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Wind Power and Natural Disasters

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Abstract

Wind power can be related to natural disasters in several ways. This licentiate thesis gives some background and introduces four papers devoted to two aspects of this relation. The first section looks into how small-scale wind energy converters (WECs) could be used to generate power after a natural disaster. For this application diesel generators are the most common solution today, but there would be several advantages of replacing these systems. A study of off-grid systems with battery storage at 32 sites showed that photovoltaics (PV) were more suitable than WECs. The results were confirmed by a study for the entire globe; PV outperformed WECs at most sites when it comes to small-scale application. This is especially true for areas with a high disaster risk. Hybrid systems comprising both PV and WECs are however interesting at higher latitudes. For the Swedish case, it is shown that gridded data from a freely available meteorological model, combined with a statistical model, give good estimates of the mean wind speed at 10 meters above ground. This methodology of estimating the mean wind speed can be used when there is no time for a proper wind measurement campaign.

The second section is directed towards wind power variability and integration. The results presented in the thesis are intended as a basis for future studies on how a substantially increased wind power capacity affects the electric grid in terms of stability, grid reinforcement requirements, increased balancing needs etc. A review of variability and forecastability for non-dispatchable renewable energy sources was performed together with researchers from the solar, wave and tidal power fields. Although a lot of research is conducted in these areas, it was concluded that more studies on combinations of the sources would be desirable. The disciplines could also learn from each other and benefit from the use of more unified methods and metrics. A model of aggregated hourly wind power production has finally been developed. The model is based on reanalysis data from a meteorological model and detailed information on Swedish WECs. The model proved very successful, both in terms of low prediction errors and in the match of probability density function for power and step changes of power.

List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I **J. Olauson**, A. Goude and M. Bergkvist, “Wind Energy Converters and Photovoltaics for Generation of Electricity after Natural Disasters”, Resubmitted after minor revision to *Geografiska Annaler: Series A, Physical Geography*, May 2014.

II **J. Olauson** and M. Bergkvist, “Modelling the Swedish Wind Power Production Using MERRA Reanalysis Data”, Submitted to *Renewable Energy*, April 2014.

III J. Widén, N. Carpman, V. Castellucci, D. Lingfors, **J. Olauson**, F. Remouit, M. Bergkvist, M. Grabbe and R. Waters, “Variability Assessment and Forecasting of Renewables: A Review for Solar, Wind, Wave and Tidal Resources”, Submitted to *Renewable & Sustainable Energy Reviews*, April 2014.

IV **J. Olauson**, J. Samuelsson, H. Bergström and M. Bergkvist, “Using the MIUU Model for Prediction of Mean Wind Speed at Low Height”, Submitted to *Wind Engineering*, May 2014.

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Contents

1. Introduction

In the early history of wind power the wind energy converters (WECs) were built to supply local energy demands including e.g. water pumping and operation of electric equipment [1]. When wind turbines were beginning to be connected to larger electric grids a rapid increase in tower, turbine and generator size started which has not ceased since. The main driver of this development has been the better wind conditions at higher hub heights and economics of scale which gives lower cost per produced energy unit for larger WECs.

Globally the accumulated wind power capacity has over the last 15 years doubled in every three years and currently roughly 3% of the world's electricity is produced by WECs. In some countries and regions wind power supplies a substantial part of the electricity. Two examples are Spain with 16% wind penetration and West Denmark with 24% [2]. By including planned and projected installations, several other regions will have a high share of wind power in the system in the near future.

The dominating design of modern wind turbines is three-bladed horizontal axis wind turbines, but other designs are also under consideration. Although the lion's share of the wind power capacity is grid-connected and large-scale, there is also an interest in small-scale wind power. This could be either for domestic use as an expression of environmental concerns and a wish to be less dependent on the energy companies or for regions without access to the main electrical grid.

Natural disasters can be linked with wind power and the electrical system in several ways. The whole electrical system is susceptible to disasters such as storms, earthquakes, extreme icing events etc. Moreover the vulnerability of the power system can be altered by the power mix; introducing large amounts of highly variable production with little or no inertia can decrease the robustness of the grid if proper measures are not taken. An idea further elaborated in this thesis is also the possibility of using small-scale wind power and photovoltaics for generation of electricity after a natural disaster. This could potentially mitigate problems related to conventional diesel generators used today.

1.1 Research objectives

The author of this thesis is a member of the research school Centre for Natural Disaster Sciences (CNDS). The original research objective was to develop and construct a portable wind energy converter, intended for generation of electricity in the immediate response and for more long-term recovery work after a natural disaster [3].

Based on the results from the preparatory studies in Paper I and IV, focus was instead shifted towards the study of wind variability and wind integration (i.e. how a higher share of wind power will affect the power system). By reviewing the existing literature it was found that significant improvements in the methods used to produce wind power time series were possible. These time series should be realistic representations of the variations to be expected with future wind power installations.

1.2 Wind power research at UU

At the Division of Electricity at the Ångström Laboratory research on straight-bladed vertical axis wind turbines have been conducted for more than ten years, focused on e.g. generators [4, 5], aerodynamics [6] and the electrical system [7]. Four wind energy converters have been designed and constructed for research purposes:

- Torsholm 200 kW [8] - Constructed by the spin-off company Vertical Wind, but now owned by Uppsala University.
- Lucia 12 kW [9] - Research wind turbine.
- Birgit 10 kW [10] - A novel concept turbine developed to electrify telecommunication towers.
- Rolf - A small wind turbine built for demonstration purpose.

Wind power research is also conducted by meteorologists at the Department of Earth Sciences. Examples of research fields are the MIUU model (see section 2.2.1), wind power in forest and mapping of icing. Paper IV has a co-author from the department of earth sciences and other collaborations between meteorologists and engineers from the Ångström Laboratory are ongoing.

1.3 Outline of thesis

In chapter 2 some background theory and methods used in the papers are presented. The following two chapters are devoted to the main results and discussion for small-scale off-grid energy systems (chapter 3) and wind power integration (chapter 4). The thesis is concluded with an outline of future work and a short summary of the four papers which this thesis is based on. The papers themselves are included as appendices.

2. Theory

In this chapter a theoretical background for the presented papers is given. For equations governing meteorological models and optimization methods the reader is however referred to relevant articles. Section 2.1-2.3 describes theory related to wind, meteorological models and wind energy converters. In section 2.4 a time-series technique (ARMA) used in one of the papers is introduced. Finally methods used for calculating photovoltaic power are described.

2.1 Wind

Large-scale wind patterns are driven by pressure differences and the rotation of the earth (the Coriolis effect). On the meso- and microscale phenomena such as sea breeze, terrain etc. also affects the wind flow. At more complex sites it could therefore be large differences in mean wind speed on the scale of hundreds of meters. In the surface layer the wind speed generally increases with height, i.e. there is a positive wind shear. The mean wind shear depends on surface roughness and orography; in e.g. forests the wind speed is generally lower near ground, but the shear is high. The shear also varies in time depending on the atmospheric stability and other factors. The wind profile is often described by the empirical power law:

$$u(z) = u(z_{ref}) \left(\frac{z-d}{z_{ref}-d} \right)^{\alpha}, \tag{2.1}$$

where u is wind speed, z is height above ground, d is (zero-plane) displacement height and α is the shear exponent. The displacement height describes the elevation of the zero level of the wind in and near cities, forest and other vegetation and is often around 0.6 - 1.0 of the canopy height. In practice, the wind speed never reaches zero, but the profile at heights relevant for wind power is better described if the displacement height is included. The probability density of wind speeds at a particular site is often considered to follow a Weibull distribution:

$$p(u) = \frac{k}{A} \left(\frac{u}{A} \right)^{k-1} \cdot exp \left[- \left(\frac{u}{A} \right)^{k} \right], \tag{2.2}$$

where p is the probability density function of wind speed u, given the Weibull scale factor A and shape factor k. The Weibull parameters A and k are linked to

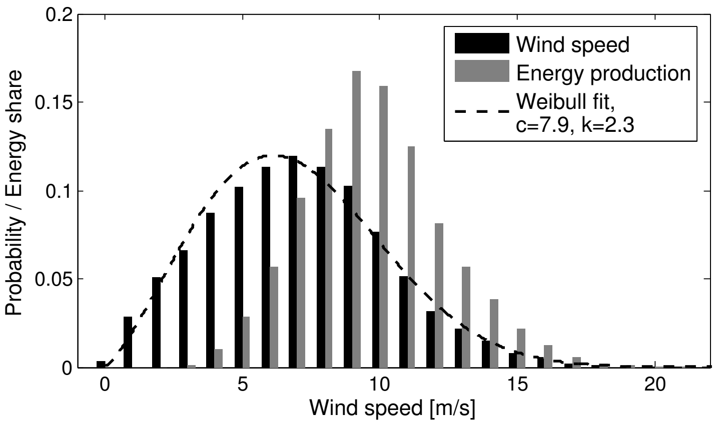

Figure 2.1. Histogram and Weibull fit of wind speed probability and energy production share. The measurement is taken 100 m above ground, mean wind speed is 7.0 m/s. Energy production is calculated for Vestas V90 2MW.

the mean wind speed $\bar{u}$; given two of the parameters the third can be calculated. If nothing more than mean wind speed is known, a Rayleigh distribution is often assumed, i.e. a Weibull distribution with shape factor equal to 2. One must though be careful assuming Weibull/Rayleigh distributed wind; some sites exhibit two peaks in the distribution and an assumed Rayleigh distribution can give severe errors in energy calculations, not at least at low heights (see Paper IV). An example of measured wind speed and Weibull fit is shown in Fig. 2.1.

The temporal variations in wind speed are significant. Seasonal and diurnal trends are present in many areas. In Sweden for instance the capacity factor (i.e. average power relative installed capacity) is around 18% in June-August and 29% in November-March (data from 2007-2012, see Paper II). An example of wind speed variations for a 100 meter measurement in Sweden is shown in Fig. 2.2.

To determine the wind conditions for a wind power park, on-site wind measurements are normally carried out during a one or two year period. Because of the long-term variability of wind speed and direction, a long-term correction (LTC) of the measurement is necessary. Normally this is done with the "MCP" method:

1. Local **m**easurement of wind speed, wind direction, temperature etc.
2. **C**orrelate the measurement with a long-term reference series. This can be a nearby wind measurement, but often data from a meteorological model is used. Several correlation methods are used, see e.g. [11]. An often used method is (directionally binned) linear regression with residual resampling.

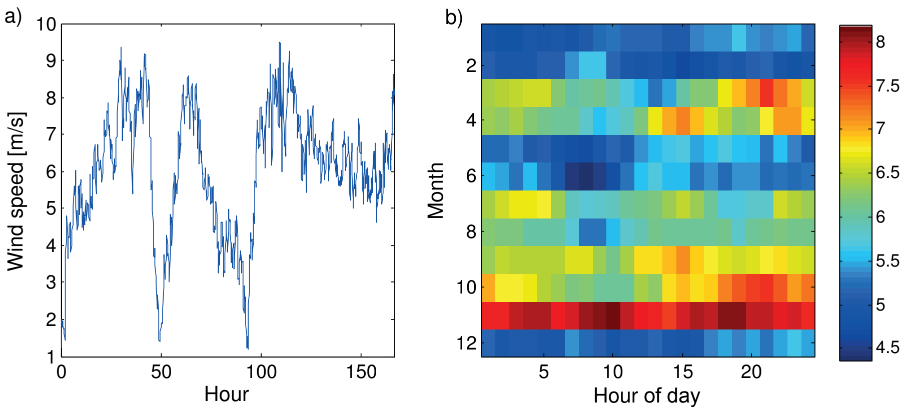

Figure 2.2. Example of one week wind speed time series with 10 minute resolution (a) and monthly/diurnal mean wind speed during one year of measurements (b).

3. **P**redict the on-site long-term wind speed distributions for each directional bin by using the relation between local and reference time series.

2.2 Meteorological models

Numerical Weather Prediction (NWP) models are used to forecast wind speed and other variables for hours up to several days ahead. In order to get more refined results the output from global models can be fed into a regional model with higher resolution, a procedure referred to as dynamical downscaling. The same (type of) models could also be run with historical data in order to produce long, high quality and homogenous data sets for research and climate services. Several of these "reanalysis" data sets are publicly available, e.g. ERA Interim, MERRA and JRA-55 [12–14]. Data from meteorological models have been used in all four papers included in this thesis. The two models used are described shortly in the following sections.

2.2.1 MIUU

The MIUU-model is a three-dimensional mesoscale model developed at the Department of Meteorology, Uppsala University [15,16]. In more recent years a method to reduce computational time for calculating the climatological mean of the wind field has been developed [17]. Using this method, only a limited number of representative weather situations are simulated and weighted to give the long-term mean. Simulations with horizontal resolution of 1 and 0.5 km respectively have been performed for the whole of Sweden. This data is publicly available and have been used extensively by wind power prospectors.

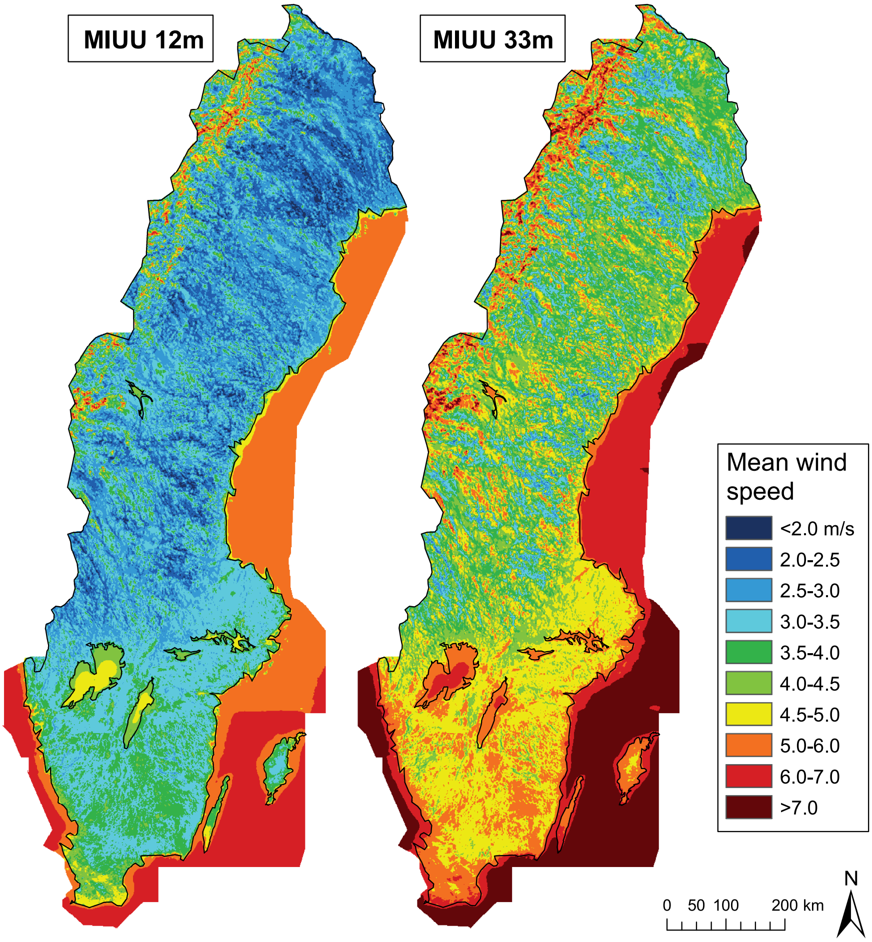

Figure 2.3. Long-term mean wind speed 12 and 33 m above displacement height according to the MIUU model. Horizontal resolution is 1 km.

Maps showing mean wind speed at 12 and 33 m above displacement height are given in Fig. 2.3.

2.2.2 MERRA

Modern-Era Retrospective analysis for Research and Applications (MERRA) is a NASA reanalysis for the satellite era, i.e. since 1979 [13]. The analysis is performed with spatial resolution of 0.5 degree in latitude and 0.67 degree in longitude and one hour temporal resolution. Variables available in the model include e.g. wind speed and direction, temperature, solar irradiation and air pressure. Because of the good correlation to measurement and the relatively high temporal resolution, MERRA is popular in industry long-term correction

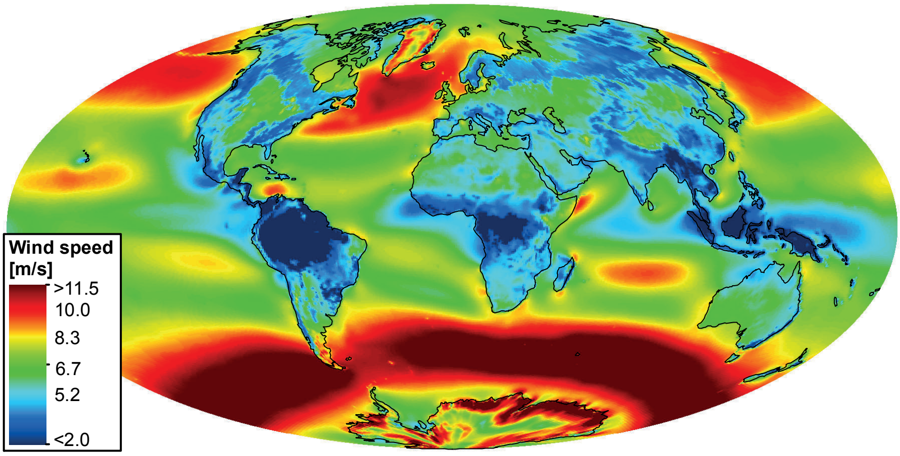

Figure 2.4. Mean wind speed 50 m above ground during the period 2004-2013 according to the MERRA model. Horizontal resolution is $0.5 \times 0.67°$.

of wind measurements. Wind speed and direction is available at 10 m above displacement height and 50 m above ground. In Fig. 2.4 the mean wind speed (2004-2013) at 50 meters is shown.

2.3 Wind energy converters

The available power P_u in the atmospheric flow is a function of the wind speed u, air density ρ and area A perpendicular to the wind direction:

$$P_u = \frac{1}{2}\rho A u^3. \tag{2.3}$$

It has been shown that even for an idealized wind turbine there is a limit to how much of the energy in the wind that could be converted to mechanical energy: 16/27 or the Betz limit [18]. A real wind turbine has a lower aerodynamic efficiency and by including mechanical and electrical losses the overall efficiency is peaking at around 45-50% for large-scale modern WECs. Because of component and grid connection costs there is a trade-off in the rating of the generator power. For a given turbine rotor area, a higher rated power will increase the yearly electricity production but also the costs. The optimum ratio of rated power to rotor area depends on the site specific wind conditions. At low, often up to 3-4 m/s, as well as at high, often above 20 or 25 m/s, wind speeds the WEC is not operating. The resulting power to wind speed relation is known as the power curve and can readily be obtained for any commercial WEC, at least for standard air density (1.225 kg/m^3). According to the IEC standard [19], the power curve is given as a function of 10 minute mean wind speeds. Some examples of normalized power curves are shown in Fig. 2.5.

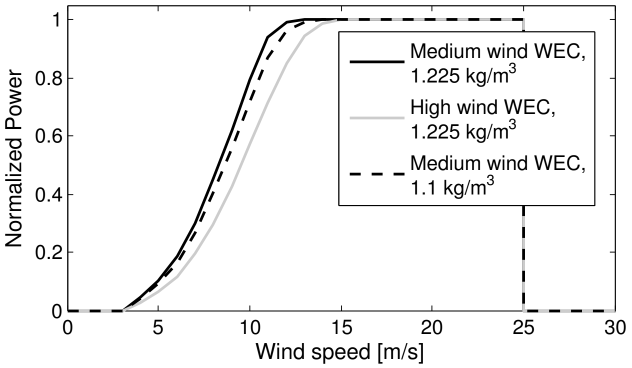

Figure 2.5. Three selected power curves for WECs with different air density and ratio of rated power to turbine area. "High wind" WECs have higher rating of the generator compared to the turbine area.

Mean power can be obtained by summing up the contributions of $P(u_i) \cdot p(u_i)$, where P and p are output power and wind speed probability for a bin centered at u_i. As can be seen in the example in Fig. 2.1, the largest share of the wind energy is often produced at relatively high, but less probable, wind speeds.

There are several factors influencing the actual power output of a WEC. The power curve accounts for aerodynamic losses and electrical losses in the WEC. Additional reductions in power are due to aerodynamic degradation from dirt and icing, hysteresis losses (after a high wind stop the WEC does not start until the wind speed falls below a certain value), grid and transformer losses and maintenance. Since the certification of the power curve is performed under certain circumstances, operation of the WEC in different conditions might change the power curve. A more turbulent flow e.g. gives higher power at low wind speeds but lower power near rated wind speed.

2.4 ARMA

Autoregressive moving average (ARMA) models and extensions of this concept is a popular and powerful time series tool used in various different fields. ARMA models can be used for short-term forecasting (up to a few hours) or to generate fictive time series. The latter could be useful for replacing missing data or for generating very long time series for e.g. power system reliability simulations. A key concept for ARMA models is the autocorrelation function, which is the linear correlation of a process with itself, shifted in time. The sample ACF at lag k of an observed time series $x_1,...,x_n$ can be calculated by

$$ACF_k = \frac{\sum_{t=k+1}^{n}(x_t-\bar{x})(x_{t-k}-\bar{x}))}{\sum_{t=1}^{n}(x_t-\bar{x})^2}. \tag{2.4}$$

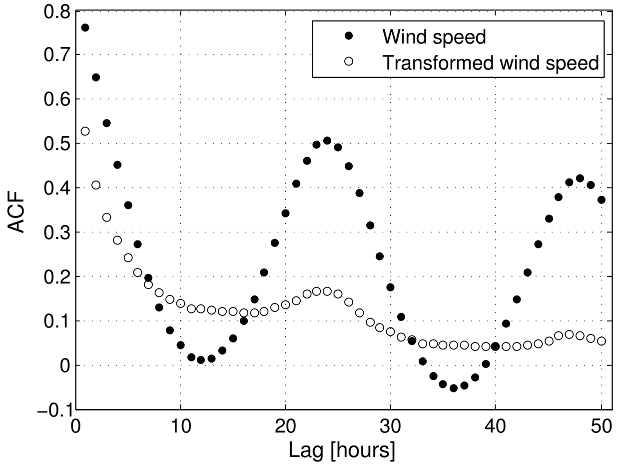

Figure 2.6. Autocorrelation for wind speed and corresponding transformed time series (10 m measurement height near Kabul, Afghanistan).

Fig. 2.6 shows an example of the autocorrelation function for wind speed (and transformed wind speed, see Eqns (2.6) and (2.7)). Diurnal patterns in the wind speed gives an increase in the ACF around $24 \cdot n$ hours and lower ACF at 12h, 36h etc.

An ARMA process with AR order p and MA order q is notated ARMA(p,q) and satisfies the equation

$$Y_t = \phi_1 Y_{t-1} + \phi_2 Y_{t-2} + \ldots + \phi_p Y_{t-p} + e_t - \theta_1 e_{t-1} - \theta_2 e_{t-2} - \ldots - \theta_q e_{t-q}, \quad (2.5)$$

where ϕ_i are AR coefficients, θ_j are MA coefficients and e is Gaussian white noise with mean 0 and variance σ^2. Be aware that different sign conventions are sometimes used for the constants in Eqn (2.5). Before an ARMA model is fitted to a time series a transformation to stationarity (time invariant mean and variance) and normality is necessary. A multitude of transformations are used in the literature. In Paper I the wind speed was transformed to stationarity using

$$y_0(t) = \frac{u(t) - \mu(m,h)}{\sigma(m,h)}, \quad (2.6)$$

where μ and σ are sample mean and standard deviation for each hour in each month. The resulting time series were subsequently transformed to approximate normality with the Box-Cox transformation

$$y(t) = \frac{y_0(t)^\lambda - 1}{\lambda}. \quad (2.7)$$

As can be noted from Fig. 2.6 the ACF of the transformed time series has a much weaker diurnal swing compared to the original time series.

2.5 Photovoltaics

In order to estimate the power output from a PV system one first needs to calculate the in-plane irradiance since, regardless the data come from measurements or from meteorological models, the irradiance is often given relative a horizontal surface. In Paper I the HelioClim-3 model was used which gives the in-plane irradiance, corrected for differences in elevation [20]. For the new results presented in section 3.1.3 horizontal global irradiance G_h from MERRA was however used. The in-plane irradiance G was calculated from G_{hor} and clear-sky irradiance G_0 using approximations given by [21, 22] and coded in Matlab by Joakim Widén (Uppsala University). The basic idea behind the calculations is that the diffuse irradiance G_d can be approximated when G_0 and G_h are known (when G_h is small relative G_0, the diffuse component must be large). Given the diffuse component, in-plane irradiance can finally be estimated.

The panels were always directed towards the equator (azimuth 0° or 180° that is). For stand-alone systems (PV/battery) the optimum tilt of the panels are generally steeper than the optimum tilt for maximized annual energy production. The reason is that the system has to be dimensioned for the production in wintertime, and this is increased with a steeper tilt. A general expression of the optimum tilt as function of latitude was found by simulations for a few hundred locations. This expression was later used when simulating hybrid systems for the entire globe (approx. 50,000 grid points, see section 3.1.3)

The model for hourly energy generated from photovoltaics was adopted from [23]. The output power is a function of in-plane irradiance G and module temperature T_{mod}

$$P(G, T_{mod}) = P_{STC} \cdot \frac{G}{G_{STC}} \cdot \eta_{rel}(G', T'), \tag{2.8}$$

where η_{rel} is instantaneous relative efficiency. Subscript STC indicates standard test conditions and prim values are normalized to STC; $G' = G/G_{STC}$ and $T' = T_{mod} - T_{mod,STC}$ where $G_{STC} = 1000$ W/m^2 and $T_{mod,STC} = 25$°C. Instantaneous relative efficiency is given by

$$\eta_{rel}(G', T') = 1 + k_1 \ln G' + k_2 (\ln G')^2 + T' \cdot \left[k_3 + k_4 \ln G' + k_5 (\ln G')^2\right] + k_6 T'^2. \tag{2.9}$$

T_{mod} can be estimated from ambient temperature and irradiance by

$$T_{mod} = T_{amb} + c_T G. \tag{2.10}$$

The constants $k_1 - k_6$ and c_T can be fitted to measured data for a certain PV configuration, e.g. crystalline silicon.

3. Small-scale off-grid energy systems

Electrical power systems are highly susceptible to natural disasters and power outages are common after e.g. hurricanes and earthquakes [24]. Autonomous, small-scale power generation might be needed both in the immediate disaster response and for more long-term recovery work. The conventional method is to use diesel generators, but fossil fuels have a negative environmental impact and can be problematic to transport to remote sites. Both transportation and storage of diesel also constitutes a security risk since the fuel is attractive to thieves and bandits.

In addition, the cost of producing (diesel based) electricity in isolated systems can be high. According to a report from 2001 [25], the cost varies over a wide range:

- Low cost 0.20 USD/kWh
- Medium cost 0.45 USD/kWh
- High cost 1.0 USD/kWh

One could expect electricity generation after a natural disaster to fall in the high cost range and thus it could be a considerable economic gain in reducing the diesel consumption. Taken altogether there are good incentives for reducing or eliminating the use of fossil fuels during and after a natural disaster.

There has been substantial research interest in hybrid energy systems comprising combinations of e.g. wind power, photovoltaics, conventional diesel generators and battery storage. One of the underlying motives for the studies have been that wind and solar often have complementary characteristics and thus a hybrid system utilizing the two sources can have a more smooth power output, higher reliability and lower overall cost. Relatively recent reviews of methods and models used when optimizing a hybrid system can be found in [26, 27]. A systematic but older review together with operational guidelines, an overview of operating hybrid systems etc. is found in a series of reports from Risø ([28] and sub-reports). An example of a hybrid system topology without diesel generator is shown in Fig. 3.1.

In conventional wind energy projects the wind conditions are measured at site for at least one year. As pointed out in [29] proper anemometry is costly and this approach is unrealistic for small-scale wind projects. For generation of power after a natural disaster time is also a factor ruling out normal wind measurements. It would therefore be advantageous to have tools to assess the wind resource at low heights.

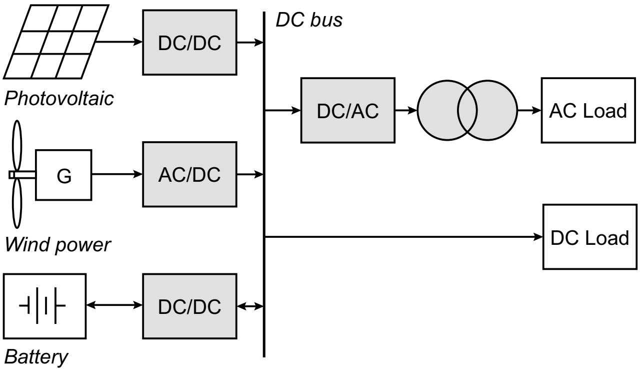

Figure 3.1. Hybrid system comprising WEC, PV and battery bank. Fig. 1 from Paper I.

3.1 Results

The results presented in this section are based on Paper I and IV. Paper IV presents an evaluation of using the MIUU meso-scale model to predict mean wind speed at 10 meters above ground in Sweden. These results are summarized in section 3.1.1. In Paper I the feasibility of using small-scale wind power and a battery storage for power supply after a natural disaster was evaluated and compared with systems containing photovoltaics. The results from this paper are summarized in section 3.1.2. Finally some unsubmitted results, produced using mainly the methodology developed in Paper I, are presented in section 3.1.3.

3.1.1 Predicting mean wind speed at low height

The MIUU model is a meso-scale meteorological model developed at the Department of Meteorology, Uppsala University. The model has been used to generate wind climatologies for Sweden, and mean wind speed on a grid with 0.5 and 1 km horizontal resolution for a few heights are freely available. In Paper IV the model output was compared to 128 wind measurements at 10 m above ground from the Swedish Meteorological and Hydrological Institute (SMHI). Maps showing MIUU modelled wind speeds at two vertical levels are found in Fig. 2.3. In Fig. 1 in Paper IV the same maps are shown together with measured wind speed in the SMHI station network.

To calculate the mean wind speed at the measurement position bilinear interpolation and the power law (Eqn (2.1)) was used. A statistical model was also developed to improve the predictions. The idea was to group the measurements according to their main terrain type and apply multiple regression. Five terrain categories were initially used, see Fig. 3.2, but in the statistical modelling forest and urban terrain were merged into “canopy” and the (too few) measurements taken in bare mountain terrain were excluded.

Table 3.1. *Model errors for MIUU and MIUU with statistical model. Subscript "all" indicates all 128 measurements and subscript "s" the 118 measurements included in the statistical modelling. Positive bias implies a model overestimation.*

	$MIUU_{all}$	$MIUU_s$	$MIUU_s$ + Statistical
MAE	0.58 m/s	0.52 m/s	0.39 m/s
MAE (%)	20%	20%	15%
RMSE	0.78 m/s	0.65 m/s	0.51 m/s
Bias	+0.01 m/s	+0.12 m/s	-0.00 m/s

Fig. 3.2 show mean wind speed according to MIUU and observation, grouped by terrain type. Table 3.1 show a couple of error metrics for raw MIUU data and after the statistical correction was performed. Even without the statistical correction MIUU performed relatively well with mean absolute error (MAE) of 0.52 m/s, or 0.58 m/s if the measurements in bare mountain terrain were included. Measurements in or near forest and urban terrain generally show low mean wind speed. Without taking into account the displacement height the MIUU model, as expected, overpredicts these winds. In open landscape there was no obvious bias in MIUU predictions, but coastal stations generally have higher mean wind speed than anticipated from MIUU. For measurements in highly complex "bare mountain" terrain, the errors were much larger than for other terrain types.

The statistical model reduced the MAE with 24% to 0.39 m/s. The predicted and observed mean wind speeds are shown in Fig. 3.3. The proposed model is simple to use, only requiring information on terrain type at the site, and should therefore be suitable even for persons without deeper knowledge in wind engineering. The combined model can be used to complement on-site measurements or, if measurements are not viable, replace those. It was found that the model prediction accuracy is equivalent to from less than one up to five months of on-site measurements, depending on whether long-term correction was used and whether one looked at all sites or only sites with mean wind speed above 4 m/s.

3.1.2 Hybrid system simulations

The aim of Paper I was to evaluate which type of renewable, small-scale, off-grid system was best suited for Swedish Civil Contingencies Agency (MSB) foreign operation. As case studies all 32 of active MSB operations as of the end of 2012 was chosen. Three topologies were considered:

- WEC with battery storage
- PV with battery storage
- WEC, PV and battery storage

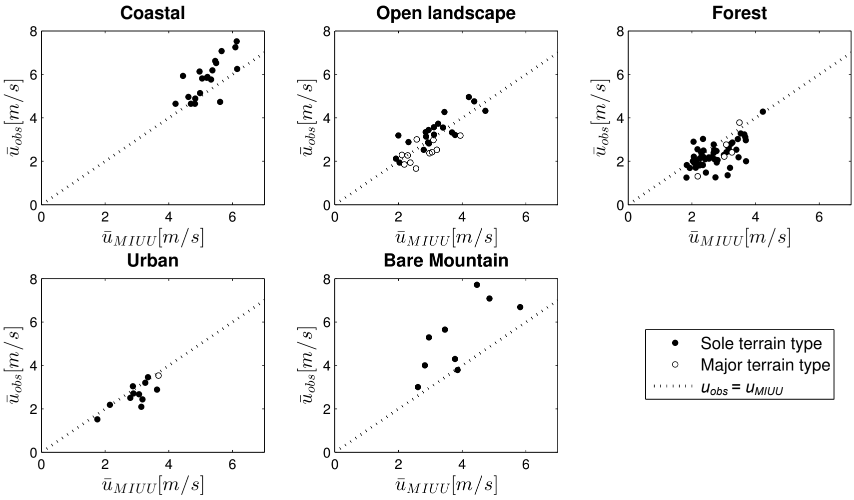

Figure 3.2. MIUU vs observed mean wind speed for different terrain classes. “Sole” terrain type means that 100% weight was given to this type in the regression. “Major” terrain types however only got 2/3 weight. Fig. 2 from Paper IV.

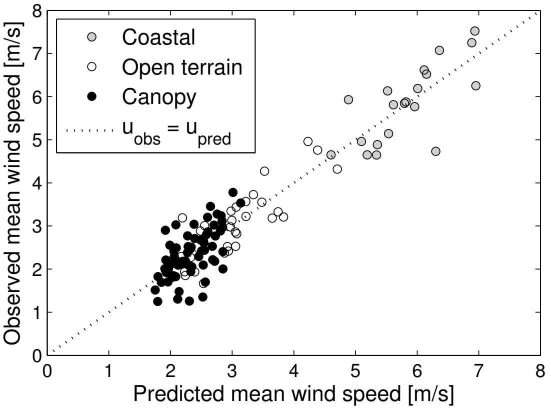

Figure 3.3. Predicted and observed mean wind speed. The predictions are based on MIUU data and a statistical model. Fig. 4 from Paper IV.

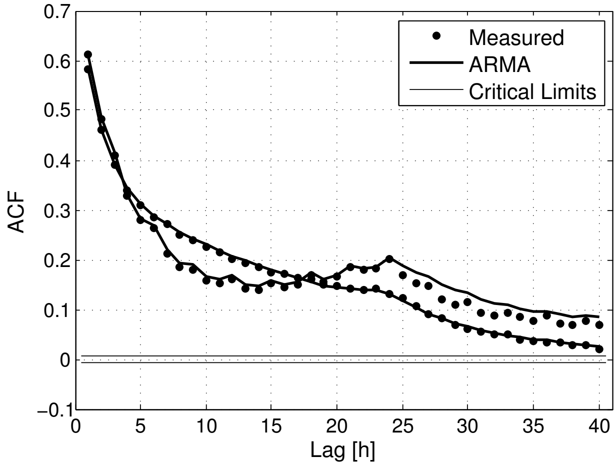

Figure 3.4. Two examples, one relatively good and one relatively bad, of the match of ACF of transformed observed wind speed and corresponding ARMA process. Fig. 5 from Paper I.

Most of the sites were located in Africa and in the Middle East. The quality of the on-site wind measurements was very shifting, and in a few cases no measurements were found at all. Because of the large amounts of missing data autoregressive moving average (ARMA, see section 2.4) models were trained and used to generate hourly time series of wind speed. For comparison, and for the sites where no measurement stations were available, data from the MERRA meteorological model was also used.

The use of ARMA models to generate fictive wind speed time series proved successful, even when the data availability of the original measurement was extremely low. Fig. 3.4 and 3.5 show examples of how the ARMA models were able to capture autocorrelation and seasonal/diurnal variations of the observed wind speed.

With complete time series of wind speed and solar irradiation the hourly production could be calculated according to the methodology given in section 2.3 and 2.5. Loads with maximum of 2 and 20 kW respectively with summer-peak profile according to [30] were then used to simulate hybrid systems. The system cost was minimized given an accepted loss of load probability (proportion of time where the system fails to supply the load) of 3%. Batteries, with an assumed cost of 100 €/kWh, were always included. Some assumptions for the WEC and PV used in the medium size (20 kW peak load) system are given in Table 3.2 and 3.3 respectively.

For the evaluated sites wind power was not able to match PV; the cost per produced kWh was higher, the risk for extended periods with very little production was higher and the cost of an optimized stand-alone system including batteries was substantially higher (see Fig. 3.6). The differences were larger

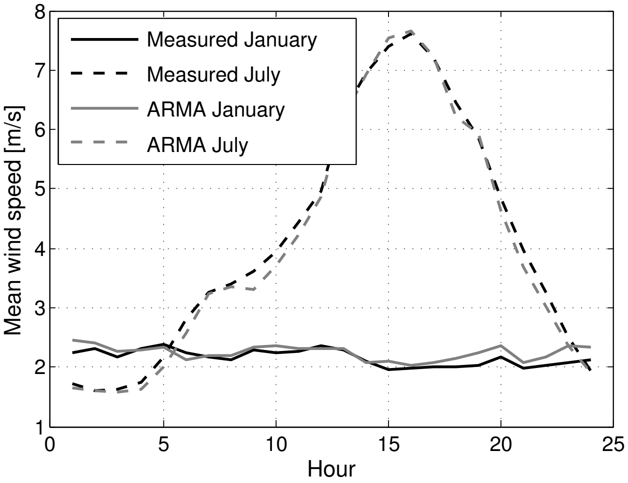

Figure 3.5. Hourly mean wind speed in January and July for observed and simulated time series (Kabul station). Fig. 6 from Paper I.

Table 3.2. *Assumptions for WEC in medium size hybrid system simulations.*

Rated power/swept area	144 W/m^2
Efficiency	Up to 39%
Additional losses	10%
Hub height	40 m
Cost	4.8 €/W

Table 3.3. *Assumptions for PV in medium size hybrid system simulations.*

Type	Crystalline-Si
Losses	16.6% + Loss(T,G), see section 2.5
Tilt	Optimized for maximum energy production
Cost	1.8 €/W

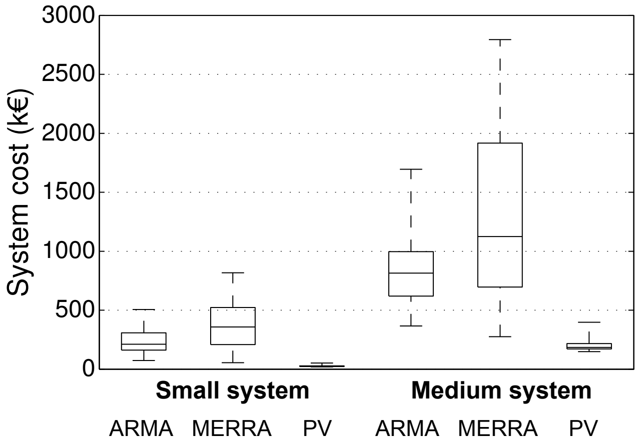

Figure 3.6. Cost of optimized hybrid systems. ARMA indicates calculations based on wind speed from an ARMA model (trained on actual on-site data). "MERRA system used wind speed from a meteorological model. Fig. 12 from Paper I.

for the small system (2 kW peak load). The results are robust according to the performed sensitivity analysis.

The results are quite different to what was found in the literature, where wind or wind/PV systems often outperformed PV only systems. Three main reasons were identified explaining the observed differences: i) The sites were not chosen based on good wind conditions (contrary to what is seen in many publications), ii) All sites were at relatively low latitudes with small seasonal variations in solar irradiation and iii) Strongly reduced costs for PV during the last years.

3.1.3 Global hybrid system simulations

Off-grid systems for 32 different sites were evaluated in Paper I, and PV/battery systems was superior for both the small load (2 kW peak) and medium load (20 kW peak) for all sites. The question was however raised if the results could be generalized to the entire globe or whether there are regions where wind/battery or wind/PV/battery systems are more suitable?

In order to answer this question simulations for all on-shore (including a 20 km buffer) MERRA grid points north of latitude -65° were conducted. Ten years of MERRA data was used in the simulations and the same methodology as given in section 3.1.2 was used with a few exceptions: No wind or irradiation measurements were included, only MERRA reanalysis data. The tilt of the panels were optimized for off-grid systems rather than maximum yearly energy yield (the difference in hybrid system cost was however small). In the optimization the Matlab function *fminsearchbnd* [31] was primarily used. If

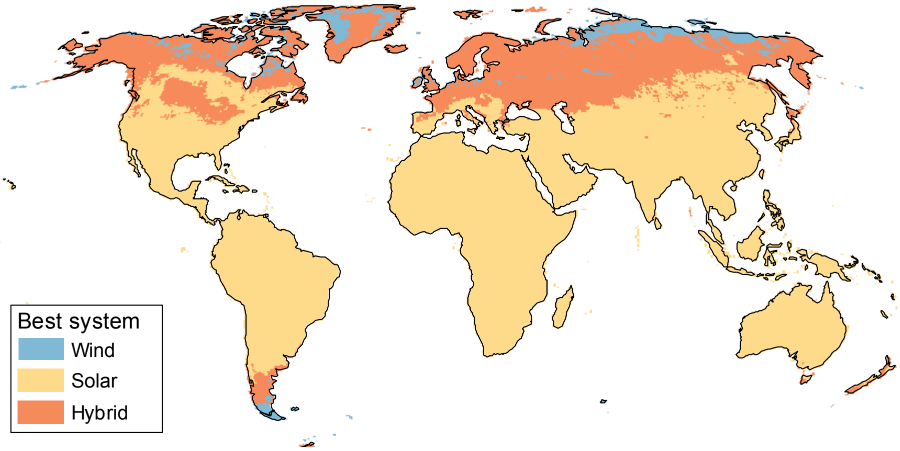

Figure 3.7. The best medium size system for off-grid application, based on simulations with MERRA reanalysis data. A hybrid (wind/PV/battery) system was considered best if the cost was 90% or less of the best single source system.

the maximum number of function evaluations was exceeded or NaN:s were produced the procedure described in Paper I was employed. Finally, only the medium-size system was considered, and no sensitivity analysis were performed.

The result of the simulations are shown in Fig. 3.7 and 3.8. For latitudes lower than 40° the PV/battery system is almost universally best, also for very windy areas. Between approx. latitude 40° and 60° hybrid systems are generally optimal, while wind only systems are often, but not always, best closer to the poles. Hybrid systems were considered best if the cost was 90% or less of the lowest cost single source system.

Weighted by grid cell area pure wind systems were found to be best for 3% of the land mass excluding Antarctica while pure PV systems were best for 73%. The remaining 24% were best suited for hybrid systems comprising both wind and PV.

3.2 Discussion

By using the MIUU model and the proposed statistical model (Paper IV) the mean wind speed at 10 m can be predicted with relatively good accuracy, at least in not too complex terrain. But what about the energy produced? Depending on the distribution of wind speeds two sites with the same mean wind speed could in theory have very different annual energy yield. The relation between mean wind speed and energy production (calculated with the actual distributions of wind speeds) are shown in Fig. 3.9. For comparison calculations based on Weibull distributions with shape factor 1.5 and 2 are also

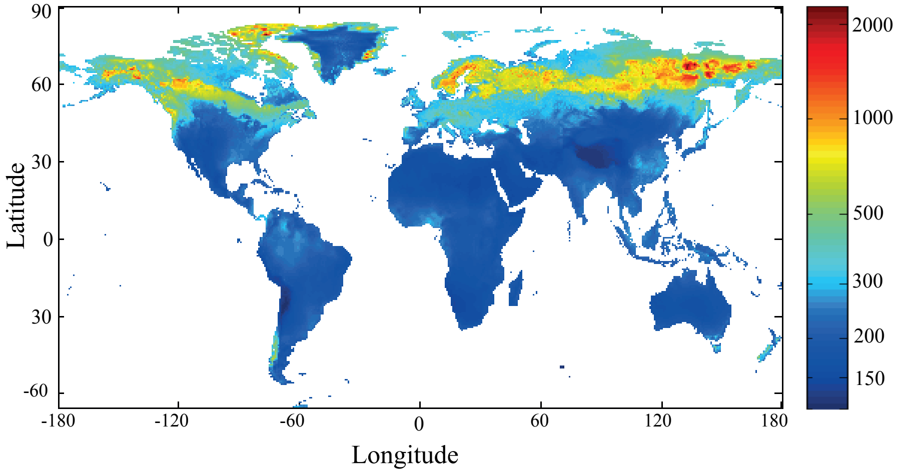

Figure 3.8. Cost of the cheapest system in k€. The color scheme is logarithmical to facilitate comparison in the most interesting cost range.

shown. Although there are some spread in the results the error obtained by using Weibull approximation is not too severe and the conclusion that the model could be useful as complement to or replacement for on-site measurements holds. One can note that it appears more appropriate to use a Weibull shape factor of 1.5 for mean wind speeds below 4 m/s.

The simulations of off-grid energy systems in section 3.1.2 and 3.1.3 showed that PV/battery systems are most suitable for a large part of the world, although hybrid systems with wind and PV are favourable at higher latitudes. One should bear in mind that the simulations in section 3.1.3 were performed assuming a medium-sized system (20 kW peak load) and a WEC with a large turbine compared to rated power. For smaller loads and with more normal ratio of rotor to generator rating, the wind based systems would have even harder to compete.

For comparison a country-wise disaster risk index (DRI) is shown in Fig. 3.10. The DRI is a combination of exposure and vulnerability to natural disasters [32]. The general trend is that PV power is most suitable for countries with a high DRI.

Diesel generators have not been included in any of the simulations. Would the proposed renewable systems be able to compete economically with conventional diesel generation? This question should of course be answered on a site-to-site basis, but it can nevertheless be interesting to make some rough calculations. Based on figures from [25] the cost of diesel electricity can vary over a wide range, with low cost at 0.20 USD/kWh and high cost at 1.0 USD/kWh. In a natural disaster context it is reasonable to expect high fuel transportation cost. By assuming 0.5 €/kWh for diesel electricity, neglecting maintenance and interest costs for the renewable systems and assuming in to-

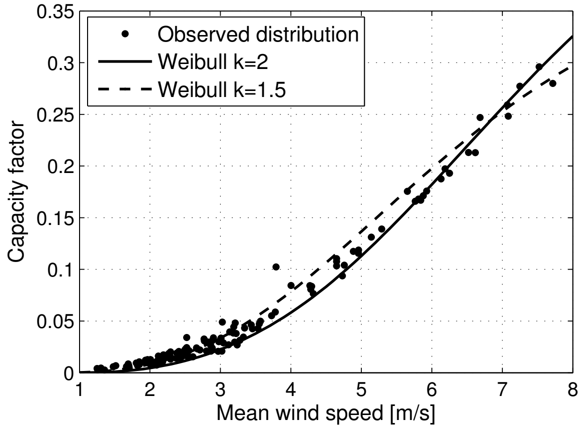

Figure 3.9. Capacity factor with observed distribution of wind speeds and Weibull distributions based on observed mean wind speed. Power curve for Bergey 10 kW wind energy converter was used in the calculation and 10% losses were included. Fig. 6 from Paper IV.

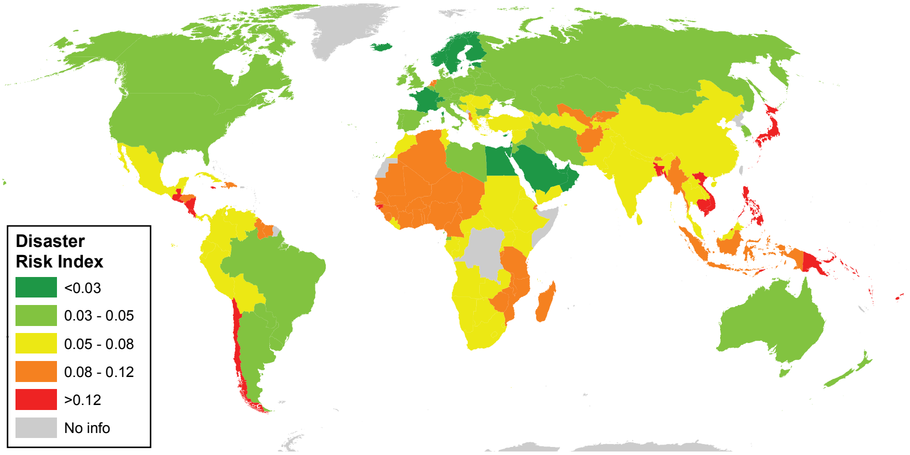

Figure 3.10. Countrywise Disaster Risk Index (DRI) according to [32]. The DRI is a combination of exposure and vulnerability to natural disasters.

tal 10 years of continuous operation one get a estimate of the upper cost limit for the renewable systems to be interesting to consider. For the medium size system the corresponding cost is around 500 k€. Judging from Fig. 3.8, the largest part of the globe are of interest for replacing diesel based off-grid electricity generation. Below latitude 40 the cost of PV/battery systems are often 150-300 k€, i.e. well worth consideration.

Based on the results presented in this chapter, it was decided to shift focus from small-scale wind energy converters to wind variability and integration. This research area will be introduced in the following chapter.

4. Wind power integration

In the last decade or so the installed capacity of wind power has in several countries increased to a level where the impact on the power system is significant. The projections for the near future is a continued growth, and it is only natural that the research field of wind power integration has also grown. Examples of research questions in focus are wind power forecasting, impact on voltage and frequency stability, increased reserve requirements, effects on electricity price and transmission system reinforcements. All these issues are tightly connected to the variability of the wind. For recommended practices and a summary of wind integration studies performed within the IEA Task 25 framework, the reader is referred to [33] and [2] respectively. The stability of the power system can also be related to its vulnerability to natural disasters. An important question is whether an increased share of wind power in the production mix will make large disturbances from natural disasters more likely.

In Sweden the wind power penetration has increased from a relatively low level, and now (2013) accounts for around 10 out of 150 TWh total generation. Based on projects under construction and with all permits ready, this figure could however increase quickly. One could argue that Sweden, with its large hydropower reserves, should be one of the best suited countries for handling a large share of wind, wave, PV and other intermittent renewable energy sources. Although most political parties at the moment seem to embrace a continued expansion, there are however other actors who argue against this.

This section is based on the results from Paper II and III and is intended as a foundation for future work on wind integration in Sweden and the Nordic countries in particular.

4.1 Results

4.1.1 Variability and forecastability

As a background for future studies a review on variability and forecastability of non-dispatchable renewable energy sources was conducted in collaboration with solar, wave and tidal power researchers (see Paper III). The aim of the paper was to summarize the main results and compare the methodologies used for the different sources. The focus was primarily on temporal variability and the effects of aggregation and not so much on spatial variability.

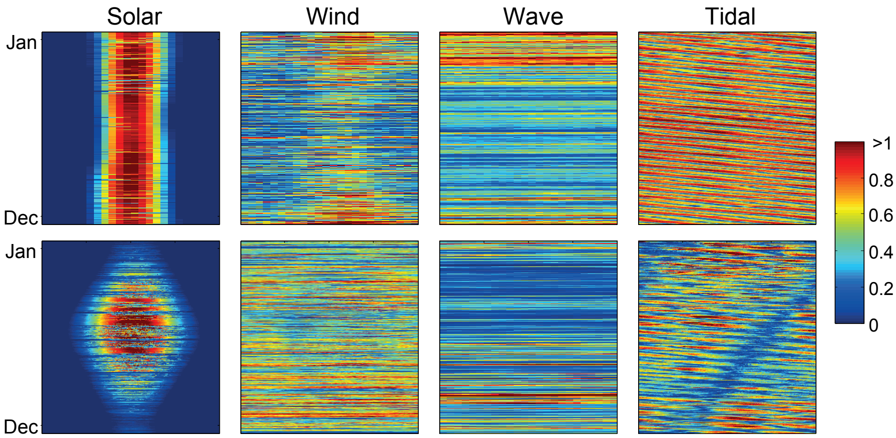

Figure 4.1. Site specific examples of variability at two sites per energy source (solar irradiation, wind speed, significant wave height and tidal current speed). The temporal resolution differs from 1 minute to 1 hour. Results are normalized to the 98th percentile measured for each site (Fig. 2 from Paper III).

Although both wind and wave power is driven by energy from the sun, the temporal characteristics of the three sources are strikingly different. The solar irradiation has a clear maximum defined by geographical location and time. Cloud movements can however introduce an almost binary pattern, where the point irradiation switches between zero and maximum. Because of this research focus is now on the short variations. Wind speed can also have seasonal and diurnal patterns, although the strength of these vary from place to place. The more stochastic variations of the wind are substantial and it has been shown that wind variations on the scale 1-6 hours could be challenging for the power system. Waves are induced by the wind, but the variations are smoothened out. The diurnal variations are therefore small and seasonal variations are perhaps more interesting. Tidal currents finally are driven by the gravity of the moon, and follows very regular patterns. Commonly tides are semi-diurnal with two high tides and two low per day, corresponding to four times per day with high tidal current speed. Fig. 4.1 shows examples of variability of the different sources during one year.

Of great importance is also the correlation of production from spatially distributed sources. High correlation implies large variations for a distributed fleet of generation units, while lower correlation gives a smoothing of the aggregated power. The correlation of wind power often exhibit an approximately exponential-decay relation to distance. Averaging over longer time-periods gives higher correlation, while the short-term variations are more independent. Two models of wind power correlation as a function of separation distance are shown in Fig. 4.2. The solar irradiance also shown has a substantially higher

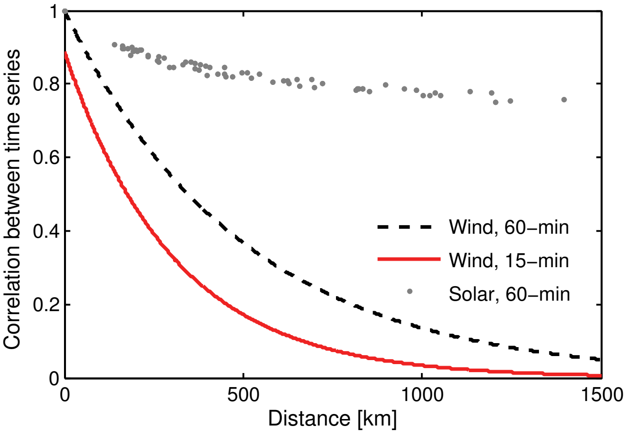

Figure 4.2. Two models for the correlation between wind power outputs and empirical correlation coefficients for pairs of solar irradiance in Sweden (Fig. 3a from Paper III).

correlation than wind power. Note though that the solar example is from Sweden, which has a small longitudinal extent; the same separation in east-west direction would give lower correlations.

Forecasting of intermittent renewables becomes increasingly important as the penetration levels increase. A lot of research and practical experience is available, not at least for wind power. Forecasting systems, often using both physical NWP models and statistical models, are operational in several countries, and the results have improved considerably over the past years. A conclusion from the review was that the accuracy of the forecasts are often hard to compare since different metrics are used for the different fields. The accuracy of wind power forecasts are also highly dependent on the system size and the complexity of the terrain.

A general conclusion was that more studies on combinations of the sources would be desirable. The disciplines could also learn from each other and benefit from the use of more unified methods and metrics.

4.1.2 Model of aggregated wind power production

In order to study the impact from future wind power installations a model has been developed. The model is based on MERRA reanalysis data (see section 2.2.2) and detailed information on WECs in Sweden including calculated annual energy production. Parameters included are e.g. losses for different wind sectors, a smoothing parameter for the power curve and seasonal and diurnal correction terms. Air density and wind shear was calculated for each hour at the WEC positions. The model parameters were optimized through a random restart hill-climb technique. In Paper II the parameterization, training and evaluation of the model is described in more detail. Data from year 2007,

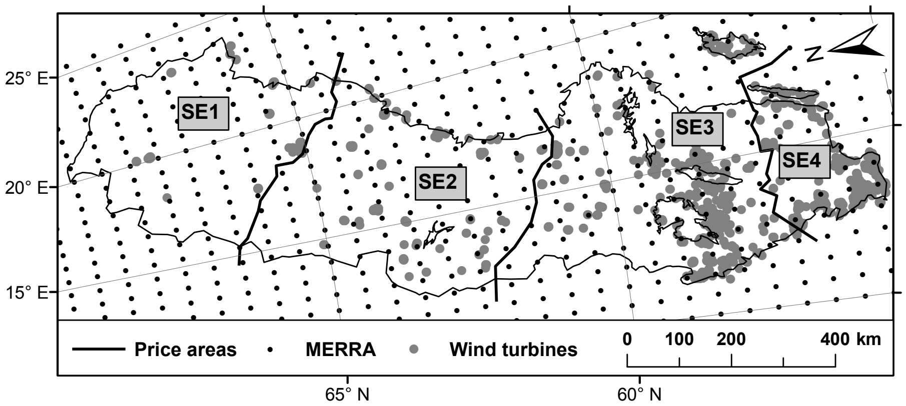

Figure 4.3. Figure visualizing MERRA grid points, distribution of WECs (end of 2012) and the four price areas in Sweden (Fig. 1 from Paper II).

Table 4.1. *Model performance; results for the evaluation years 2008, 2010 and 2012. The errors are given in % of the installed capacity. dP stands for step change in power.*

	Sweden	SE2	SE3	SE4
Mean Absolute Error	2.9%	6.5%	3.7%	4.2%
RMS Error	3.8%	9.1%	5.0%	5.9%
Mean Error	-0.1%	-0.7%	-0.5%	0.4%
RMS Error dP1h	1.5%	3.0%	1.9%	2.8%
RMS Error dP4h	3.6%	6.6%	4.7%	6.1%
Correlation	0.98	0.89	0.97	0.97

2009 and 2011 was used in the optimization and data from year 2008, 2010 and 2012 in the evaluation. Besides modelling the whole Swedish production, separate models were developed for three out of four price areas (bidding areas). These are relevant to model separately since the transmission capacity is limited between the areas.

The distribution of Swedish WECs in the end of 2012 and spatial resolution of MERRA is shown in Fig. 4.3. Evaluation results, related to the installed capacity, are shown in Table 4.1 and Figs 4.4-4.5. The table gives results for both Sweden and the price areas, while the figures are for the whole of Sweden. It is clear from the results that the model can adequately capture the hourly aggregated wind power in Sweden. The separate areas are, as expected, harder to model. This could be explained by lower installed power, smaller geographical area and, for the northern SE2, icing losses not included in the model.

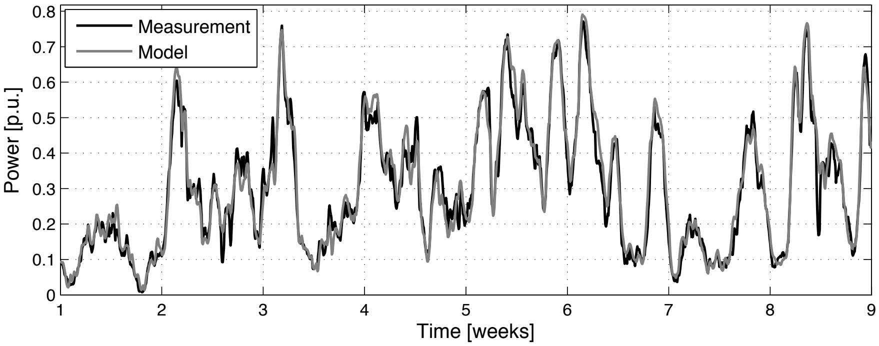

Figure 4.4. Model output and validation data for eight weeks. RMS error for the period is 3.9%, i.e. almost the same as the average for all three years of validation (Fig. 6 from Paper II).

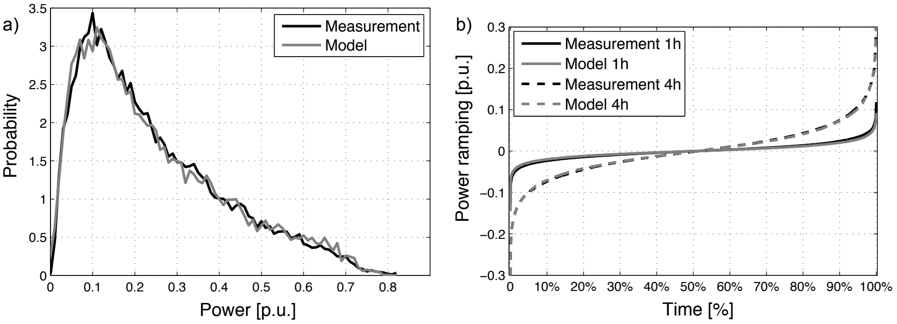

Figure 4.5. Empirical PDF calculated in bins of 0.01 p.u. (a) and duration plot of power step change for 1 and 4 hours (b). From fig. 7 in Paper II.

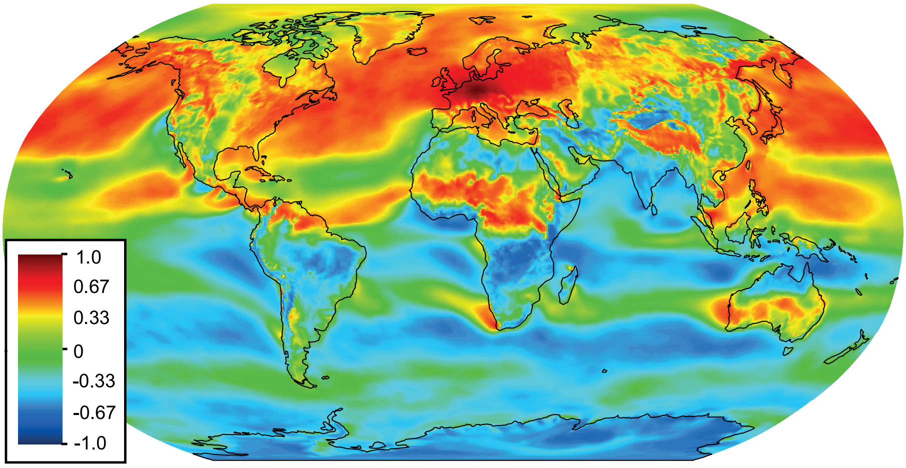

Figure 4.6. Correlation in 30-day mean wind speed to a grid point in Germany. 10 years of MERRA data was used.

4.2 Discussion

The variability review revealed differences in methodology and metrics used in solar, wind wave and tidal power research. One example is that in the solar field, a lot of attention is paid to the very short variations resulting from the motion of clouds, while longer time periods are the main interest for the other sources. In order to study the total variability and smoothing effects for combinations of sources, coordination in data collection will be needed. Although some research on combination of sources are beginning to emerge, this field is still very small compared to those of in particular wind and solar integration studies.

Smoothing effects could be accounted for when planning wind power development and transmission lines. By using a wise combination of energy sources and geographical dispersion, the net variability could be reduced and the impact on the power system could be smaller. In general the hourly correlation of wind speed decreased with distance in a relative uncomplicated manner. The seasonality of wind appears to have a more complex correlation pattern, see example in Fig. 4.6. Based on the strong negative correlation it would e.g. be interesting to study the impacts of a grid connection between central Europe and the (very windy) Moroccan coast.

Although the results from Paper II show that the aggregated hourly wind power production could be modelled to a good degree of accuracy, there are still ways to improve the model. Icing losses are not modelled directly, although these are to some degree accounted for by correcting for seasonal bias. It would be interesting to see if aggregated icing losses could be modelled using MERRA data. Time-depending wind shear was including in the model through extrapolation from wind speed at 10 meters above displacement height and 50 meters above ground using Eqn (2.1). The improvement of the result was however very small compared to using a fixed wind shear exponent. By comparing with (so far only a few) wind measurements it appears like MERRA severely underestimates the temporal variability in shear, and that the correlation is very low. It could be worth trying to apply a correction to the shear exponent based on e.g. atmospheric stability. Finally the air-density dependency of the WEC power curves could be better modelled.

Subsequently scenarios of future wind power installations will be developed and fed into the model in order to generate aggregated hourly production series from 1979 and onwards. An obvious question is whether models optimized for the present WEC fleet will perform well for future installations? Surely there are large uncertainties involved in the future technology used, the capacity factors, hub heights etc. Since the model is able to predict power output with installed capacity ranging from 600 MW in 2007 up to 3,500 MW in end of 2012 it is however likely that smoothing effects resulting from future installations will be captured in a proper way.

5. Future work

The last years of the PhD studies will mainly be focused on wind variability and integration, i.e. build upon the results presented in chapter 4. Firstly scenarios of future wind power development in Sweden will be fed into the model of hourly aggregated wind power production (described in Paper II) in order to generate realistic time series of production. Interviews with relevant actors in the wind power field have already started to get input on likely geographical and technical trends in the development. The generated time series will be more than 35 years long and have a meteorological coupling with the actual weather, and can be compared with the actual load, hydrological situation etc. during the same period. The series will thus provide a good basis for future studies on wind integration.

As the penetration of wind power increases, the sub-hourly variations can become more important to study. Most meteorological models have a temporal resolution of one or a few hours, and logging of actual production performed by the Swedish TSO is also made on an hourly basis. An idea is therefore to study power systems with higher temporal resolution in the measurements (e.g. Denmark, Germany and some areas in USA) and develop a statistical model to simulate the sub-hourly fluctuations. These variations are not stationary, but varies with e.g. wind power output and ramp rate. The results should also be applicable to other non-dispatchable renewable sources.

The collaboration with researchers in solar, wind, wave and tidal power (see Paper III) will continue. The next step will be to study the variability of the different sources, and combinations of sources, in Sweden and/or the Nordic countries. A collaboration is also ongoing between Uppsala University and KTH with the aim of studying the effects of connecting large (scale of thousands of kilometers) regions with HVDC links. How will the different time zones, load profiles and meteorological conditions contribute to reduce the overall variability in the net load? Are some regions more or less suitable to connect?

6. Summary of papers

Paper I

Wind Energy Converters and Photovoltaics for Generation of Electricity after Natural Disasters

Wind energy converters (WEC) and photovoltaics (PV) are interesting alternatives for replacing conventional diesel generation in the recovery and reconstruction phase after a natural disaster. In this paper different combinations of WEC, PV and battery storage were optimized for 32 different sites in order to supply small loads (2 and 20 kW peak respectively). Because of lack of data, ARMA modelling was employed to generate complete wind speed time series. The main conclusion is that PV outperformed WEC for all sites, in particular for the smaller load.

The author performed the analysis and wrote the paper. The optimization procedure was however programmed (and described) by A. Goude. *Resubmitted after minor revision to Geografiska Annaler: Series A, Physical Geography, May 2014.*

Paper II

Modelling the Swedish Wind Power Production Using MERRA Reanalysis Data

In order to study the impact of future wind power installations, reliable and verified models of the production variations are necessary. In this paper a (physical) model based on MERRA reanalysis data and detailed information on Swedish wind turbines was described and verified. The model takes into account e.g. time varying air density and wind shear and includes parameters describing the losses in different wind sectors as a function of time. It was shown that the model can adequately capture the hourly aggregated production in Sweden (RMSE 3.8%) as well as the hourly step changes, the monthly energy production etc. For individual "price areas" the errors were larger, in particular for the northern area SE2.

The author collected the data, developed the model and wrote the paper. *Submitted to Renewable Energy, April 2014.*

Paper III

Variability Assessment and Forecasting of Renewables: A Review for Solar, Wind, Wave and Tidal Resources

Very large amounts of research has been conducted on the variability and forecastability of renewable energy sources, in particular for solar and wind power. The questions studied and methods employed however differs between the sources. This review attempts to summarize and compare the research done so far, and points out research gaps and areas of possible learning between the fields.

The author collected and read the references related to wind energy and wrote the corresponding raw text. The author participated in discussing the results and merging the text. Finally the author analyzed data and produced Figs 1 and 2. *Submitted to Renewable & Sustainable Energy Reviews, April 2014.*

Paper IV

Using the MIUU Model for Prediction of Mean Wind Speed at Low Height

The objective of this article was to evaluate the potential of using the MIUU meso-scale model for a first evaluation of wind conditions at low heights. This was done by comparing the model to observed wind speed from around 130 measurements stations of SMHI (Swedish Meteorological and Hydrological Institute). In order to improve the predictions measurements were classified into five categories depending on the surrounding terrain and roughness and a statistical model was applied to correct for the discrepancies between MIUU and observations. The mean absolute error in the predictions was 0.39 m/s. This is comparable to the uncertainty related to several months of on-site measurements. The proposed method could therefore be a valuable complement to wind measurements.

The author came up with the idea to the work, collected and processed the data and wrote the article except for section 1.1 and 2.5. *Submitted to Wind Engineering, May 2014.*

7. Svensk sammanfattning

Vindkraft kan relateras till naturkatastrofer på flera olika sätt. Den här licentiatavhandlingen ger bakgrund till och introducerar fyra artiklar som beskriver två aspekter av detta samband. I den första avdelningen undersöks hur småskalig vindkraft skulle kunna användas för att generera el efter en naturkatastrof. I dagsläget är det dieselaggregat som används för detta ändamål, men det skulle finnas stora fördelar med att övergå till förnybara system. En studie av 32 platser (myndigheten MSB:s utlandsstationeringar augusti 2012) visade att solceller var mer lämpade än vindkraftverk. Resultaten bekräftades av en studie för hela världen; solceller ger billigare system än småskaliga vindkraftverk för de flesta platser, inte minst om man tittar på områden som är utsatta för naturkatastrofer. Hybridsystem med både solceller och vindkraftverk var dock intressanta på högre breddgrader. För Sverige så visas det att data från en fritt tillgängliga meteorologisk modell tillsammans med en statistisk korrigering beroende på terrängtyp ger bra uppskattningar av medelvinden på 10 meters höjd. Den föreslagna metodiken kan vara användbar som ett komplement till vindmätningar eller om det inte finns tid eller möjlighet till en riktig mätkampanj.

Den andra avdelningen är inriktad mot vindens variabilitet och integrering av vindkraft i kraftsystemet. De resultat som presenteras i denna avhandling är tänkta som en bas för framtida studier av hur en kraftigt ökad andel vindkraft påverkar elsystemet med avseende på stabilitet, nödvändiga nätförstärkningar, ökade krav på balanskraft etc. En översiktsstudie av variabilitet och prognosbarhet för intermittenta förnybara energikällor gjordes tillsammans med forskare inom sol-, våg och tidvattenkraft. Även om mycket forskning pågår inom dessa områden så var en slutsats att mer studier för kombinationer av olika källor skulle vara önskvärt. Forskare inom de olika disciplinerna skulle också kunna lära från varandra och dra fördel av gemensamma metoder och mått. Slutligen har en modell av aggregerad timvis vindkraftproduktion tagits fram. Modellen baseras på data från en meteorologisk modell samt detaljerad information om vindkraftverk i Sverige. Modellen visade sig vara mycket träffsäker, både vad gäller låga prediktionsfel och i överensstämmelse av sannolikhetsfördelning av effekt och stegförändring av timvis effekt.

8. Acknowledgements

First of all I would like to thank my supervisor Mikael Bergkvist. It feels like your door is always open (although your room might then be jammed by students, PhD students and others). A special thanks for helping me out when I started to have second thoughts about the whole PhD thing.

Doing research and writing articles is much more fun if you don't do it yourself. I would like to thank my co-authors Anders, Micke, Joakim, Nicole, Valeria, David, Flore, Mårten, Rafael, Jonatan, Hans, Matthias and Staffan. I hope we will have the chance to work more together in the near future! Joakim is especially acknowledged for providing code for calculation of in-plane irradiance. Thanks also to teaching colleagues and students.

My room mates Yue, Maria and Tobias, the people in the wind power group and all staff at the division. Thank you for creating a good ambiance, contributing to me working more than ever. I used to be a fan of 6 hours working days... An extra salute to Jon who initiated me into the beautiful world of electronics and practical engineering work. Good try, I am a hopeless case. Maria and Gunnel for always being helpful, even when you have your own deadlines hanging over yourself. Thanks to Thomas for pimping my computer and for GIS discussions. Thanks also to the organizers (in particular Sven), senior researchers and PhD students at CNDS. Colin, next time we will write that paper.

Former colleagues at the wind & site, infrastructure, environmental permit and energy market groups at Sweco. You taught me a lot. Thank you Fredrik for being a very flexible manager (i.e. still paying my phone and inviting me to parties and ski trips) and to Olle and Pelle. I would also like to thank Oskar Sämfors (Svenska Kraftnät), Daniel Gustafsson (Vattenfall), Lennart Söder (KTH), Anton Steen (Svensk Vindenergi) and Matthias Mohr (UU, Geo) for valuable input. Many persons have also helped with data access and interpretation. To mention a few: Marcus Flarup and Sverker Hellström at SMHI, Mattias Wondollek at Svensk Vindenergi, Birger Fält at Svenska Kraftnät and Kari Fougman at Sweco.

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