Austrian Wind Potential Analysis (AuWiPot)

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Abstract: Previous estimations of the achievable wind potential in Austria were only based on criteria of regional planning, but other crucial parameter for wind farms, like technical development of turbines and profitability have been neglected so far. This combined with inaccurate wind resource estimations caused severe uncertainties. In order to overcome these shortcomings, a novel modelling approach for near surface wind was developed in order to calculate a detailed wind resource map with very high resolution (100 m × 100 m grid spacing) and accuracy and allows a subsequent comprehensive modelling of the wind potential that is theoretically achievable under changing economical/technological conditions. Based on the calculated wind map, that captures mean annual wind speeds with a standard deviation of biases of 0.8 m/s, the theoretically achievable wind potential sums up to a total of more than 10 TW installable power, which remarks an idealised upper boundary limited by technical and economical constraints.

Keywords: wind field modelling, complex terrain, wind energy, AuWiPot

1 Introduction

Due to the variability of the Austrian topography with its complex terrain and distinct river valleys in the West as well as flat areas in the East, the Austrian wind resources are characterised by a large variety of local winds, low level jets and supra-regional flows. The interaction of different wind systems on different scales and their dependencies from heat fluxes within the Planetary Boundary Layer (PBL) prevents near surface wind conditions from being sufficiently captured by models, neither by dynamic atmospheric models as they are broadly applied in numerical weather prediction (NWP) and climate research (as regional climate models), nor by simpler diagnostic/mass-consistent flow models applied in day-to-day engineering project work, nor by statistical or geo-statistical techniques. For instance, *Walter et al. [2006]* found varying biases of between -2.5 m/s and 1.0 m/s in four regional climate models in Germany; *Kunz et al. [2004]* found mean absolute errors of 1.5 m/s for an observation based geo-statistical interpolation method.

Previous estimations of the wind potential in Austria are broadly spread in range between 3 TWh and 20 TWh *[Hantsch and Moidl, 2007]*, indicating large uncertainty not only stemming from unreliable calculations of wind conditions, but also from the technical development of wind turbines and crucial economic factors (like feed-in tariff). In fact, earlier potential analyses were mostly based on criteria of land use planning combined with inaccurate wind resource estimations which caused severe uncertainties in the results.

In order to overcome these shortcomings, the project “Austrian Wind Atlas and Wind Potential Analysis (AuWiPot)” (http://windatlas.at), funded by the Austrian Research Promotion Agency (FFG), was initiated in March 2009. The project has lasted for two years and was finished in April 2011. The aim of this study was (1) the development and testing of a new modelling approach to calculate a detailed wind resource map with very high resolution (100 m × 100 m grid spacing) and accuracy covering the Austrian territory, (2) the subsequent comprehensive modelling of the theoretically achievable wind potential under changing economical/technological constraints, and (3) to provide this flexible modelling approach for the wind potential to the general public via a web-based GIS application allowing fast “on-the-fly” calculations.

2 Methodology

2.1 Wind Resources

Due to the strong dependency of near surface wind on surface characteristics on local scale as well as on the dynamics of the atmosphere on synoptic scale, accurate highly resolved wind climatologies in complex terrain are difficult to obtain. Earlier attempts in the European Alpine region were purely based on geo-statistical interpolation methods or dynamical models. The accuracy of geo-statistical methods highly depends on the density and quality of wind observations while dynamical models are extremely time consuming and an appropriate horizontal resolution of 100 m grid spacing is not achievable in long-term simulations covering periods long enough to represent current mean climate conditions *[cf. Truhetz, 2010 and references therein]*.

During AuWiPot, a novel hybrid dynamical/geo-statistical modelling approach for near surface wind has been developed and employed for the Austrian territory. It consists of two downscaling steps and an integrated bias correction.

In the first step, the dynamic model MM5 *[Dudhia, 1999]* is applied to the reanalysis dataset ERA-40 *[Uppala et al., 2004]* in multiple-nested model domains to successively increase the resolution of the meteorological fields from 80 km × 120 km grid spacing (ERA-40) to 30 km × 30 km (Europe, domain A1, Fig .1), 10 km × 10 km (Alpine region, domain A2, Fig. 1), and finally to 2 km × 2 km (Austrian territory, domain A3, Fig. 1). Thereby, the nesting steps over 30 km and 10 km were conducted during the Austrian regional climate modelling project “Research for Climate Protection: Model Run Evaluation” (reclip:more) *[Loibl et al., 2007]*. In the step to reach 2 km, MM5 was driven in dynamic initialisation mode, in order to keep the computational load on a maintainable level. From the MM5 output of domain A3 on the 2 km grid annual mean wind speeds as well as shape and scale parameters of the Weibull distribution were derived and handed over to the geo-statistical interpolation.

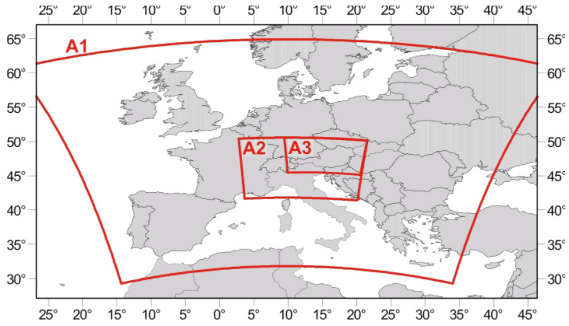


Figure 1: Nested simulation domains of the dynamic model MM5 with 30 km (A1), 10 km (A2), and 2 km (A3) grid spacing; from *Truhetz et al. [2010].*

The geo-statistical interpolation technique, which remarks the second downscaling step of the overall procedure, was originally developed for the spatial interpolation of frequency distributions of wind speeds purely based on surface observation stations. The method is able to capture local effects, like the speed-up effect due to mountain ridges, by means of empirical modification functions. In AuWiPot, this method was extended to merge both, gridded datasets from dynamical models and observational data from surface stations. Hence, the combined dynamic/geo-statistic approach captures atmospheric phenomena on synoptic and regional scale by means of the dynamic model and local scale phenomena by means of the empirical/statistical method based on observational data. In addition, a bias correction for the dynamic model was implemented in order to increase the accuracy and reliability throughout the entire wind modelling procedure.

In the geo-statistical interpolation scheme, the mean annual wind speeds and Weibull parameters of domain A3 are re-gridded to the 100 m grid via bi-linear interpolation and successively modified by (1) a domain-averaged vertical gradient of wind speed (derived from MM5 domain A3), (2) bias correction terms derived from model observation comparison, (3) correction terms with respect to local orographic features (slopes, narrow valleys, mountain ridges), and (4) local terms derived from observation stations. Thereby, the digital elevation model of the shuttle radio topography mission (SRTM) *[Rabus et al., 2003]* provides the bases for the orographic analyses. As a result mean annual wind speeds and Weibull parameters are derived in multiple heights above ground (between 50 m and 130 m), which are used as input variables for the technical/economical potential estimation.

The downscaling method was applied on the year 1999 for development purposes and on the period 1981 to 1990, representing current climate as it was given by the simulation results in reclip:more, and thoroughly evaluated by means of observation stations provided by he Austrian Central Institute for Meteorology and Geodynamics (ZAMG), private companies, federal Austrian governments, the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss), the German National Meteorological Service (DWD), the Southern Tirol Weather Service, and the University of Innsbruck. However, since the density of the station network in Austria was not increased until the 1990ies by the installation of automatic observation stations (TAWES), a subset of selected 65 TAWES stations was transferred back into the 1980ies by means of 11 long-term reliable climate stations and a statistical method called quantile mapping *[Themeßl et al., 2011]*. Based on hypothesis tests of the statistical significance of this method during a training period (1995 to 2007) it was shown that the annual wind speed of an unknown period can be reconstructed with an expected error smaller than 5% (i.e. 0.15 m/s) *[Truhetz and Gobiet, 2011]*. By means of this reconstruction step, the number of ingested observation stations increased to 200.

The climatological representativeness of the period 1981 to 1990 was investigated by statistical analyses of observed long-term time series of selected observation stations (eleven reliable anemometer measurements of high quality), analyses of proxy data (i.e., air pressure, temperature, precipitation, duration of sunshine, and cloudiness), as well as modelled data from Europe’s largest regional climate modelling project, so far, the ENSEMBLES project *[Hewitt and Griggs, 2004]*. From these investigations shown by *Truhetz and Gobiet [2011]* no extraordinary climatological position with relevance for near surface wind of the period 1981 to 1990 compared to the period 1971 to 2000 can be deducted. Under future climate conditions, however, decreasing annual wind speeds in mountainous regions are indicated by highly resolved climate simulations due to projected decreasing snow cover *[Truhetz, 2010]*.

2.2 Achievable Wind Potential

In general, various and varying impacts influence the ability of utilizing wind power at a certain geographic location: in addition to wind conditions in terms of mean annual wind speed and frequency distribution, distances to buildings, terrain slopes, protected areas, and economic considerations are crucial criteria for the installation of wind farms. In AuWiPot, a GIS-based bottom-up potential estimation was designed to project imaginary wind farms on possible locations in Austria under technical/economical constraints on a 100 m × 100 m grid, as it is given by the dynamic/geo-statistically derived wind climatologies. Based on national and international studies *[BMU, 2011 and references therein]*, expert consultations, and work shops these technical/economical constraints were investigated to give reasonable default values for the GIS-based potential estimation. Since the technical/economical criteria are varying with turbine sizes, the potential estimation was set into a dynamic framework in order to allow the user to manually select/change these criteria. The entire potential estimation is embedded into a web-GIS application (http://www.windatlas.at) allowing “on-the-fly” calculations.

Based on a digital elevation model, land use data, settlements and buildings, transport network, protected areas, and existing wind farms all grid cells are analysed with respect to their potential applicability for wind turbine installations, in a first step. Thereby, limitations are defined by surface altitude, terrain slope, land use, type of protection (national parks and other nature protection areas), and distances to settlements, buildings, streets, and railroads are applied sorting out grid cells which do not come into further consideration.

In a second step, mean annual energy yields are calculated separately for each of the remaining grid cells based on the modelled climatological wind conditions, specific power curves of wind turbines, required minimum distances between turbines, technical losses and wake losses. In other words, for each of the remaining grid cells imaginary wind farms are projected and their expected energy yield is estimated. From this energy yields and economic specifications (installation costs, costs of operation, capital costs, machine life) site-specific production costs are estimated. This gives a second (economic) criterion for exclusion: if the site-specific production costs are lower than the feed-in tariff, the grid cells are excluded from the overall wind potential estimation.

Finally, the modelled annual energy yields, the underlying actual power, and number of the imaginary wind turbines are aggregated and presented as potential annual energy yield and possibly installable power on administrative district levels.

3 Results

3.1 Wind Resources

The evaluation of the dynamical part of the wind modelling approach based on 65 reconstructed TAWES stations shows a reduction of mean absolute errors (averaged over the stations) of modelled mean annual wind speeds (period 1981 to 1990) along the nested downscaling procedure: from 2.6 m/s (ERA-40) to 2.2 m/s (MM5 domain A2, 10 km grid spacing) and 1.7 m/s (MM5 domain A3, 2 km grid spacing) (cf. Fig. 2, left panel). The frequency distributions are also improved in general: the station-averaged Kolmogorov-Smirnov statistic is reduced from 0.5 (ERA-40) to 0.41 (domain A2) and 0.36 (domain A3). This also indicates model improvements due to higher resolutions (i.e. reduction of grid spacing from 10 km to 2 km). However, the dynamic model shows significant deviations from station data when single stations are concerned. For instance, while at the station “Galzig” the performance clearly follows the station-averaged results, the improvement at the station “Rax” is limited to the MM5 domain with 10 km grid spacing (cf. Fig. 2, middle and right panels).

Based on earlier evaluation results *[Truhetz et al., 2010]* of the year 1999, which was used to setup the interface between MM5 and the geo-statistical method, and from experiences beyond AuWiPot it was known that MM5 tends to overestimate near surface winds. This is again confirmed when the mean annual wind speed at 100 m above ground level (a.g.l.) of MM5 is compared with 200 surface stations extrapolated to the same height a.g.l.: relative (positive) biases up to 100 % and more are detected (cf. Fig. 3, left). Moderate overestimations (up to 20 %) can be found in north and eastern regions of Austria, while in the mountainous regions the overestimation is stronger pronounced. Due to the application of the bias correction technique, these overestimations are drastically reduced (cf. Fig. 3, right).

The final wind map at 100 m a.g.l. is shown in Fig. 4 (left panel) as it is provided to the general public by the web-based GIS application.

In order to estimate the uncertainty in the final wind climatologies, a cross-validation was conducted. That means the 200 surface stations are subsequently taken out of the entire modelling procedure one-by-one and compared with the final wind map. This allows a statistical analysis of the uncertainty. As a result, the standard deviation over all stations gives 0.8 m/s. A spatial analysis of the cross-validation (cf. Fig. 4, right panel) shows further that in lesser complex regions with a high density of stations, the uncertainty is reduced (0.4 m/s). In complex regions where two neighbouring stations have large differences due to the strong influence of local effects, the bias correction induces large differences at the location of the left out station. Hence, the uncertainty at locations highly influenced by local phenomena is increased (up to 1.6 m/s).

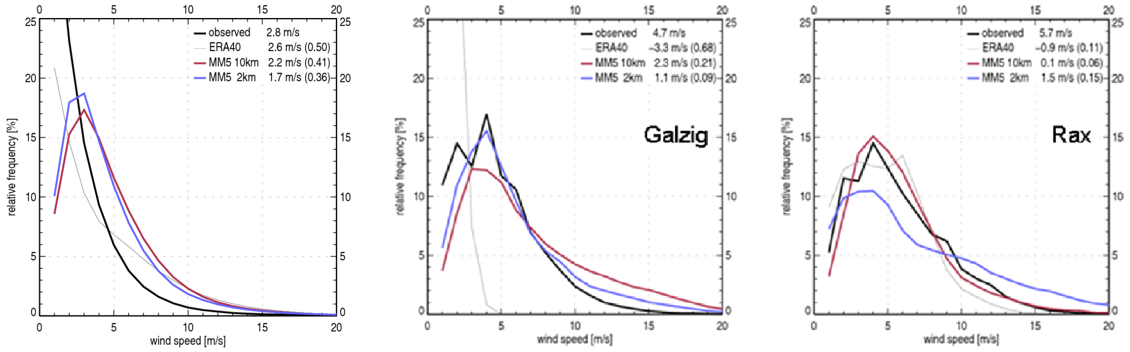


Figure 2: Modelled and observed frequency distributions of wind speed averaged over 65 observation stations (left panel), at station Galzig (middle panel), and at station Rax (right panel). Observations (thick black line), driving data ERA-40 (thin black line), and the MM5 outputs with 10 km (A2) and 2 km (A3) grid spacing (red and blue lines, respectively) are shown. From *[Truhetz and Gobiet, 2011].*

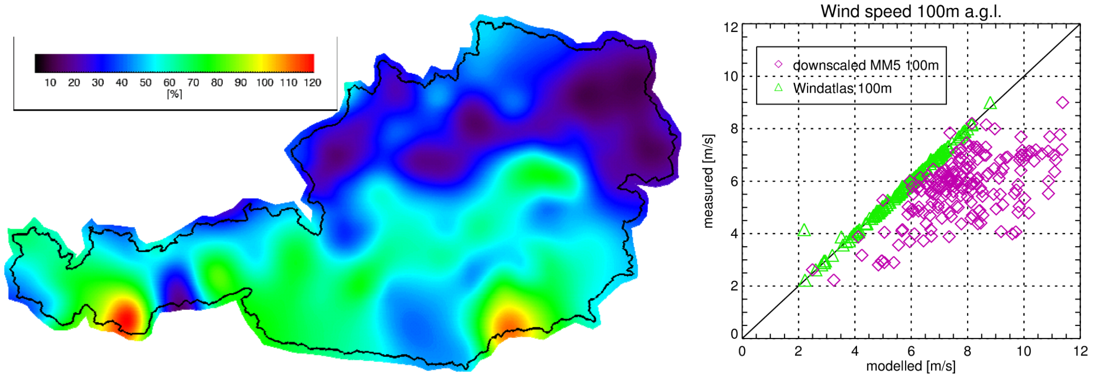


Figure 3: Relative bias of mean annual wind speeds at 100 m a.g.l. from MM5 domain A3 (left panel). Scatter plot of modelled and observed mean annual wind speeds at 100 m a.g.l. from MM5 domain A3 without bias correction (magenta) and from the final wind map (green).

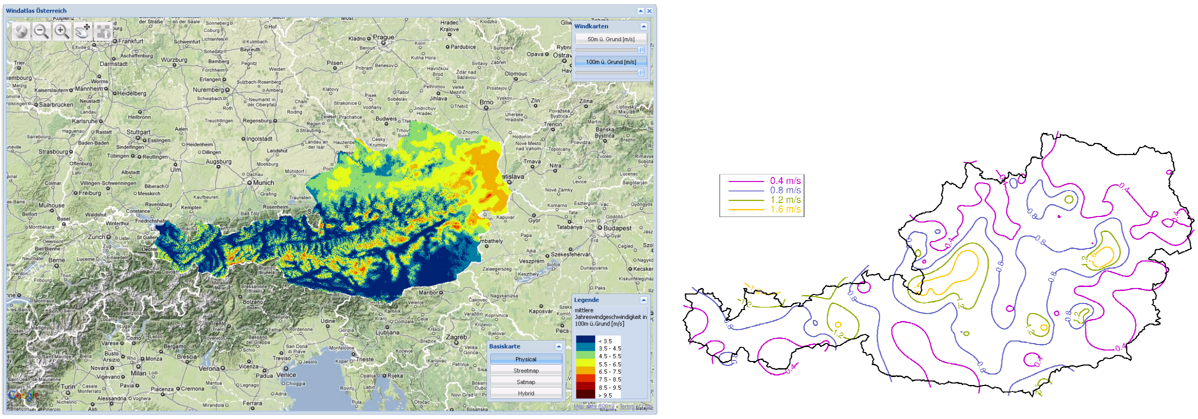


Figure 4: Final wind map (mean annual wind speed) at 100 m a.g.l. on a 100 m × 100 m grid (left panel). Spatial distribution of the standard deviation of biases at 100 m a.g.l. derived from cross-validation based on 200 surface stations (right panel).

Comparing the result of the cross-validation with the evaluation results of the dynamic part of the modelling approach clearly indicates an improvement due to the application of the geo-statistical interpolation scheme.

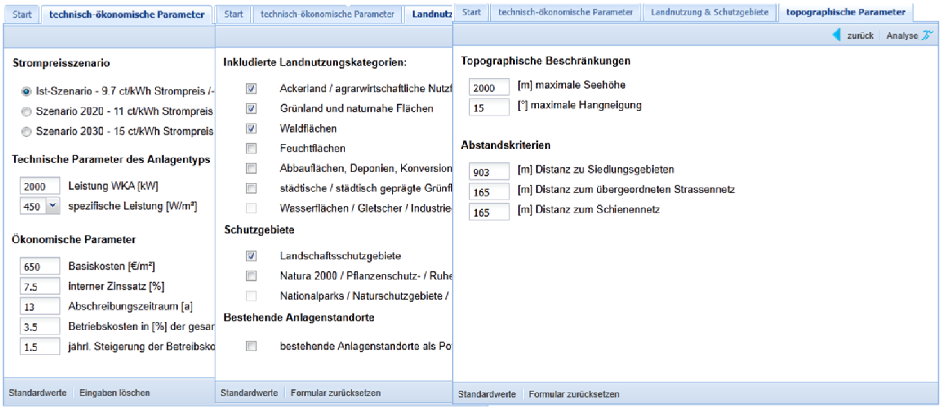
The effect of the uncertainties of the annual wind speeds on estimated energy yield is estimated by means standard calculations the expected energy yield as they are usually applied in project work. Depending on the wind conditions and the underlying type and size of wind turbines, the uncertainty in the estimated energy yield varies. For instance, in Lower Austria with 6 m/s annual wind speed at hub height with an estimated uncertainty of ±0.4 m/s, the energy yield of a typical 2 MW wind turbine lies within a boundary of ±15 %.

3.2 Achievable Wind Potential

Based on the national and international studies, expert consultations, and work shops default values concerning technical and economical constraints have been derived in a consensual manner. Hence, these parameters (cf. Fig. 5) reflect the current status of the Austrian wind energy community (referred to as “IST Szenario”) and may be seen as a common suggestion to be taken for the wind potential analysis in Austria.

When the wind potential analysis tool as it is available on the project’s web-page is fed with these parameters, the graphical user interface (GUI) of the web-GIS application provides an estimation of the technical/economical (or theoretical) wind potential on a district level (cf. Fig. 6). For entire Austria the potential sums up to a capacity of ~12.8 TW installable power and an overall annual energy yield of ~30TWh. Highest potentials can be found in Lower Austria, Burgenland, and Styria with ~7 TW and ~2.3 TW, respectively.

Since the calculations and the underlying datasets do not reflect any socio-political condition (e.g. conflicting interests, acceptance by the population, praxis in awaiting approvals etc.) these results refer to an idealised upper boundary purely limited by technical and economical constraints.



Strompreisszenario

● Ist-Szenario - 9.7 ct/kWh Strompreis /-
○ Szenario 2020 - 11 ct/kWh Strompreis
○ Szenario 2030 - 15 ct/kWh Strompreis

Technische Parameter des Anlagentyps

2000 Leistung WKA [kW]
450 spezifische Leistung [W/m²]

Ökonomische Parameter

650 Basiskosten [€/m²]
7.5 interner Zinssatz [%]
13 Abschreibungszeitraum [a]
3.5 Betriebskosten in [%] der gesar
1.5 jährl. Steigerung der Betreibsko

Inkludierte Landnutzungskategorien:

☑ Ackerland / agrarwirtschaftliche Nutzf
☑ Grünland und naturnahe Flächen
☑ Waldflächen
☐ Feuchtflächen
☐ Abbauflächen, Deponien, Konversion
☐ städtische / städtisch geprägte Grünfl
☐ Wasserflächen / Gletscher / Industrie

Schutzgebiete

☑ Landschaftsschutzgebiete
☐ Natura 2000 / Pflanzenschutz- / Ruhe
☐ Nationalparks / Naturschutzgebiete /

Bestehende Anlagenstandorte

☐ bestehende Anlagenstandorte als Po

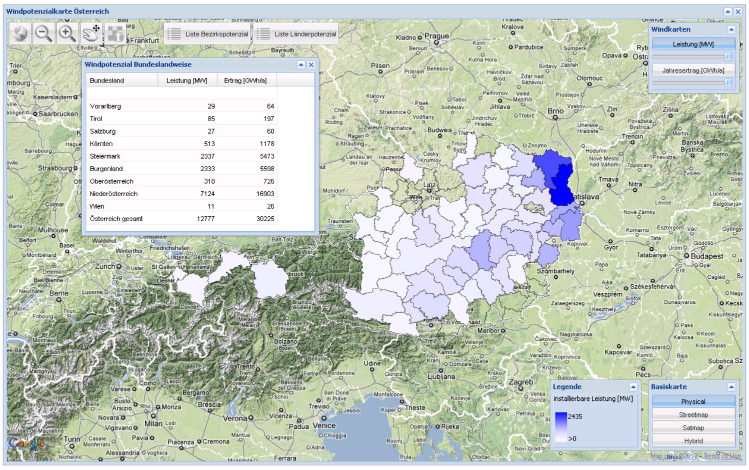
Topographische Beschränkungen

2000 [m] maximale Seehöhe
15 [°] maximale Hangneigung

Abstandskriterien

903 [m] Distanz zu Siedlungsgebieten
165 [m] Distanz zum übergeordneten Strassennetz
165 [m] Distanz zum Schienennetz

Figure 5: Default values for the technical/economical parameters.



Windpotenzial Bundeslandweise

Bundesland	Leistung [MW]	Ertrag [GWh/a]
Vorarlberg	29	64
Tirol	85	197
Salzburg	27	60
Kärnten	513	1178
Steiermark	2337	5473
Burgenland	2333	5598
Oberösterreich	318	726
Niederösterreich	7124	16903
Wien	11	26
Österreich gesamt	12777	30225

Figure 6: Results of the theoretically achievable wind potential in Austria visualised by the GUI of the web-based GIS application.

In order to increase the relevance of the potential estimations for practical applications, the theoretically achievable wind potential was related to the total amount of currently planned wind farms as an addition to the project AuWiPot. These planned wind farms have been collected by means of expert consultations within the Austrian wind energy community and may refer to an achievable wind potential under realistic (including socio-political) conditions reflecting the current consensual opinion. From this subjective point of view the achievable wind potential is about 2.8 TW installable power *[Krenn, 2011]* and hence multiple times smaller than the theoretically achievable potential.

4 Conclusions

By means of the combined dynamic/geo-statistical wind modelling approach it is possible to capture synoptic and local effects on near surface wind in order to generate highly resolved wind climatologies of high quality on the 100 m scale. The investigations have shown that the advantages of both models were combined in a complementarily way. The remaining uncertainty of 0.8 m/s shows the general improvement due to the combined modelling approach. However, the investigations have also shown the limited applicability of raw model output from dynamic models and high-lightened the necessity of a bias correction method. Further improvements can be expected from increasing the resolution of the dynamic model, increasing the number of ingested observation stations for bias correction and geo-statistical interpolation, and the implementation of spatially varying correction functions based on the quantile mapping method.

The technical employment of the web-based GIS application was a challenging task and required notably innovative developments with respect to data management in order to enable user-tailored scenario generation “on-the-fly”.

The presented wind potential refers to an idealised upper boundary limited by technical and economical constraints. For estimating the achievable wind potential under realistic conditions, further investigations including socio-political constraints are required. Nonetheless, since the estimation of the theoretical potential is based on objective methods, the influence of (other subjective) socio-political constraints on the wind energy sector in Austria is revealed.

Acknowledgements

We would like to thank the Jülich Supercomputing Centre (JSC), Germany, and the Centre for IT services of the University of Graz, Austria, for the provision of computational resources. Observational data were provided by the Austrian Central Institute for Meteorology and Geodynamics (ZAMG), private companies, federal Austrian governments, the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss), the German National Meteorological Service (DWD), the Southern Tirol Weather Service, and the University of Innsbruck, Austria.

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