 1024 pixels. Maximize the window containing the resource map. Choose the KMS-background map in scale 1:500.000. Use a 50% zoom. Calculate the map over night. First perform a test on certain specific municipalities that the right intervals are chosen. When the calculation is ready (next morning), then place (by dragging) the top left corner of the KMS-map into the upper left screen corner. This may take some time because of the redrawing of the screen. Save the map using 5 screen pictures downwards and 3 screen pictures right. Now entire Denmark (excluding Bornholm) is in one file. Perform a calculation with Bornholm. Use a 100% zoom. Save one screen only containing Bornholm in order to include the headings and legends. Import these two files in a program for editing images/pictures, e.g. Paint Shop Pro. Cut the legend from the Bornholm map, save the legend file. Resize to 200% cut and insert on the Danish map. Now select Bornholm and reduce by 50%. Cut Bornholm and insert on the Danish map.

References

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