Experiences with the Application of the Non-Hydrostatic Mesoscale Model GESIMA for assessing Wind Potential in Complex Terrain

Detlev Heinemann, Heinz-Theo Mengelkamp*, Martin Strack, Hans-Peter Waldl
Department Energy and Semiconductor Research, Faculty of Physics
Carl von Ossietzky University of Oldenburg, D-26111 Oldenburg, Germany
Fax: +49 441 798-3326, e-mail: office@ehf.uni-oldenburg.de, www.physik.uni-oldenburg.de/ehf
*GKSS Research Center Geesthacht, Max-Planck-Straße 1, D-21494 Geesthacht, Germany

To asses wind potential in complex terrain three dimensional non-hydrostatic models become more and more popular. These models are capable of taking into account the flow pattern in complex terrain. Numerical flow models usually are quite complicated in the modelling itself and experiences on the impact of model parameters are limited. Especially the accuracy of predictions with these models for wind energy applications is still questionable.
This paper presents results from numerous calculations using the meso scale model GESIMA for an area of $47 \times 74\ \mathrm{km}^2$. The calculations are verified using wind speed measurements and wind power data from wind turbines placed in the area of interest. For practical use a criterion for numerical convergence of the model and its unsecurity of results is derived. Sensitivity analysis on the variation of the most important input parameters shows well reproducable results for different model parameters. To reduce computing resources several strategies to speed up the calculations are discussed and first results presented.

Keywords: Siting, Wind Potential, Complex Terrain, Models (Mathematical)

1 Introduction

After an enormous growth of wind energy use in Germanys coastal regions the inland becomes more and more interesting for the installation of wind turbines. In 1997 60% of the newly installed wind power has been placed in interior regions [2]. In many cases this means that wind turbines are placed in a complex structured orography where winds show large variations due to orography induced changes of flow and channeling effects of valleys.

To ensure the required accuracy when planning wind energy converter (WEC) sites and also for the declaration of areas with a priority for wind energy use methods to estimate the wind energy potential are required. While the European Wind Atlas [3] has been proven to be suitable for plain and moderate hilly terrain it can not deal with complex terrain due to the implemented simplified orographic model ([4],[5]).

Using a mesoscale non-hydrostatic flow simulation the wind flow reflecting all relevant orographic effects can be calculated in complex terrain. These methods have been used increasingly for wind power potential estimations (e.g. [6], [7]). In most cases these models have been designed to calculate the instationary spreading of air pollutants. Experiences concerning their suitability for wind potential assessments are very limited.

The following application of the non-hydrostatic flow model GESIMA deals with the calculation of the wind energy potential for an area of $47 \times 74\ \mathrm{km}^2$ around the german city of Osnabrück. The experiences concerning the accuracy and chance to reproduce results are reported.

2 Application of GESIMA

2.1 The flow model GESIMA

The mesoscale non-hydrostatic flow model GESIMA has been developed at the GKSS Research Center in Geesthacht, Germany ([8]). It numerically solves the three-dimensional equations of motion *(Reynolds equations)* for the flow. The equations are solved on a discrete grid which follows the terrain surface. Its horizontal resolution is $1 \times 1\ \mathrm{km}^2$, the vertical spacing varies from 20 m at ground level to 400 m at the upper boundary of the model volume at approximatly 4 km height.

The use of the non-hydrostatic approach makes it possible to take into account dynamic pressure variations. This complicates the computations but is indispensable due to the required spatial resolution.

2.2 Operation of GESIMA

The computation of the wind potential is based on a 12 year radiosonde time series (1979-1991) of geostrophic wind and vertical temperature gradient in

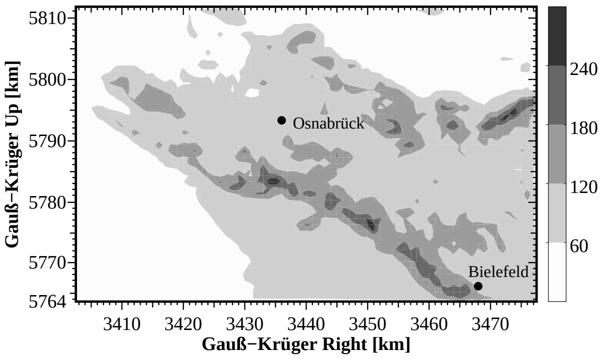

Figure 1: Orographic structure of the computed area in meters above sea level.

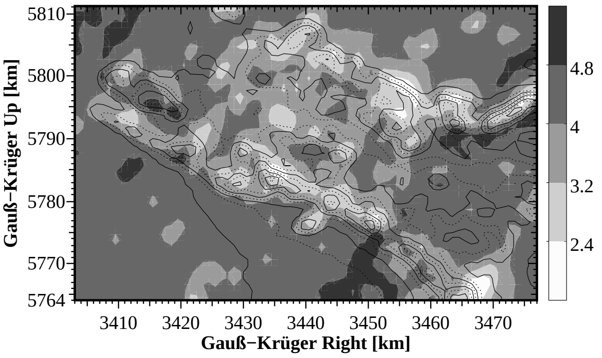

Figure 2: Computed wind speed [m/s] in 30 meters height for a wind blowing from SSW.

heights between 100 and 1500 meters. The data was provided by the *Deutscher Wetterdienst* and processed by a *cluster analysis*. This leads to a classification into 143 typical flow situations (*clusters*) which are characterized by the geostrophic wind vector and state of the atmospheric thermal stability.

For each cluster a GESIMA simulation is being run where the geostrophic wind serves as a driving force on the flow field. The atmospheric stability is used as an additional parameter. The model is run in quasi-stationary mode. This means that after an initialisation of the model volume, an iteration process leads to a (more or less) stationary state of the model.

The resulting wind fields are weighted with their frequency in each cluster. A summation yields the annual wind speed distribution and direction for each grid point of the model.

3 Wind Power Potential in the Computation Area

The area for which the simulation is run comprises the southern half of the ”Landkreis Osnabrück” for which an earlyer study with GESIMA already determined the wind power potential ([6]). The orography of the area is depicted in figure 1. Two mountain ranges can be seen. The larger one of them is the ”Teutoburger Wald” with heights up to 300 meters and densely covered with forest. The other one is the ”Wiehengebirge” placed at the eastern border of the area. The flat areas are mostly used as farmland with only a few trees on it.

3.1 Flow effects

Figure 2 shows the computed wind speed field at 30 meters height above ground level for a cluster with a surface wind blowing from SSW. Several typical effects for the area can be observed. Over the wooded summits and in the according sheltered zones downwind of the hills the wind speed is drastically reduced. Speed ups due to orography have no remarkable impact because of the high roughness length of the forest and a resulting displacement height. In comparison two uncovered smooth hills at coordinates (3415,5795) and (3470,5794) show the expected behaviour: The wind speed increases in comparison to the vicinity.

3.2 Verification based on measured data

The computed final results have been compared with long term measurements of surface winds (see Table 1) at two sites. For the stations of ”Osnabrück” (data taken from 1980 to 1994) and ”Greven” (1982-1994) the mean wind speeds differ within a range of ± 0.3 m/s from the measured data. The energy flux density deviates by 20%. The station ISET 2022 shows the largest deviations which might be caused by the different time period (1991-1995) in which the data has been taken.

Site,	v [m/s]		P [W/m^2]	
Height [m]	sim.	meas.	sim.	meas.
Greven, 10	3.4	3.7	59	74
ISET 2022, 10	3.5	2.9	64	45
Osnabrück, 18	3.0*	3.2	41*	42
Osnabrück, 30	3.8	3.8*	81	88*

*Table 1: Comparison of simulated (*sim.*) and measured (*meas.*) values of the average wind speed (*v*) and the energy flux density (*P*). * = value gained by vertical interpolation.*

In general the comparison with measured ground wind data should not be trusted too much especially for low measurement heights. These measurements usually reflect local influences from roughness and obstacles which cannot be taken into account with GESIMA at the chosen resolution.

3.3 Verification of Energy Yields

The energy yields of large WECs are suited better for the verification of the calculation results since the

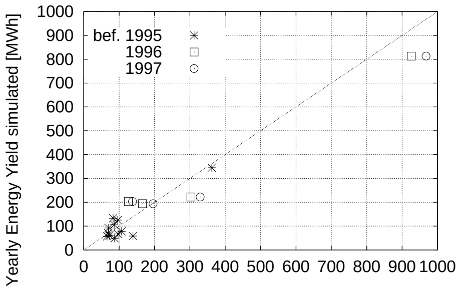

Figure 3: Comparison of measured and simulated WEC energy yields.

wind speed at mostely larger hub heights is almost uninfluenced by local conditions and also because of the averaging over the rotor area. Data for some small (< 100 kW) WEC and a few large WEC for the area is available. The scatterplot in figure 3 shows the results for the yearly energy outputs which have been computed from the simulated wind speed using the power curve of the WECs. Simulated energy yields are plotted versus measured values.

The largest of the WECs is a 500 kW model with 50 meters hub height. It can be seen that results differ from 12% to 16% depending on the considered time interval. The next WEC in size shows deviations of about 5%. In the set of medium sized WECs there is one which is underestimated by 60% - this machine is located at the city limits of the town of ”Osnabrück” and has a sourrounding with very heterogeneous roughness lengths. Some small WECs which are stronger influenced by local effects, show larger deviations. For these models an additional uncertainty might be introduced to the energy yield calculations by the power curves which are based on manufacturers specifications.

4 Examination of the Model

4.1 Convergence criterion and its error

The quasi-stationary mode of operation of GESIMA requires a criterion to detect the stationary state and stop the calculations. This criterion is called the *convergence criterion* and has been implemented in GESIMA based on the total vertical momentum flux in the modelled volume: If this value remaines constant between subsequent iterations, the flow field is considered to be stationary.

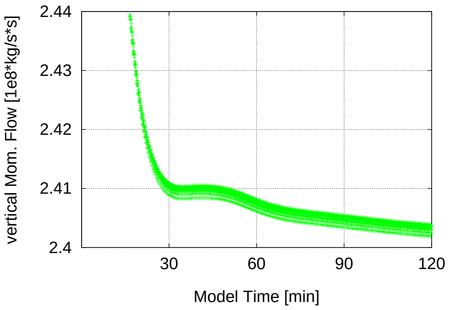

Figure 4: Development of the total vertical momentum flux during the simulation time of 120 minutes.

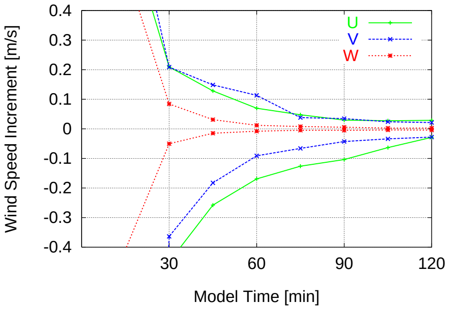

Figure 5: Development of the increment of the velocity components u, v and w during the simulation described in figure 4.

Figure 4 shows the development of this parameter for a typical simulation run: The curve converges quite fast and is relatively constant after 30 minutes of model time. To get a different estimation of the development of the stationarity for the same model run, the values of the wind speed increments of the u, v and w components have been saved every 15 minutes of model time. The maximum values of these increments are plotted in figure 5. It can be seen that after 120 minutes none of the three components deviates more than 0.05 m/s from its value 15 minutes ago. Therefore the wind field can be considered stationary. The comparison with figure 4 leads to the conclusion that a constant momentum flux is not sufficient to conclude that the system is in a stationary state within the required accuracy. The momentum flux seems to be constant after 45 minutes of model time, but there are still wind speed changes within 15 minutes of the order of 0.3 m/s.

As a consequence of these calculations, a new criterion with respect to the maximum wind speed increments has been formulated: If they are on the order of ±0.2 m/s in the surface layer, then the field is considered stationary. This condition is a compromise between computing time and accuracy.

It is also possible to estimate the *convergence error* by looking at the long time behaviour of the increments of maximum wind speed increments. The error for incomplete stationarity in this study is ±0.29 m/s which follows from a worst-case assumption: Only if there is a point which results in the maximum instationarity for every cluster one of the values reaches the limit. The actual convergence error should be much smaller.

4.2 Numerical instabilities

The application of the model leaded in some cases to divergent computations (1.6% of all cases) and also to non-stationary model runs (2.1%). Such instabilities do not influence the overall result. It was possible to represent them in all cases by clusters of the same set of static stability parameters and nearly the same set of wind vectors (deviation max. 10 deg.). This data was fitted according to the clusters wind speed.

4.3 Parameter variation

The most important model parameters have been varied to estimate the differences in model outcome:

- Application of a significant variation of the *initialisation wind field* causes slightly different results with a deviation of 0.2 m/s. The model does not satisfy the theoretical demands which state that different initialisations should not have an impact on the results within reasonable computing efforts. Therefore a physical reasonable initialisation is required. This could be done for example with a mass consistent flow model.
- The size of the area does not have an significant influence on the computed results in the interior of the area, if one disregards perturbations or instabilities which might be caused by an unlucky choice of the borderlines.

5 Computing Resources for this Study

For the chosen configuration of 74×47×19 grid points the model GESIMA requires approximately 90 MB RAM. Therefore common PC's can be used to run the model. If 4 PC's with 400 MHz CPU frequency are used, the complete wind potential calculation can be finished within two weeks. There are ways to reduce computing time:

- Cluster analysis of geostrophic wind data can be optimised for the application of wind potential prediction. This means to minimise the amount of clusters for low and very high wind speeds. For a typical 600 kW WEC, clusters with very low wind speeds amount 20% of the computing time but only 1.5% of the energy yield. These clusters can be omitted.
- Introduction of a variable model time step and automatic evaluation of the convergence criterion to effectively minimise computing time.

6 Summary and Outlook

The application of GESIMA has proven to be a suitable method to calculate the wind power potential of a region while taking the numerous relevant effects in complex terrain into account. The verifications in comparison with measured wind speed and energy yield data point to a promising direction but should be expanded.

An approximation of the error which results from the iteration procedure or the choice of parameters shows that the accuracy is satisfying for the discussed application in wind energy.

Within the framework of further applications of GESIMA additional verification of the procedures is planned. A special focus should concentrate on the numerical stability of the model. The measures to speed up the computation (see 5) will be taken.

In order to apply the method for the siting of wind turbines, the resolution of 1×1 km^2 has to be improved. Local improvements or a nesting of models with higher resolution are planned.

References

[1] M. Strack: *Untersuchungen zur Anwendung des mesoskaligen nicht-hydrostatischen Strömungsmodells GESIMA zur Windpotentialbestimmung in komplexem Gelände*. Diplomarbeit, Carl von Ossietzky Universität Oldenburg, 1998.

[2] K. Rehfeldt: *Windenergienutzung in der Bundesrepublik Deutschland*. DEWI Magazin, 12, pp. 6–24, 1998.

[3] I. Troen and E. Petersen: *European Wind Atlas*. Meteorology and Wind Energy Department, Risø National Laboratory, 1989.

[4] A. Bowen and G. Mortensen: *Exploring the limits of WAsP - the Wind Atlas and Application Programme*. In: *Proceedings of European Wind Energy Conference, Göteborg*, pp. 584–587, 1996.

[5] G. Gerdes, B. Schwenk und T. Pahlke: *Ergebnisse von WASP in mäßig strukturiertem Gelände*. DEWI Magazin, 11, pp. 39–43, 1997.

[6] H. Th. Mengelkamp: *Bestimmung des Windenergiepotentials im Binnenland*. Potentialstudie im Auftrag des Landkreises Osnabrück, GKSS Forschungszentrum Geesthacht, 1996.

[7] K. Sattler and S. Traup: *Winddaten und Windkarten für Windenergienutzer*. In: *Tagungsband der 3. Deutschen Windenergie Konferenz, Wilhelmshaven*, pp. 101–105, 1996.

[8] H. Kapitza: *Das dynamische Gerüst eines nicht-hydrostatischen Mesoskalen-Modells der atmosphärischen Zirkulation*. GKSS 87/E/35, GKSS-Forschungszentrum Geesthacht, 1987.