A downscaling method for application in wind resource assessment and wind power forecasting

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Abstract: A method to downscale data from an atmospheric model (HiRLAM or other), and applications of this method in wind resource assessment and wind power forecasting are presented. The applications include maps and spreadsheets with mean wind speeds, distributions of wind related parameters, forecasting services and historic forecasts

Keywords: Wind energy, Wind resource assessment, Wind power forecasting

1 INTRODUCTION

In wind energy site selection detailed information on the wind is needed even before a measurement campaign is started. In addition, wind energy integration requires wind power forecasts at the day before and at the day of delivery.

For these purposes numerical wind atlas methods and wind power forecasting methods have been developed. A numerical wind atlas method creates local information on the wind in the past from data originating from an operational numerical weather prediction model[1]. In wind power forecasting these data are employed to create local information on the wind power in the near future. In both cases a downscaling method calculates the local information. (In downscaling finer resolution information is obtained from courser resolution information.) For details on these topics the reader is referred to the excellent overviews of wind resource assessment (Landberg et al., 2003) and wind power forecasting (Lange and Focken, 2005).

This paper addresses a downscaling method which has been designed to employ data from either the High-Resolution Limited Area Model HiRLAM (Undén et al., 2002), or any numerical weather prediction model that delivers the required input data in the required format. This downscaling method is described in section 2. Next, in section 3 wind resource assessment and wind power forecasting on basis of this downscaling method are addressed. The applications presented there are based on data from the HiRLAM. Finally, in section 4 the conclusion is presented.

2 THE DOWNSCALING METHOD

2.1 Overview

The downscaling method consists of a geometrical/physical method in combination with an output statistics module. The physical method is a post-processor to the HiRLAM (appendix A), or any numerical weather prediction model that delivers the required input data (two

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[1] Here and in the rest of this paper prediction denotes the outcome of a model calculation which is valid at a given moment either in the past or in the future

horizontal wind speed components, potential temperature and pressure in two vertical levels on a horizontal grid covering the sites to be considered) in the required format (GRIB). If wind speed and/or wind power observations are available, the output statistics module can be employed in order to compensate for systematic errors (appendix B). Technical aspects of the downscaling method are described separately (Brand and Kok, 2003; Brand, 2008a, 2008b; Donkers, 2010; Donkers et al., 2011).

2.2 Interpolations

The downscaling method translates information in grid points at various model levels to the location and the height of interest. The translation consists of two steps: a horizontal interpolation between grid points at the same model level and a vertical interpolation between grid points at different model levels. These interpolations are sketched in figure 1.

Now consider the wind speed components and the potential temperature in the four grid points at the same level that form the corners of the cell that contains the location of interest. These data are geometrically interpolated to the location of interest by using a bilinear interpolation scheme.

The wind speed components and the potential temperature in the levels above and below the height of interest are interpolated by employing a physical method, taking into account the local influences of roughness, obstacles and stability. This method is described below.

For sites with a fetch less than 10 km of open water the upstream surface roughness length is determined from a roughness map. In the Netherlands this information consists of 0.1x0.1 km^2 patches from the roughness map of the Netherlands as developed by the Netherlands met office KNMI (Verkaik, 2000). For other sites the upstream surface roughness length z_0 is determined from the wind speed by using Hsu's relation for shallow sea (Hsu, 1973):

$$z_0 = \frac{H}{T\sqrt{gd_s}} \frac{u_*^2}{g} ,$$

which relation employs the wave height H, the wave period T, the sea depth d_s, the friction velocity u_* and the acceleration of gravity g. In the Dutch part of the North Sea the information on wave height and wave period originates from the Netherlands Ministry of Transport (Historische waterdata, 2010), whereas the information on sea depth originates from the Hydrographic Service of the Royal Netherlands Navy (Dieptemeten, 2010).

The effect of upstream obstacles on the wind speed U and the potential temperature θ is modelled by employing the displacement height d:

$$\frac{U(z)}{u_*} = \frac{1}{\kappa}\left[\ln\frac{z'}{z_0} - \Psi_M(z',L)\right] \text{ and } \frac{\theta(z)}{\theta_*} = \frac{1}{\kappa}\left[\ln\frac{z'}{z_0} - \Psi_H(z',L)\right] \text{ with } z' = z - d .$$

Here κ is the von Karman constant. The effect of the atmospheric stability on U and θ is determined by using Holtslag speed and temperature profiles (in moderate to very stable conditions) or Businger-Dyer profiles (in the other conditions) in combination with the Obukhov length L determined from the speed difference and the temperature difference in two vertical levels (Holtslag, 1984; Businger et al., 1971). To be specific, if the atmosphere is unstable, that is if $z'/L < 0$, the deviations from the logarithmic shape are given by:

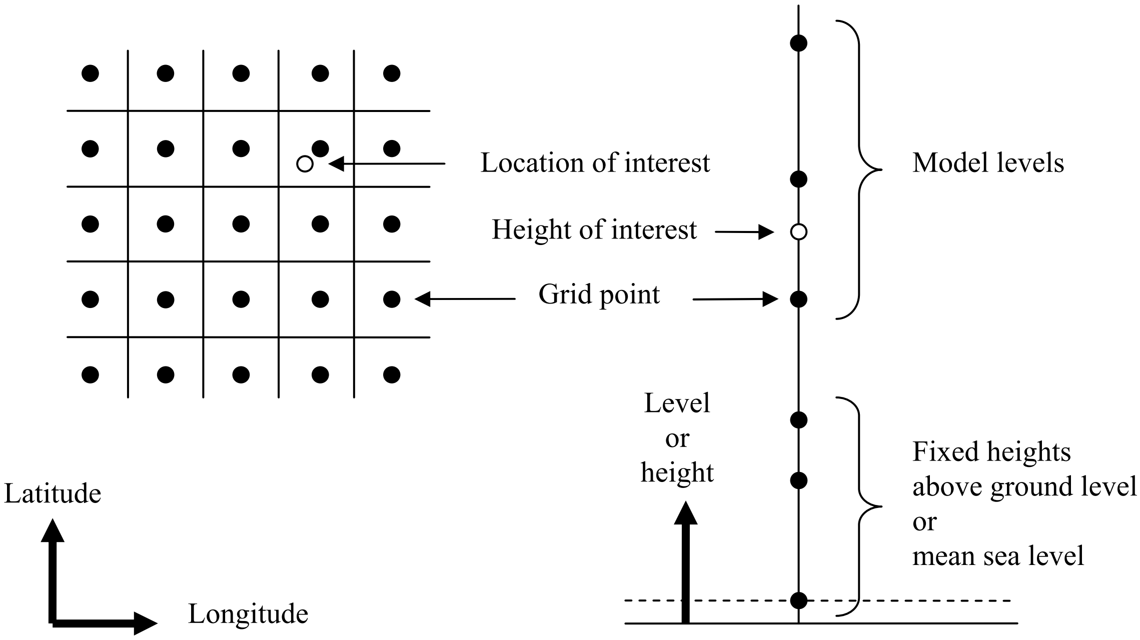

Figure 1: Horizontal (left) and vertical (right) interpolation from the grid points to the location and height of interest

$$\Psi_{M,u}(x) = 2\ln\frac{1+x}{2} + \ln\frac{1+x^2}{2} - 2\arctan x + \frac{\pi}{2} \text{ and } \Psi_{H,u}(x) = \ln\frac{1+x^2}{2} \text{ with } x = \left(1 - 16\frac{z'}{L}\right)^{0.25}.$$

If on the other hand the atmosphere is stable, that is if z'/L > 0, using y = z'/L, the deviations are given by:

$$\Psi_{M,s1}(y) = -5y \text{ if } 0<y<0.5, \text{ or } \Psi_{M,s2}(y) = -7\ln y - \frac{17}{4}\frac{1}{y} + \frac{1}{2}\frac{1}{y^2} - 0.852 \text{ if } y>0.5, \text{ and } \Psi_{H,s}(y) = -5y.$$

As to the wind power the method employs the directional standard power curve of a wind turbine, a wind farm, or a cluster of wind turbines and/or wind farms. The directional power curve relates for a given wind direction the mean wind speed at the turbine hub height to the mean produced power, where mean refers to an averaging period of 10 minutes. Effects of the variability of the wind at a shorter time scale, like low or high wind speed cut-in or high wind speed cut-out, are not represented. In the standard power curve power is normalised to the standard value of air density.

2.3 Operating modes

The downscaling method can be operated in two modes: wind or power.

In the wind mode the method gives the expected value of the 10 or 15-minute averages of the wind speed, the wind direction, the Obukhov stability length, the temperature and the pressure as well as the turbulence intensity (i.e. the ratio of the wind speed standard deviation and average) at given height above ground or mean sea level at 10 or 15-minute intervals up to 48 hours after initiation of the underlying run of the atmospheric model.

In the power mode the method delivers the expected value of 15-minute averaged power of a single wind turbine, a wind farm or a cluster of wind turbines and/or wind farms at 15-minute intervals up to 48 hours after initiation of the underlying run of the atmospheric model. In addition it gives the confidence interval of the power and the expected value of the power variation intensity (i.e. the ratio of the wind power standard deviation and average), plus the expected value of the wind speed, the wind direction and the air density at turbine hub height. All power values are based on the expected value of the air density.

2.4 Uncertainty

In general there is a difference between the observed wind speed (or wind power) and the predicted wind speed (or wind power). This difference is the error of the downscaling method. In general there are two types of error: the systematic error and the random error. The systematic error is the difference between the average of a large number of observations and the average of the corresponding predictions. It is inherently small or otherwise can be minimized by correlation with observed values. The random error expresses the difference between the observed and the predicted wind speed at a given instant. It is very often large and cannot be compensated.

3 WIND RESOURCE ASSESSMENT AND WIND POWER FORECASTING

3.1 Wind resource assessment

When employing the downscaling method in wind resource assessment, a three-step approach has been developed. In this approach the downscaling method operates on consecutive sub-series of historic HiRLAM output data with a reduced length of 6 hours.

In the first step, rough and rapid estimates of the mean wind speed are obtained by inspecting maps or tables that were created by using the downscaling method (Brand and Hegberg, 2005; Donkers, 2010; Donkers et al., 2011). As an example, figure 2 shows the mean wind speed at a height of 90 m above the Dutch part of the North Sea.

In the more detailed second step, distributions in select locations are consulted. These distributions too were created by using the downscaling method. A distribution includes the wind speed, the wind direction, the turbulence intensity, and the stability class (Brand and Hegberg, 2005; Donkers, 2010; Donkers et al., 2011).

In the even more detailed third step, specific time series and distributions are created by applying the downscaling method to HiRLAM or other atmospheric model output. Parameters include the wind speed, the wind direction, the turbulence intensity and the stability class. Time series and distributions can be created over the period from the year 2001 until now, with a time step of 10, 15 or 60 minutes, and for heights up to 150 meter.

This three-step approach has been applied in studies on wind resource assessment for wind farm developers, a study on variability of wind energy in the power system (Brand et al., 2010), and a study on correlation between wind power and energy price (Nieuwenhout and Brand, 2011).

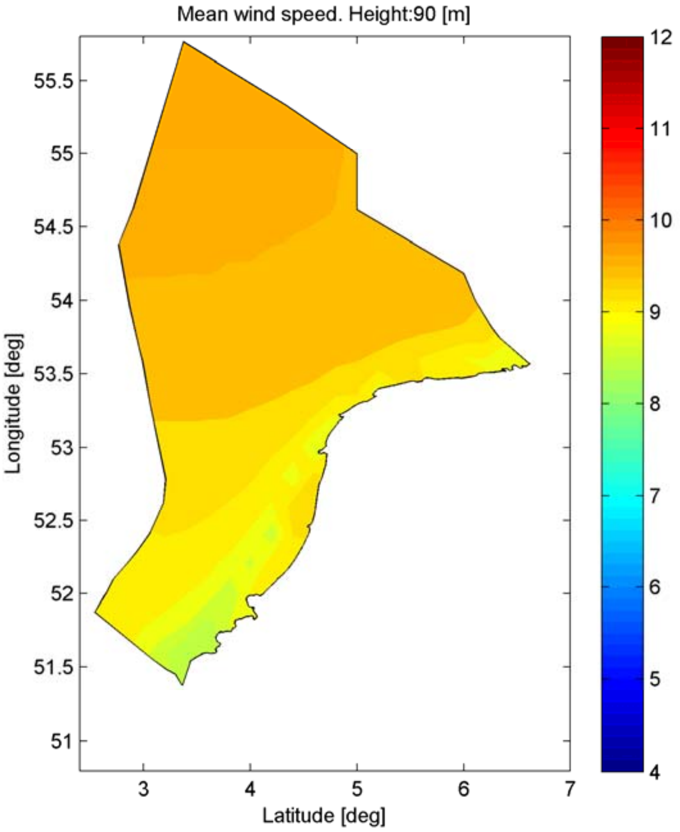

Figure 2: The mean wind speed in m/s at a height of 90 m above the Dutch part of the North Sea as calculated by using the downscaling method

On summary, the downscaling method described in section 2 can be and has been used in order to provide maps and spreadsheets with mean wind speeds and distributions of wind related parameters in the Dutch part of the North Sea, and time series and distributions of wind speed and other data in the southern part of the North Sea, the Netherlands, and most of Belgium.

3.2 Wind power forecasting

In wind power forecasting the downscaling method gives forecasts of the air density, the wind direction, the wind speed, the power variation intensity, and the power. Here the downscaling method operates on full-length series of HiRLAM output data with a length of 48 hours. An example of such a forecast for a wind farm with a nominal power of 12.5 MW is shown in the figures 3 and 4.

Wind speed and/or wind power forecasts have been applied in forecasting services for Programme Responsible Parties, evaluation studies for parties that liked to investigate whether or not to take Programme Responsibility, an evaluation study in the context of the Offshore Wind Farm Egmond aan Zee (Brand, 2008c), a study on integration of distributed generation in a power network (Kester et al., 2007), and a study on integration of wind energy in the electricity system (Brand et al., 2010). A Programme Responsible Party is responsible for balancing electricity production and consumption in its portfolio.

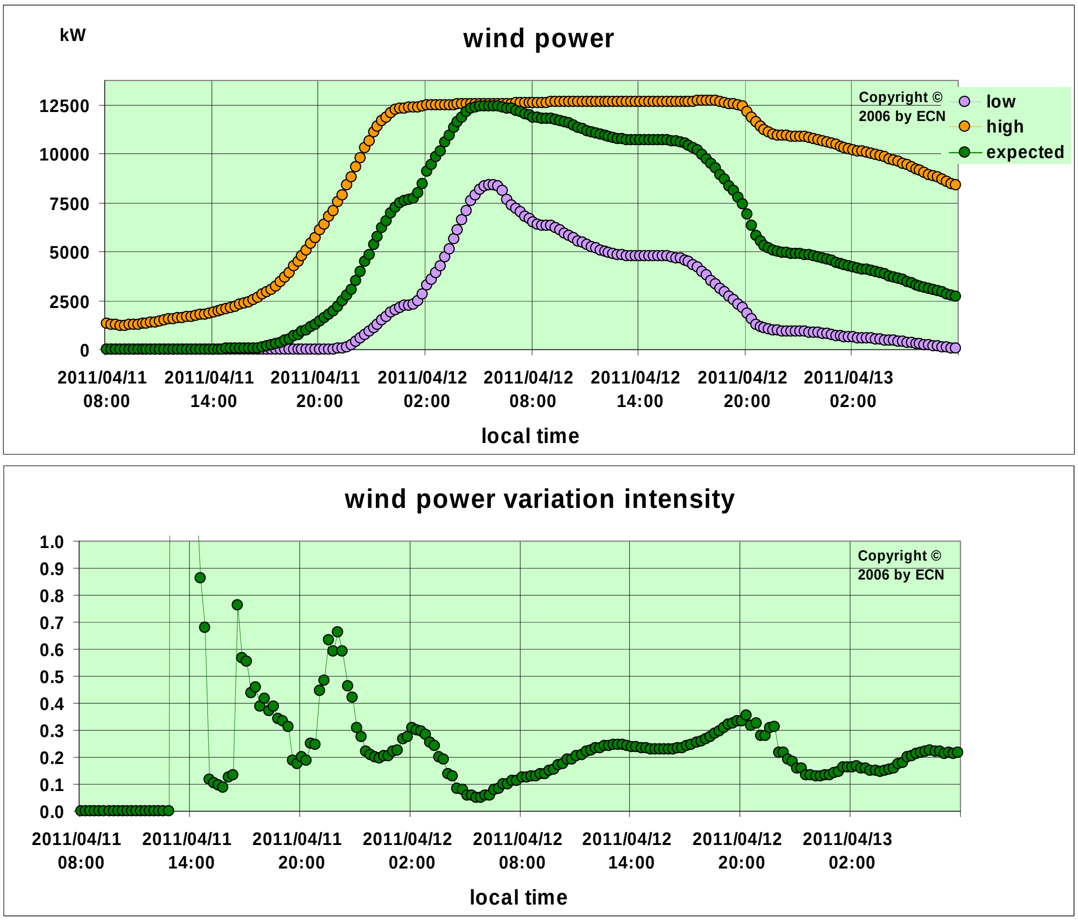

Figure 3: Forecasted wind power (top) and wind power variation intensity (bottom) for a 12.5 MW wind farm valid for the 48 hours after 11 April 2011, 08:00 h Local Time

As to wind speed and/or wind power forecasting, the downscaling method can be and has been used to provide forecasting services as well as historic forecasts. The forecasting service delivers four times per day the expected wind or power up to 48 hours in the future per grid connected wind turbine or wind farm. Historic forecasts can be delivered from June 2001 until now.

4 CONCLUSION

A downscaling method has been presented which uses data from the High-Resolution Limited Area Model HiRLAM or any weather prediction model that delivers the required input data in the required format. Application of this downscaling method in wind resource assessment and wind power forecasting has been presented on basis of output from the HiRLAM.

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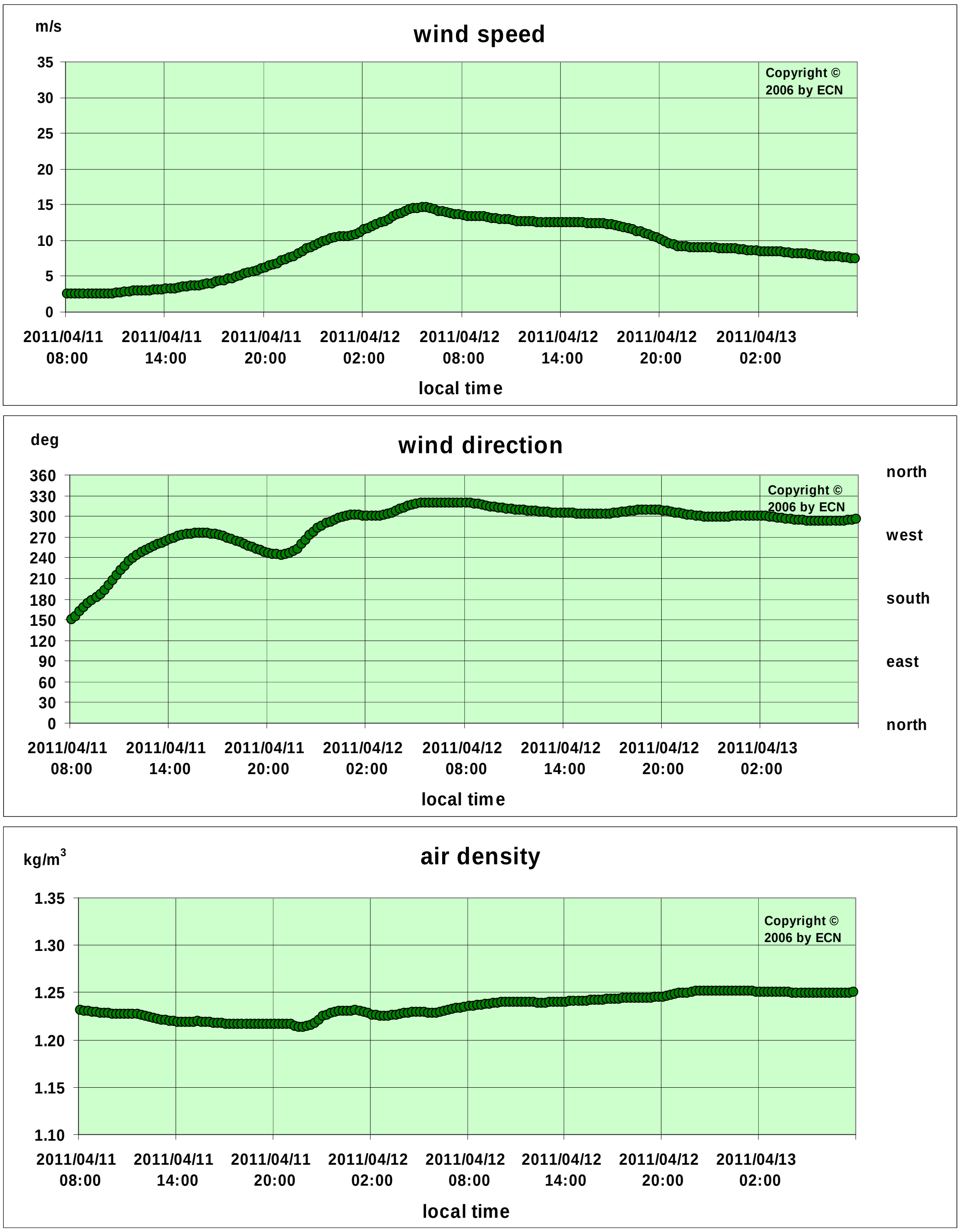

Figure 4: Forecasted wind speed (top), wind direction (middle) and air density (bottom) for a 12.5 MW wind farm valid for the 48 hours after 11 April 2011, 08:00 h Local Time

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APPENDIX A HIGH-RESOLUTION LIMITED AREA MODEL HIRLAM

The High-Resolution Limited Area Model HiRLAM is an atmospheric model operated by KNMI and other met offices (Undén et al., 2002). Like all atmospheric models HiRLAM is a numerical approximation of the physical description of the state of the atmosphere in the near future. Daily runs are initiated at 0, 6, 12 and 18 h Universal Time, starting with initial conditions originating from recent measurements. Output consists of the expected average value of physical quantities like wind speed at various vertical levels up to 30 km above mean sea level in a horizontal grid, to date with a size of 0.2x0.2 deg^2, covering Europe and vicinity and with a time step of 1 or 3 hour up to 48 hours after initiation.

APPENDIX B COMPENSATION FOR THE SYSTEMATIC ERROR

The systematic error is the difference between the average measured value and the average predicted value of wind speed or wind power. Usually, this error is site dependent. If sufficient measured wind speed data are available, wind speed predictions can be compensated for the systematic error in the wind speed. To this end a linear regression is applied between the measured and the predicted data, yielding slope and offset to be applied on the predicted speed in order to obtain the correct average. The correct average is equal to the measured average when applied to the same data set. If sufficient wind power data between zero and nominal wind power are available, in a similar way wind power predictions can be compensated for the systematic error in the wind power.

Energy research Centre of the Netherlands

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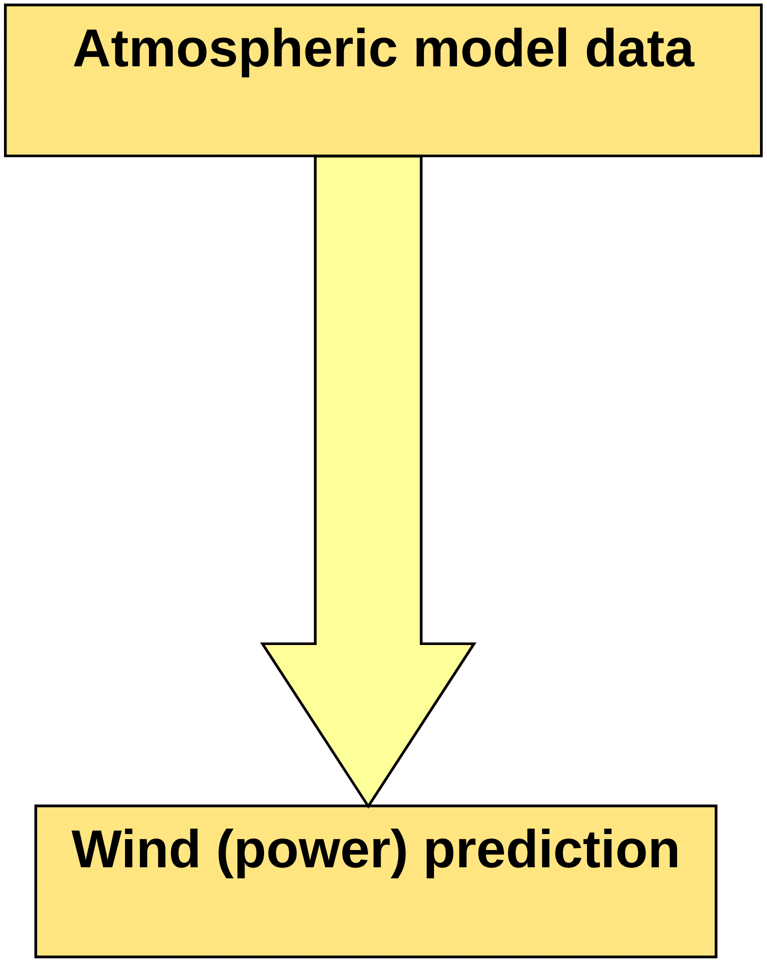
Outline

- ❑ Motivation
- ❑ Downscaling method
- ❑ Wind resource assessment
- ❑ Wind power forecasting

Motivation

- ☐ Site selection
- ☐ Grid integration

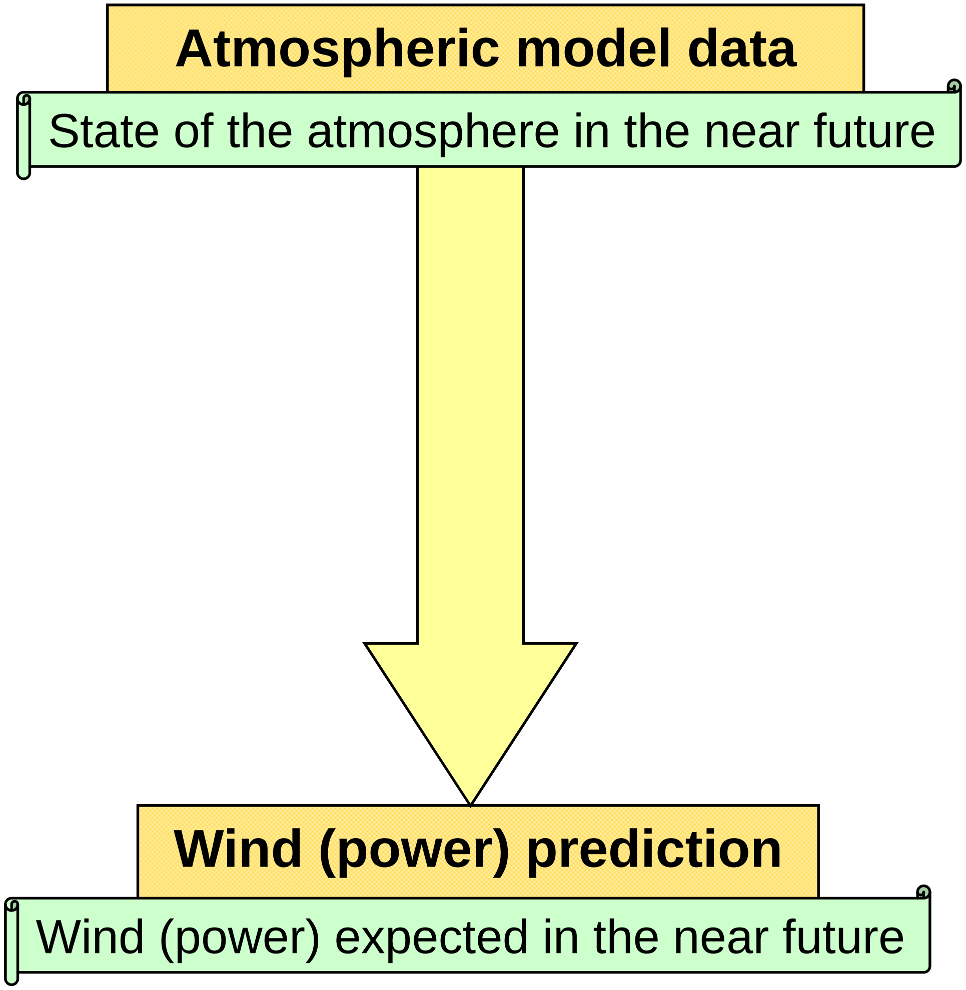
Downscaling Method



Atmospheric model data

Wind (power) prediction

Downscaling Method



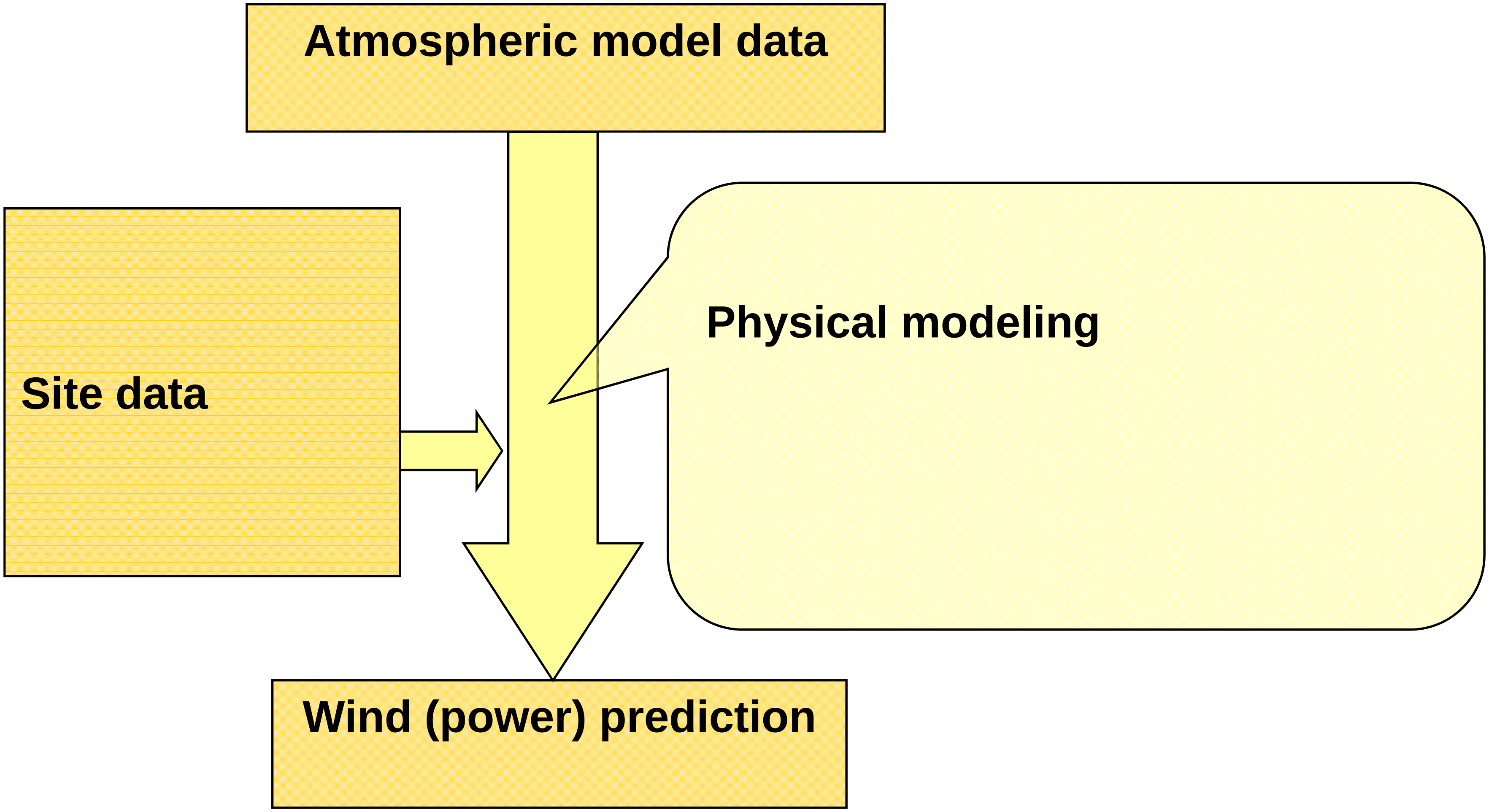
Atmospheric model data

State of the atmosphere in the near future

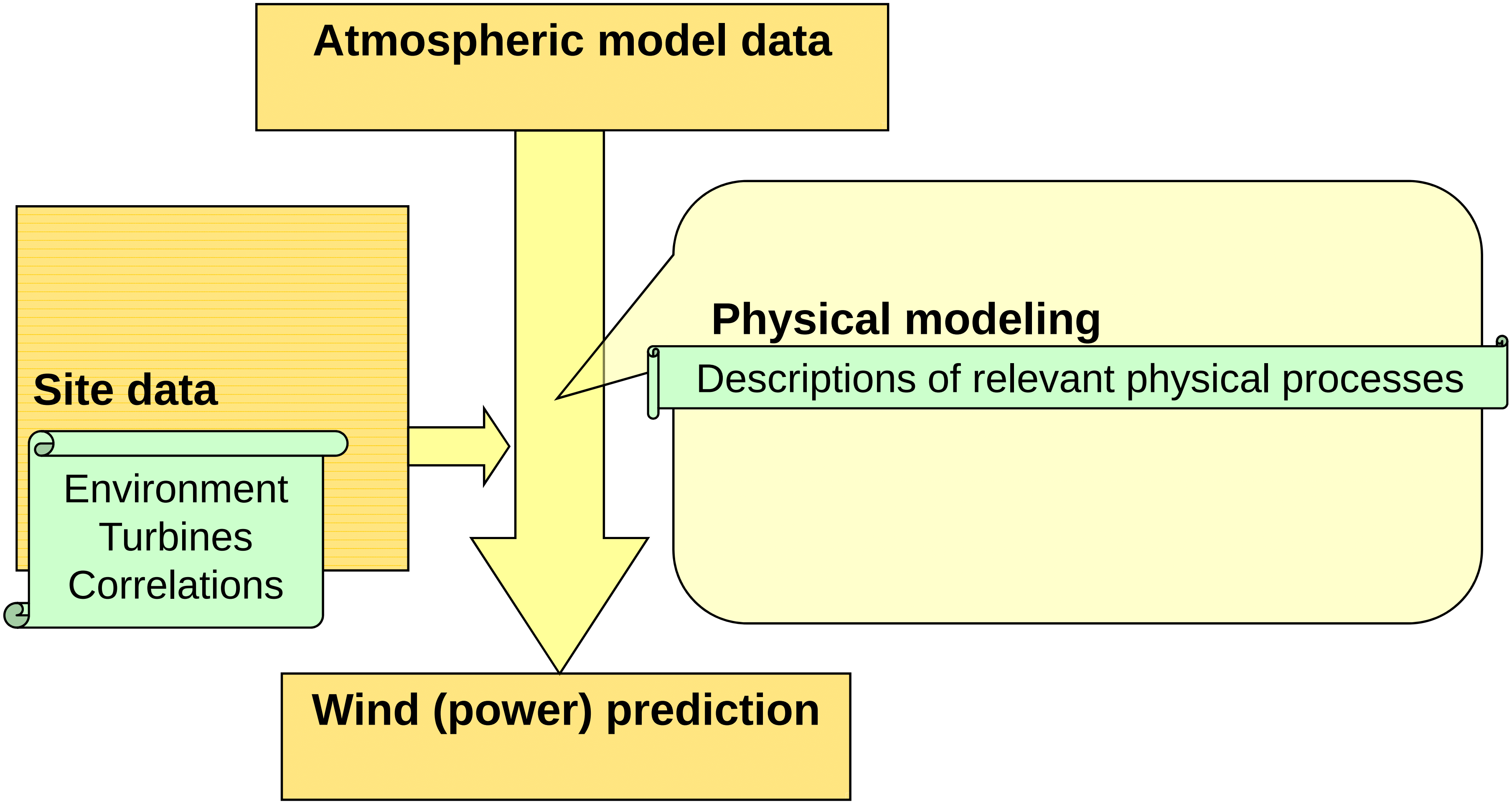
Wind (power) prediction

Wind (power) expected in the near future

Downscaling Method



Downscaling Method



Atmospheric model data

Site data

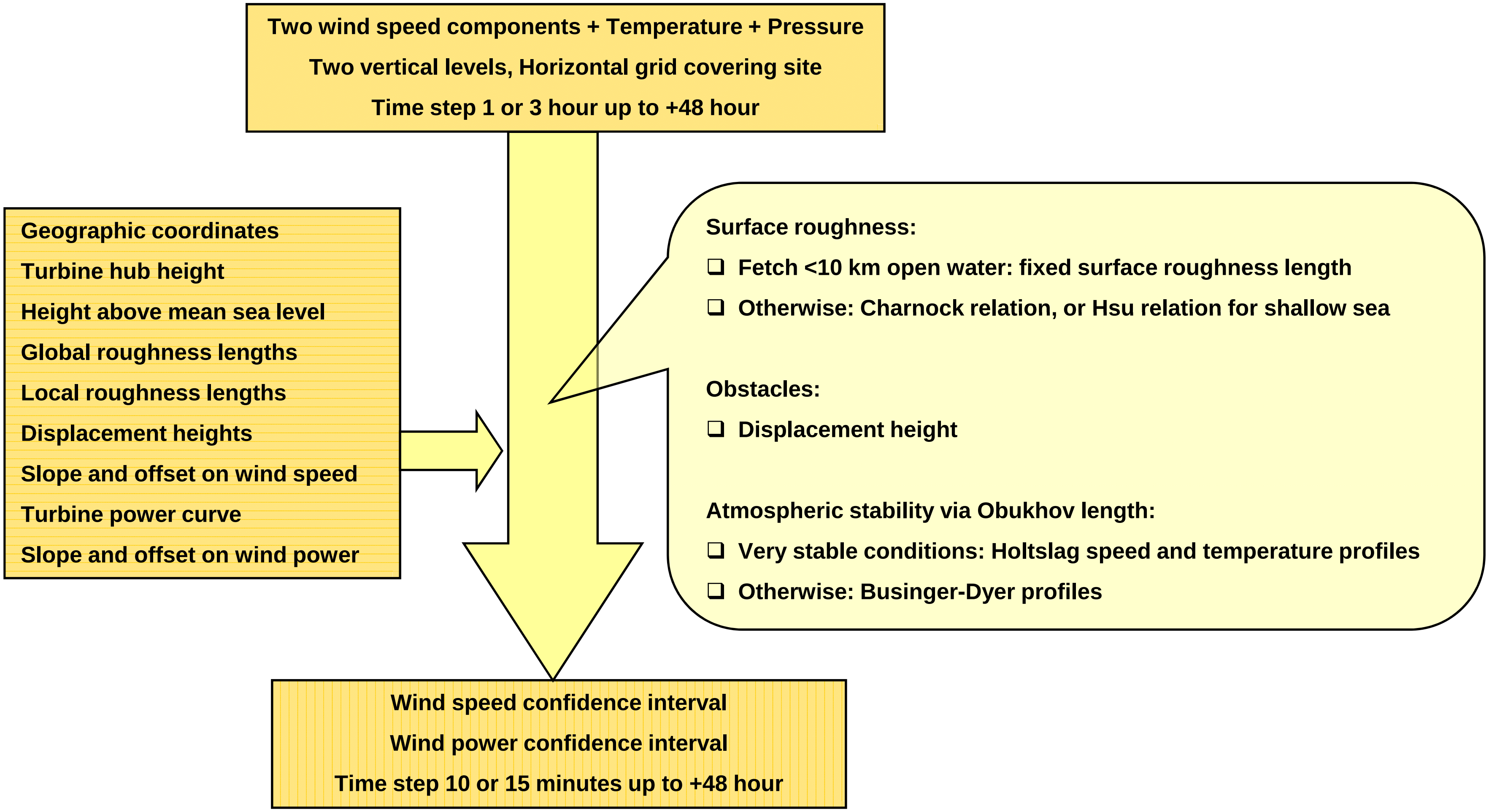
Environment
Turbines
Correlations

Physical modeling

Descriptions of relevant physical processes

Wind (power) prediction

Downscaling Method



Two wind speed components + Temperature + Pressure

Two vertical levels, Horizontal grid covering site

Time step 1 or 3 hour up to +48 hour

Geographic coordinates
Turbine hub height
Height above mean sea level
Global roughness lengths
Local roughness lengths
Displacement heights
Slope and offset on wind speed
Turbine power curve
Slope and offset on wind power

Surface roughness:

❑ Fetch <10 km open water: fixed surface roughness length

❑ Otherwise: Charnock relation, or Hsu relation for shallow sea

Obstacles:

❑ Displacement height

Atmospheric stability via Obukhov length:

❑ Very stable conditions: Holtslag speed and temperature profiles

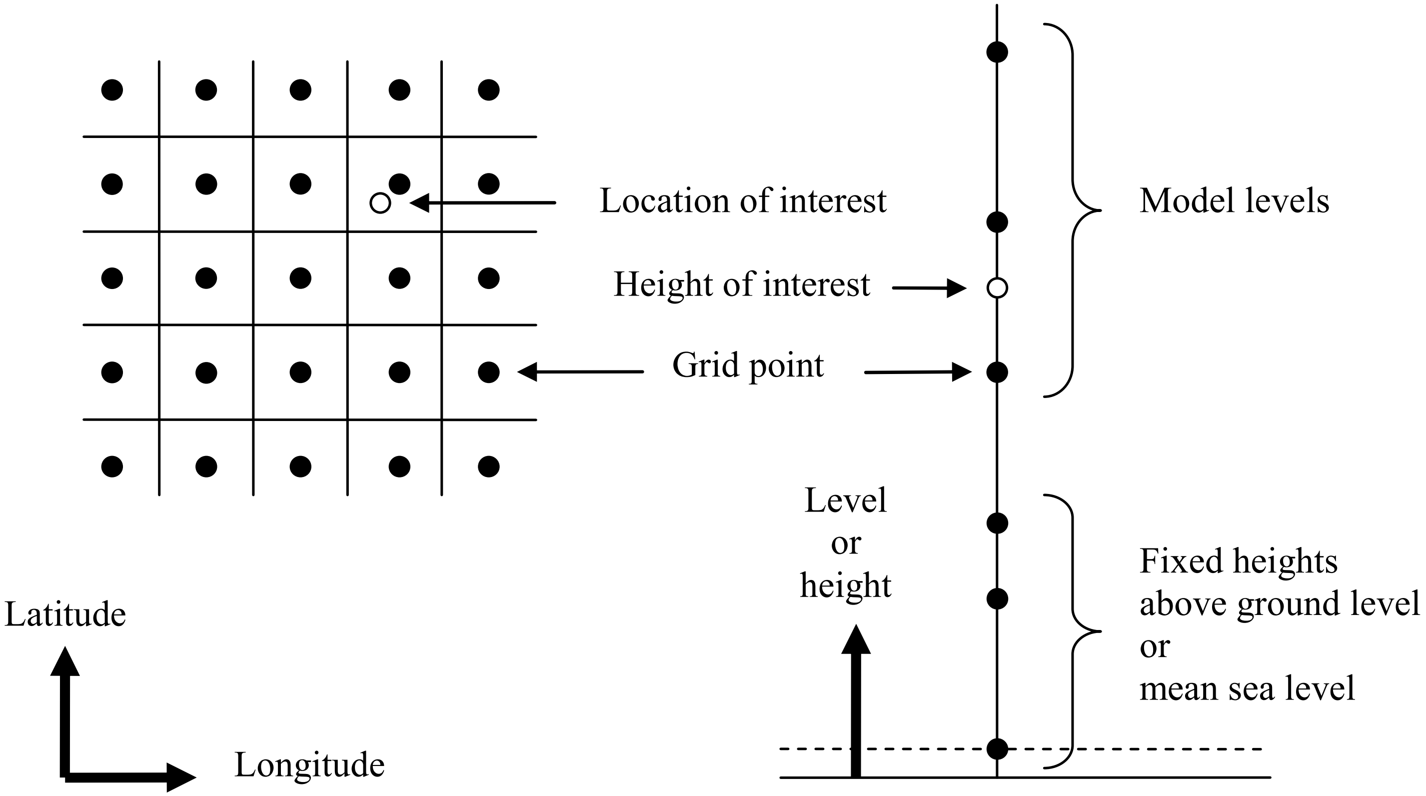
❑ Otherwise: Businger-Dyer profiles

Wind speed confidence interval

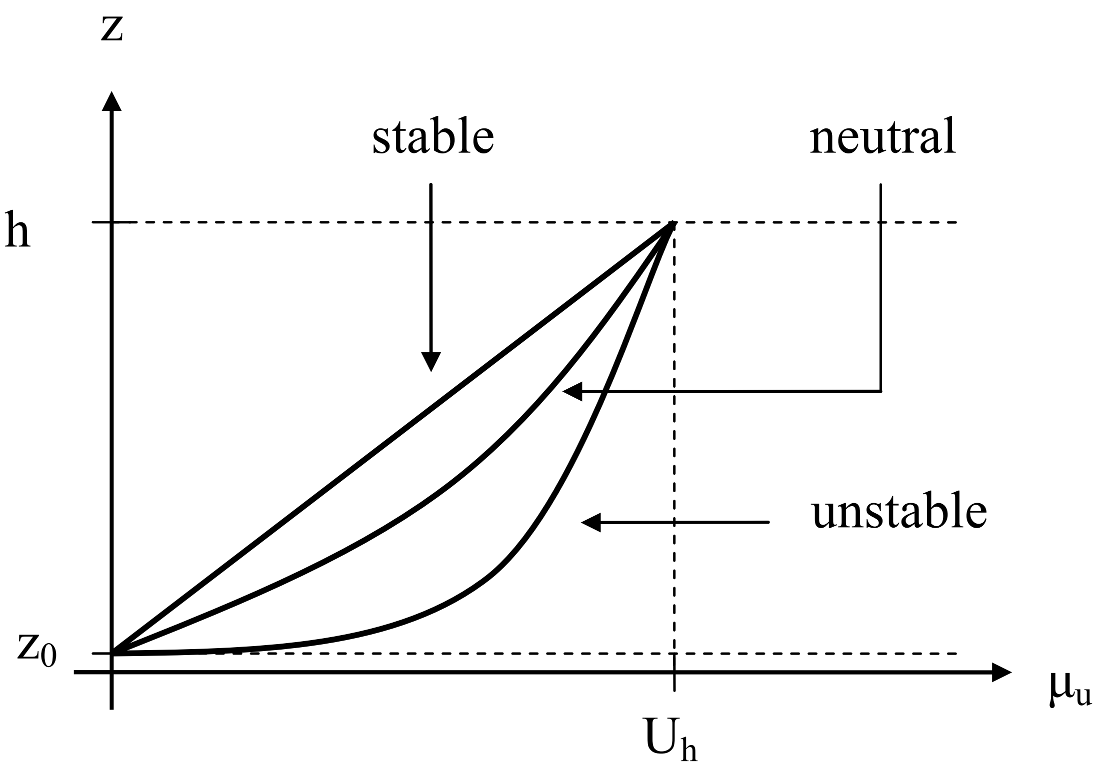
Wind power confidence interval

Time step 10 or 15 minutes up to +48 hour

Downscaling Method



Downscaling Method



Downscaling Method

Wind speed profile:

$$\frac{U(z)}{u_*} = \frac{1}{\kappa}\left[\ln\frac{z'}{z_0} - \Psi_M(z', L)\right]$$

Potential temperature profile:

$$\frac{\theta(z)}{\theta_*} = \frac{1}{\kappa}\left[\ln\frac{z'}{z_0} - \Psi_H(z', L)\right]$$

Effective height:

$$z' = z - d$$

Surface roughness:

$$z_0 = \frac{H}{T\sqrt{g d_s}}\frac{u_*^2}{g} \quad \text{or} \quad z_0 = \alpha_c \frac{u_*^2}{g} \quad \text{or} \quad z_0 = \text{fixed}$$

Downscaling Method

Wind speed profile:

$$\frac{U(z)}{u_*} = \frac{1}{\kappa}\left[\ln\frac{z'}{z_0} - \Psi_M(z', L)\right]$$

Potential temperature profile:

$$\frac{\theta(z)}{\theta_*} = \frac{1}{\kappa}\left[\ln\frac{z'}{z_0} - \Psi_H(z', L)\right]$$

Neutral:

$$\Psi_M(x) = 0$$

$$\Psi_H(x) = 0$$

ECN

Downscaling Method

Wind speed profile:

$$\frac{U(z)}{u_*} = \frac{1}{\kappa}\left[\ln\frac{z'}{z_0} - \Psi_M(z', L)\right]$$

Potential temperature profile:

$$\frac{\theta(z)}{\theta_*} = \frac{1}{\kappa}\left[\ln\frac{z'}{z_0} - \Psi_H(z', L)\right]$$

Unstable (y < 0):

$$\Psi_M(x) = 2\ln\frac{1+x}{2} + \ln\frac{1+x^2}{2} - 2\arctan x + \frac{\pi}{2}$$

$$\Psi_H(x) = \ln\frac{1+x^2}{2}$$

$$x = (1-16y)^{0.25}$$

$$y = \frac{z'}{L}$$

Downscaling Method

Wind speed profile: $$\frac{U(z)}{u_*} = \frac{1}{\kappa}\left[\ln\frac{z'}{z_0} - \Psi_M(z', L)\right]$$

Potential temperature profile: $$\frac{\theta(z)}{\theta_*} = \frac{1}{\kappa}\left[\ln\frac{z'}{z_0} - \Psi_H(z', L)\right]$$

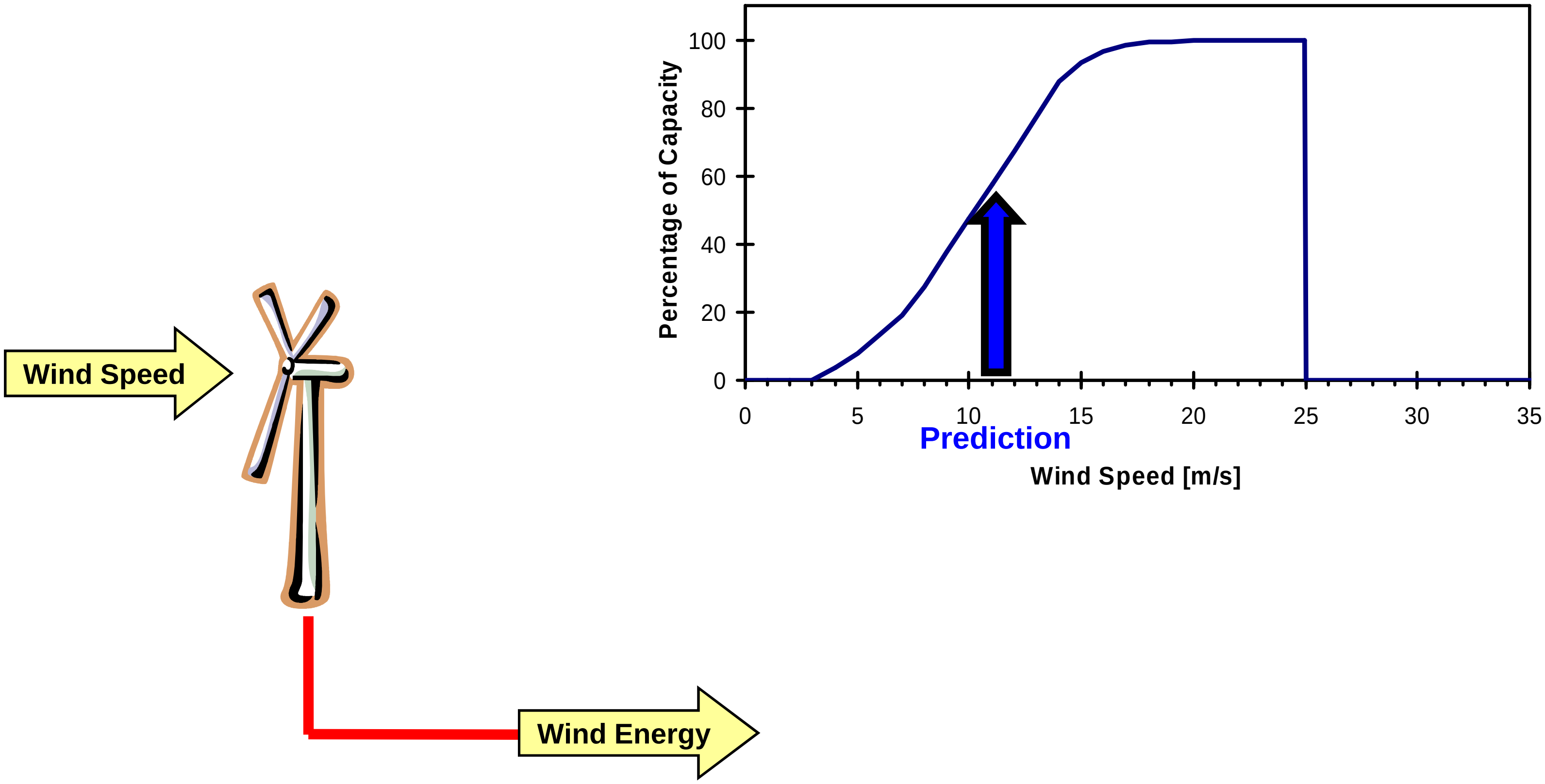
Stable (y > 0): $$\Psi_M(y) = -5y \quad \text{if } 0 < y < 0.5$$

$$= -7\ln y - \frac{17}{4y} + \frac{1}{2y^2} - 0.852 \quad \text{if } y > 0.5$$

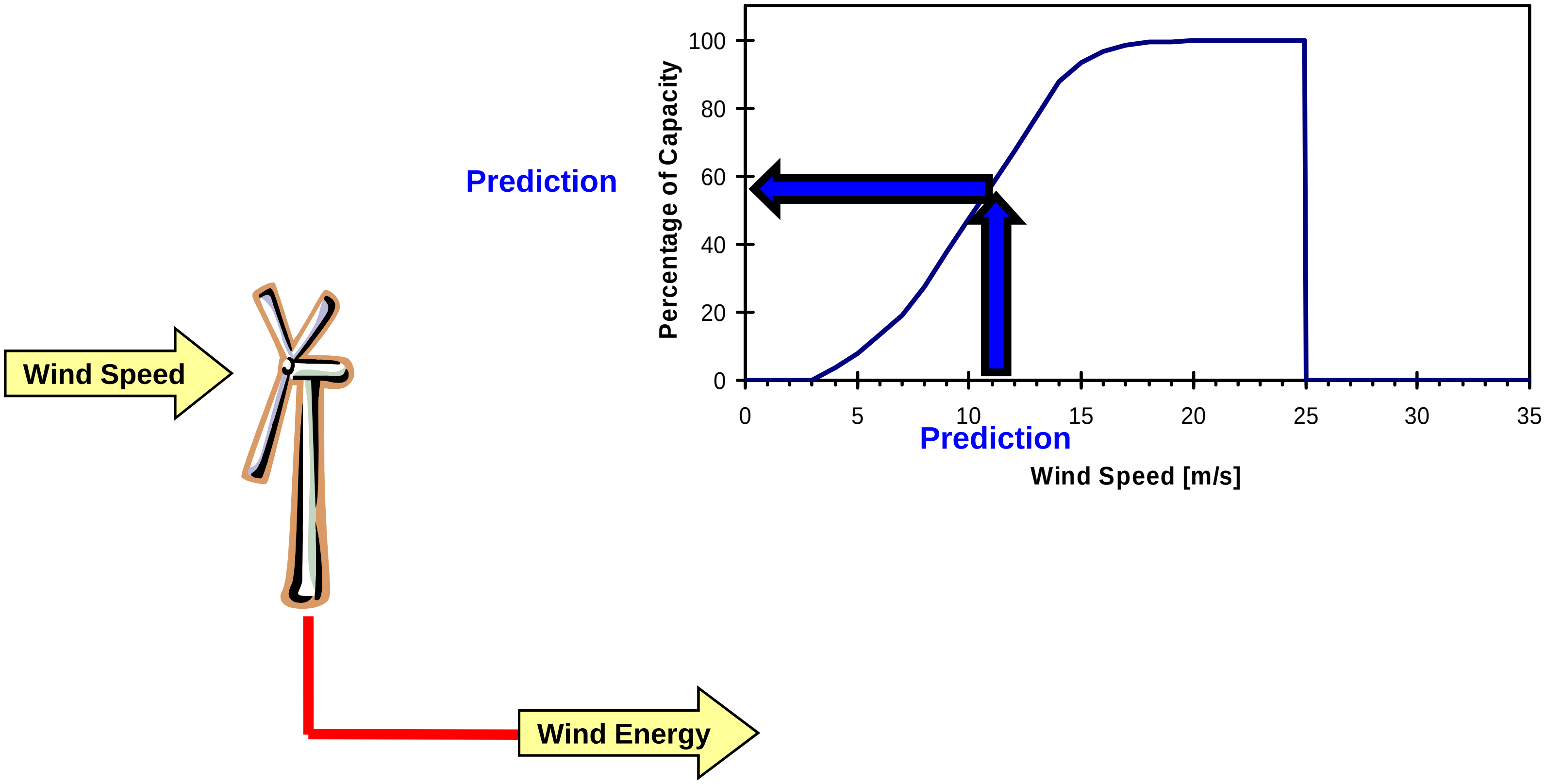
$$\Psi_H(y) = -5y$$

$$y = \frac{z'}{L}$$

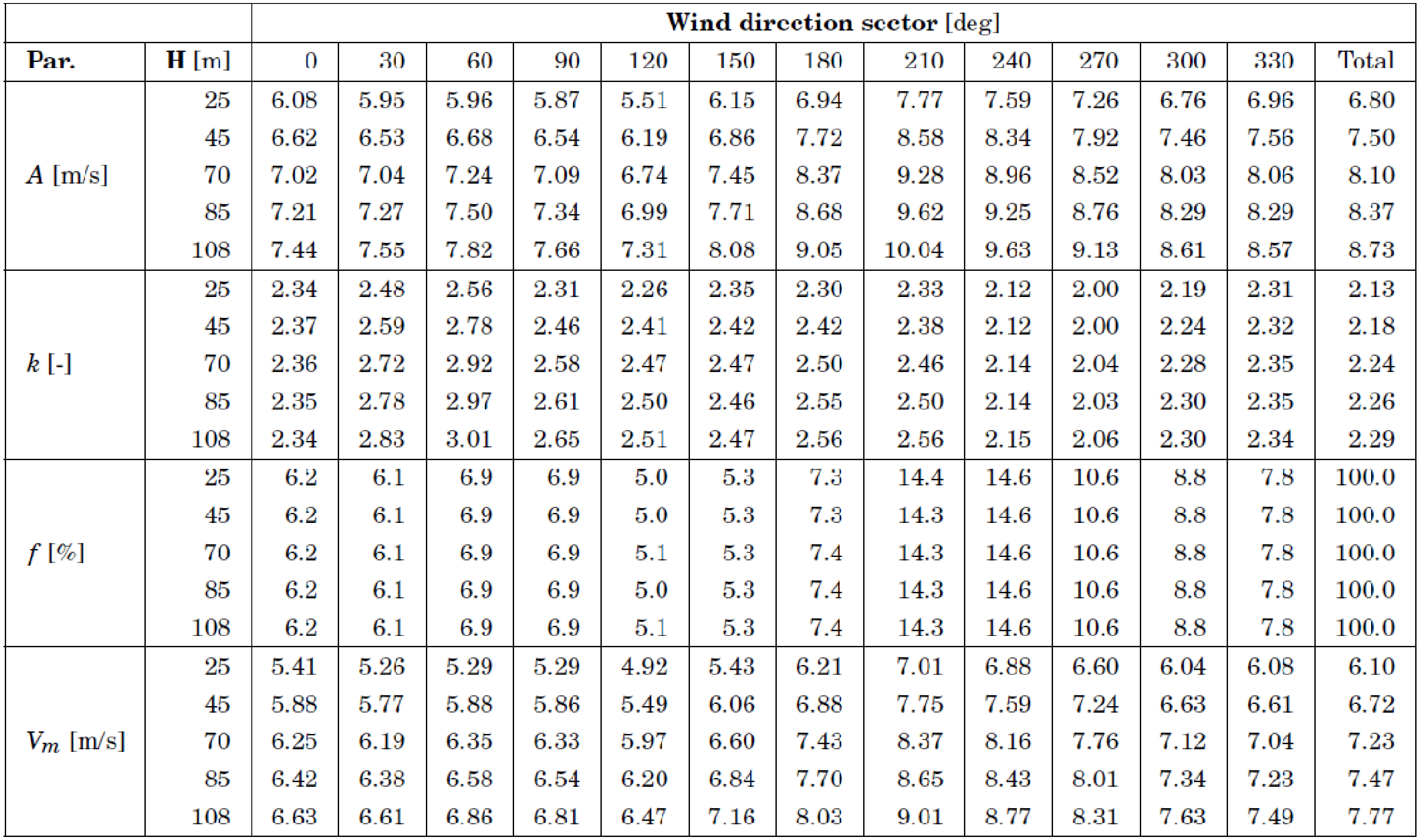
Downscaling Method



Downscaling Method

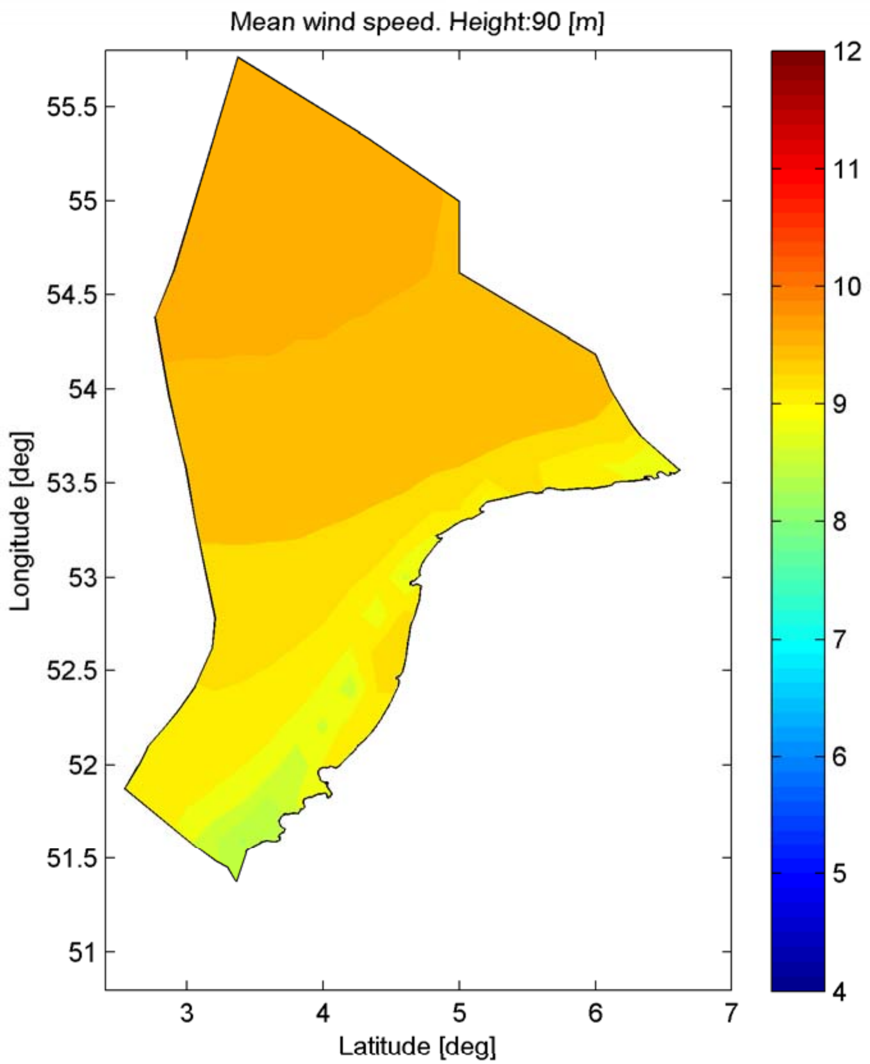


Wind Resource Assessment

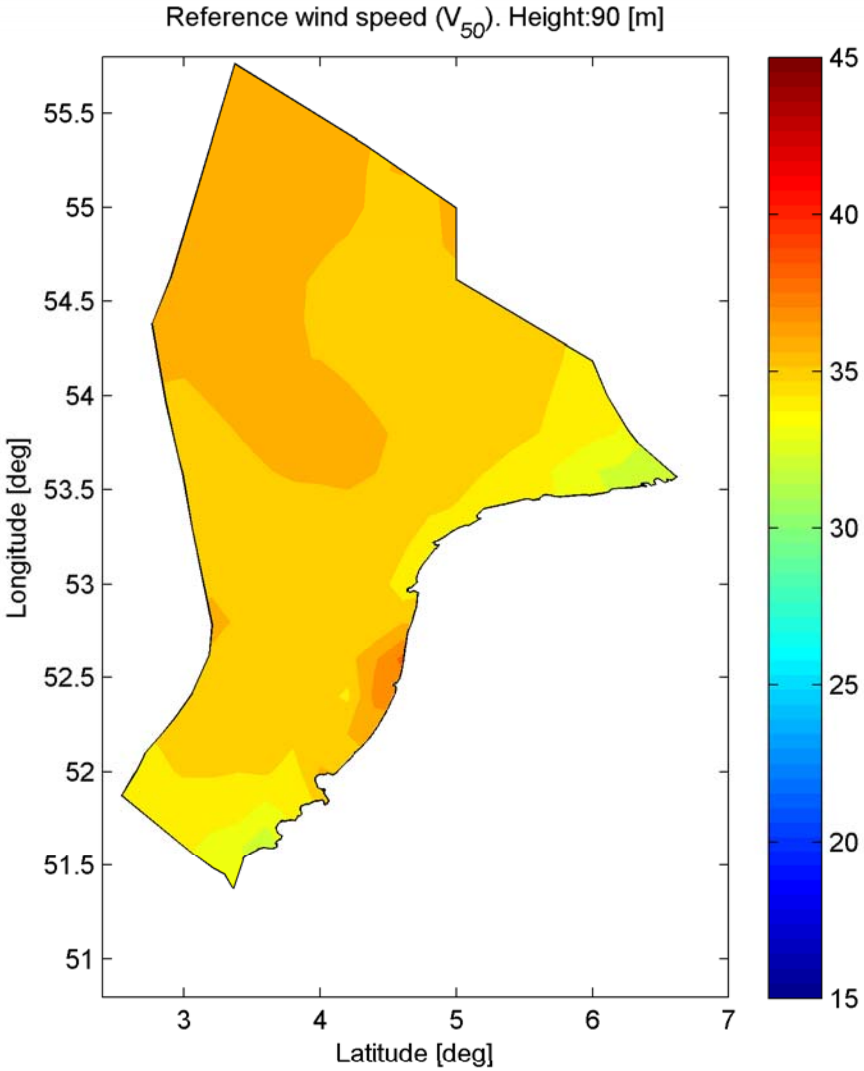


		Wind direction sector [deg]												
Par.	**H** [m]	0	30	60	90	120	150	180	210	240	270	300	330	Total
A [m/s]	25	6.08	5.95	5.96	5.87	5.51	6.15	6.94	7.77	7.59	7.26	6.76	6.96	6.80
	45	6.62	6.53	6.68	6.54	6.19	6.86	7.72	8.58	8.34	7.92	7.46	7.56	7.50
	70	7.02	7.04	7.24	7.09	6.74	7.45	8.37	9.28	8.96	8.52	8.03	8.06	8.10
	85	7.21	7.27	7.50	7.34	6.99	7.71	8.68	9.62	9.25	8.76	8.29	8.29	8.37
	108	7.44	7.55	7.82	7.66	7.31	8.08	9.05	10.04	9.63	9.13	8.61	8.57	8.73
k [-]	25	2.34	2.48	2.56	2.31	2.26	2.35	2.30	2.33	2.12	2.00	2.19	2.31	2.13
	45	2.37	2.59	2.78	2.46	2.41	2.42	2.42	2.38	2.12	2.00	2.24	2.32	2.18
	70	2.36	2.72	2.92	2.58	2.47	2.47	2.50	2.46	2.14	2.04	2.28	2.35	2.24
	85	2.35	2.78	2.97	2.61	2.50	2.46	2.55	2.50	2.14	2.03	2.30	2.35	2.26
	108	2.34	2.83	3.01	2.65	2.51	2.47	2.56	2.56	2.15	2.06	2.30	2.34	2.29
f [%]	25	6.2	6.1	6.9	6.9	5.0	5.3	7.3	14.4	14.6	10.6	8.8	7.8	100.0
	45	6.2	6.1	6.9	6.9	5.0	5.3	7.3	14.3	14.6	10.6	8.8	7.8	100.0
	70	6.2	6.1	6.9	6.9	5.1	5.3	7.4	14.3	14.6	10.6	8.8	7.8	100.0
	85	6.2	6.1	6.9	6.9	5.0	5.3	7.4	14.3	14.6	10.6	8.8	7.8	100.0
	108	6.2	6.1	6.9	6.9	5.1	5.3	7.4	14.3	14.6	10.6	8.8	7.8	100.0
V_m [m/s]	25	5.41	5.26	5.29	5.29	4.92	5.43	6.21	7.01	6.88	6.60	6.04	6.08	6.10
	45	5.88	5.77	5.88	5.86	5.49	6.06	6.88	7.75	7.59	7.24	6.63	6.61	6.72
	70	6.25	6.19	6.35	6.33	5.97	6.60	7.43	8.37	8.16	7.76	7.12	7.04	7.23
	85	6.42	6.38	6.58	6.54	6.20	6.84	7.70	8.65	8.43	8.01	7.34	7.23	7.47
	108	6.63	6.61	6.86	6.81	6.47	7.16	8.03	9.01	8.77	8.31	7.63	7.49	7.77

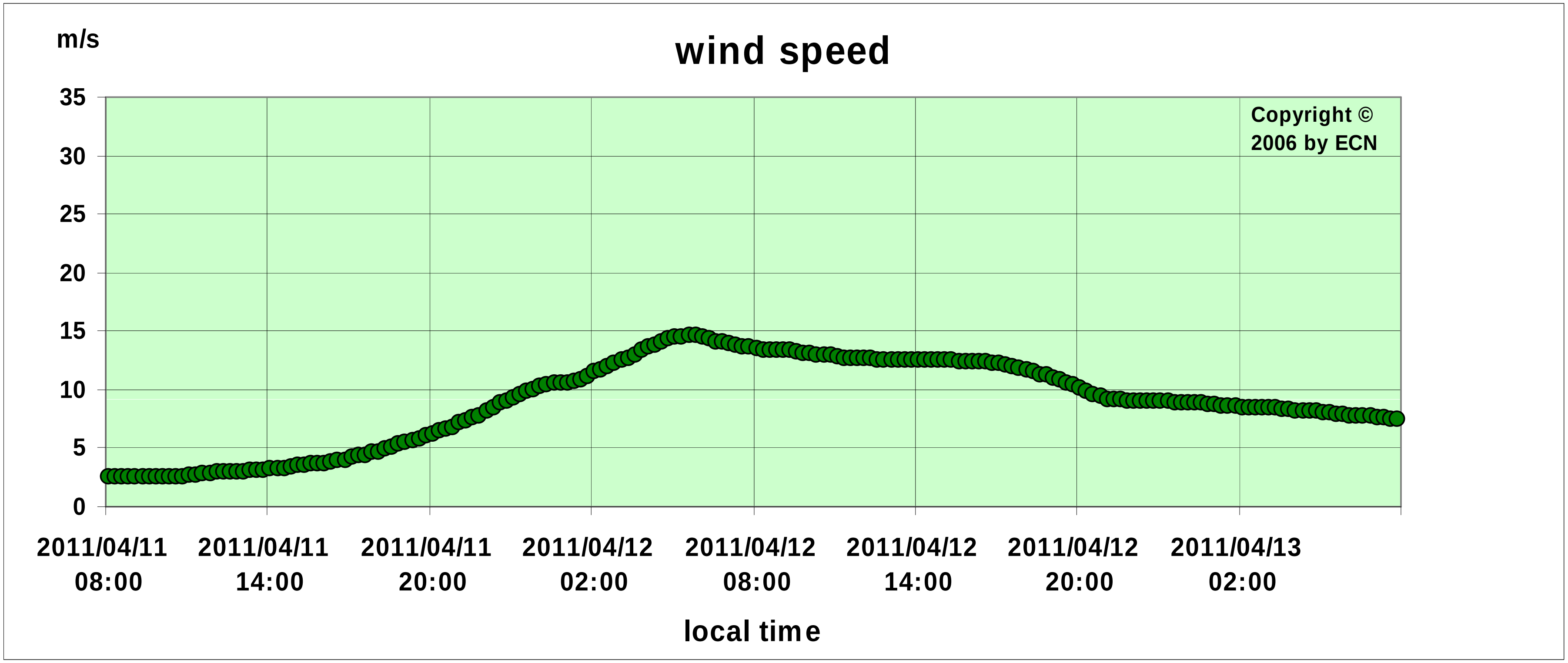
Wind Resource Assessment



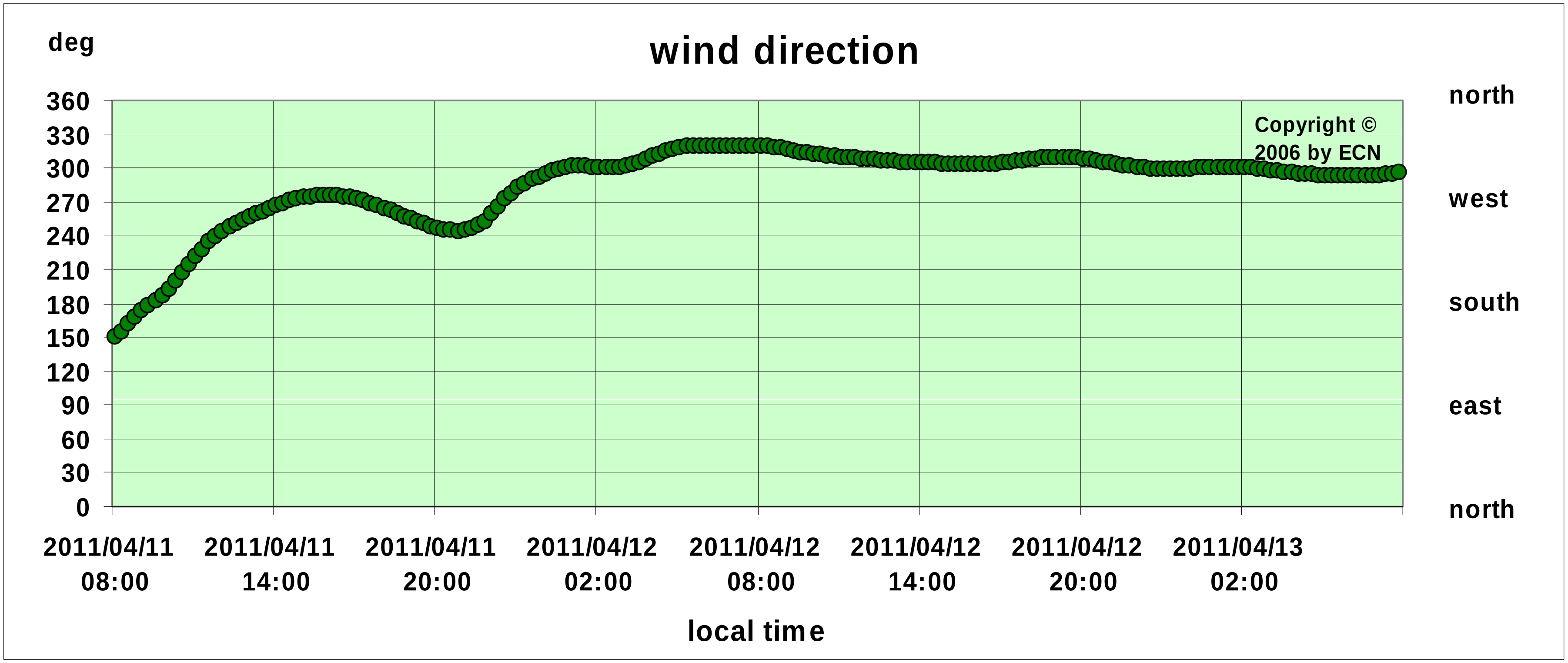
Wind Resource Assessment



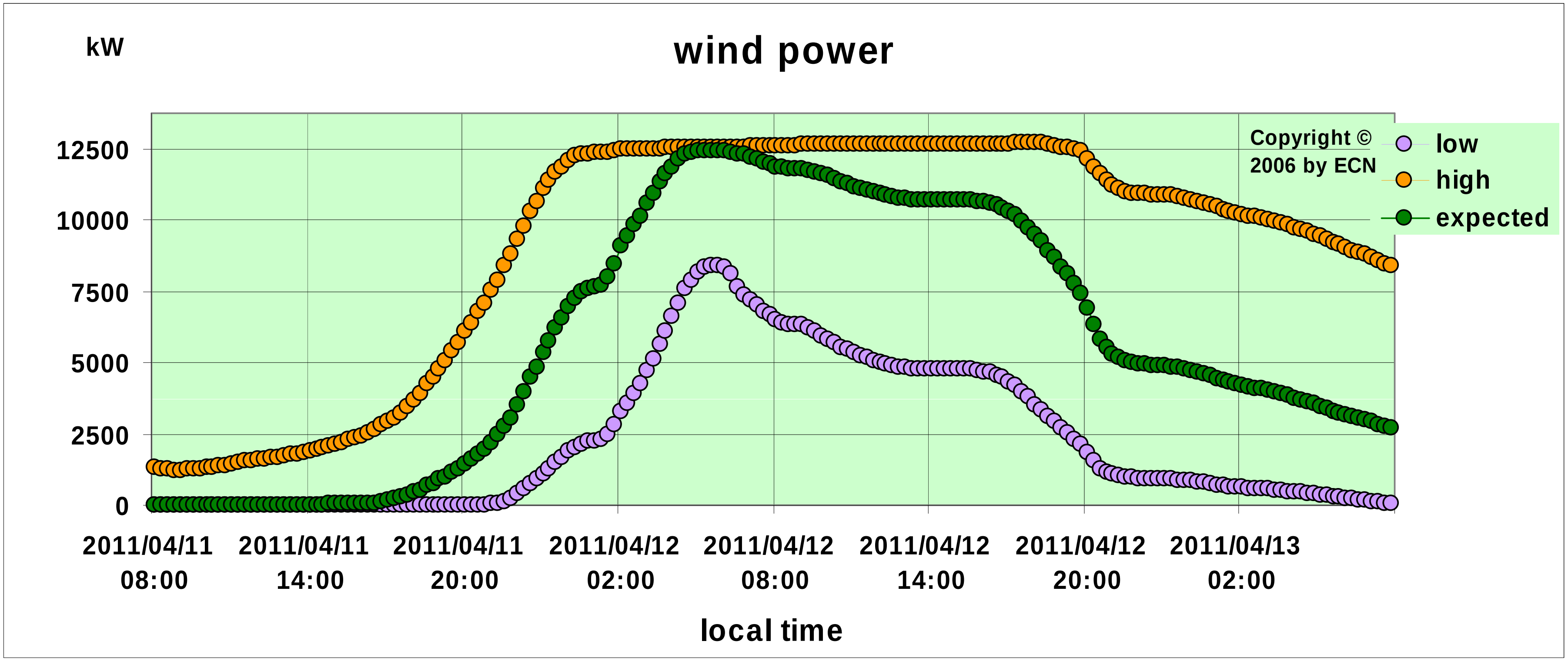
Wind Power Forecasting



Wind Power Forecasting



Wind Power Forecasting



Summary

- Downscaling method
- Wind resource assessment
- Wind power forecasting

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