Gesellschaft für Umweltmeteorologie mbH

Documentation

on the

anemos wind atlas

for Germany 3 km

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Contents **Page**

1. Introduction

The new **anemos wind atlas** for Germany 3 km (**D-3km.M2**) represents a database containing long-term time series for the atmospheric parameters wind speed, wind direction, air temperature, air pressure, relative humidity, air density, precipitation, long- and shortwave radiation. The temporal resolution of the wind atlas is 10 minutes, the horizontal resolution is 3 x 3 km². It covers whole Germany as well as great parts of the North and Baltic Sea. Fig. 1 shows the process chain of the development of the anemos wind atlas. The three main issues are:

- Optimization of the model settings with subsequent WRF main simulation (Downscaling)
- Wind Atlas remodelling (Optimization of the WRF main simulation)
- Verification of the WRF main simulation with wind measurements

More detailed explanations of these three issues can be found in chapters 4 - 8.

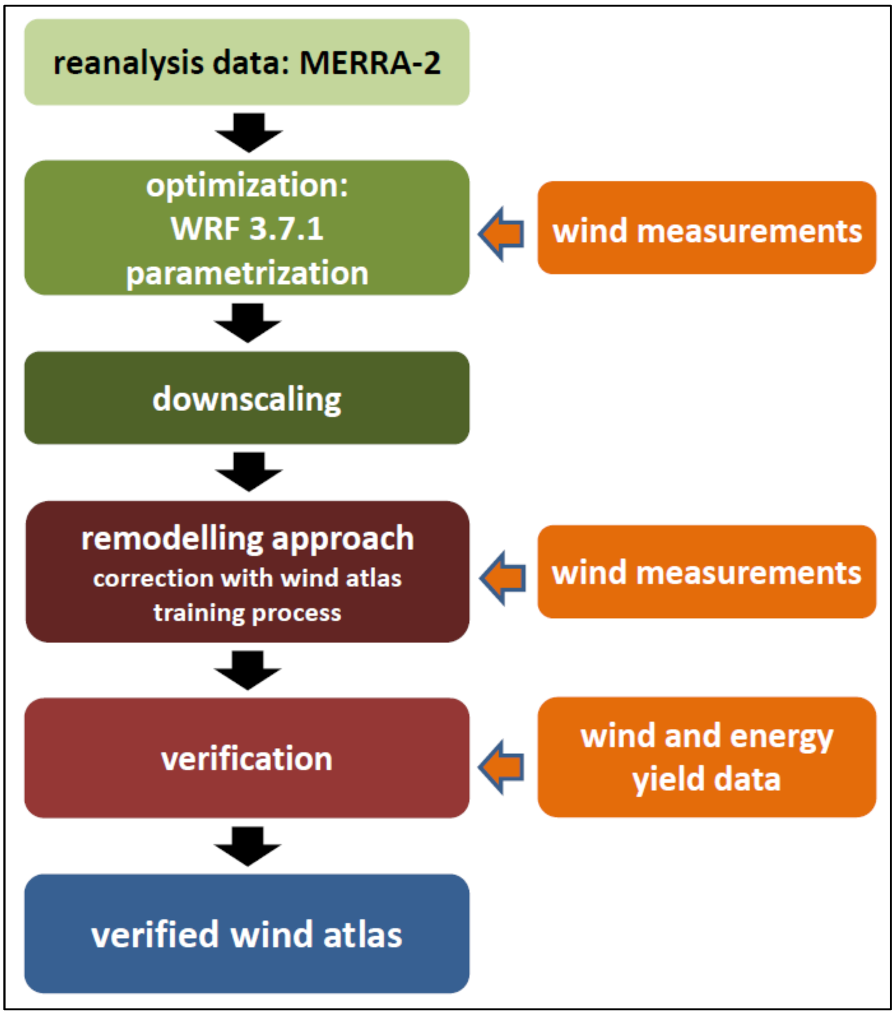

Fig. 1: Developmental steps of the new anemos wind atlas for Germany 3 km.

2. The WRF model

The wind atlas **D-3km.M2** is created by means of the meteorological mesoscale model **WRF** (**W**eather **R**esearch & **F**orecasting model with the version 3.7.1). The WRF model is a state-of-the-art weather forecast system (coupled atmospheric-land surface model) of the next generation which was developed in the 1990s at **NCAR** (**N**ational **C**enter for **A**tmospheric **R**esearch).

WRF is a non-hydrostatic model (explicit calculation of the vertical velocity) and estimates for each time step the Navier-Stokes equations, which describe the atmospheric flow. Mesoscale processes such as the land-sea wind circulation or deep convection (thunderstorms) can be sufficiently resolved by the model. However, microphysical processes as well as shallow convection, radiation or planetary boundary processes have to be parameterized.

The WRF model with its so-called multi-nesting ability allows for a simultaneous calculation of several model domains with different grid resolutions (Fig. 2). This way, regional high-resolution simulations of the atmospheric circulation are possible, which employ detailed ground level information in order to take into account the impact of vegetation, roughness and orography.

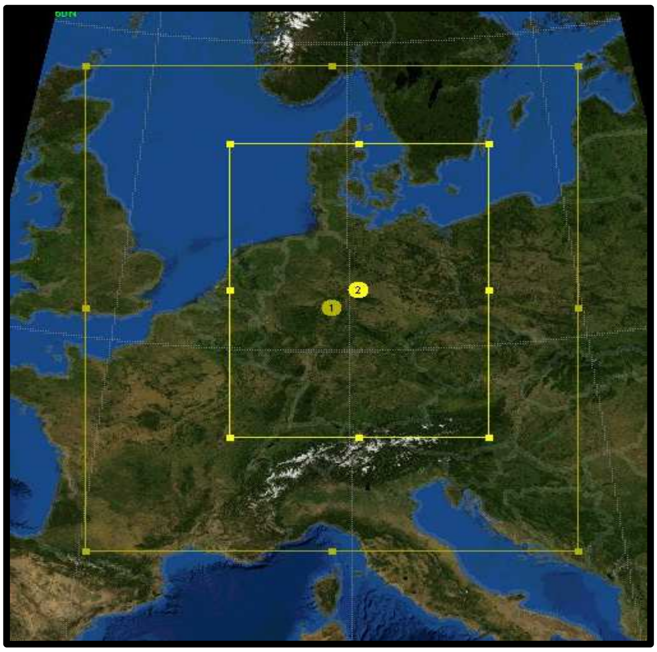

Fig. 2: Multi-nesting process with two domains of the anemos wind atlas Germany 3 km. Domain 1 with 15 x 15 km² and domain 2 (Nest) with 3 x 3 km².

For the wind atlas **D-3km.M2** a nest with two domains is applied (Fig. 2). The simulation area consists of a coarser exterior domain inside which a high-resolution interior domain is nested. The exterior domain covers great parts of central Europe and has a spatial resolution of 15 x 15 km². The interior domain covers Germany with a spatial resolution of 3 x 3 km². During the simulation process, both domains communicate with each other. The exterior domain supplies the boundary conditions for the interior domain, while latter feeds the exterior domain with high-resolution calculations.

During the simulation, new input data are assimilated into the WRF model every three hours, which forces the model into the right direction (nudging process). The atmospheric state variables are stored every 10 minutes for each grid point on a grid. The simulation covers the period 1997 up to date and is continuously extended. The vertical model structure of the atmosphere has a high resolution with 25 vertical layers. The lower heights, which are relevant for wind turbines (up to 250 m) contain already 8 of the 25 vertical layers.

3. Input data

The WRF model requires surface data (soil temperature, soil moisture, snow, etc.) as well as all important atmospheric parameters (wind, temperature, pressure, relative humidity, etc.) as input data. For the wind atlas **D-3km.M2** the new, worldwide available MERRA-2 reanalysis data are used as input and driving data.

The MERRA-2 reanalysis data are of higher quality than the former MERRA reanalysis data regarding consistency and correlation. Therefore, the advantages of the MERRA-2 reanalysis data such as consistency, homogeneity, length of time series, continuous updates, onshore as well as offshore availability can be preserved or even amplified by the WRF model. In addition, the disadvantages of relatively low spatial (0.5° latitude, 0.625° longitude, corresponding to approx. 40 x 40 km²) and temporal resolution (3 h) of MERRA-2 reanalysis data are surmounted by the anemos wind atlas **D-3km.M2**.

The surface data are taken from the **CFS** data set (NCEP **C**limate **F**orecast **S**ystem). It consists of four surface levels and contains soil moisture, soil temperature and snow. The CFS data have a temporal resolution of six hours and a horizontal resolution of 0.2° latitude and 0.2° longitude.

The ground level elevations are taken from the **SRTM** data set (**S**huttle **R**adar **T**opography **M**ission, USGS EROS Data Center) and interpolated onto the model grid. These data were collected in the year 2000 and are available with a spatial resolution of about 90 m. The vertical resolution is 1 m. Any information about vegetation or roughness conditions within the boundaries of the simulation area are derived from the **CORINE** data set of the European Environment Agency (**EEA**). This information is based on data of the satellite LANDSAT 7 scaled 1:100.000. The grid data are available in a spatial resolution of 100 m.

4. Optimization of the model settings

The model settings and parameterizations (e.g. planetary boundary scheme, surface scheme, radiation scheme) were tested prior to the main simulation and optimized for the relevant atmospheric parameters (wind speed and wind direction). More than 30 different model settings for selected months in spring, summer, autumn and winter were tested and verified with wind measurements (met masts and LiDAR, see Fig. 1). These tests show how the wind field near the ground reacts to different parameterizations and schemes (sensitivity tests). The setting which yields the lowest deviations between model and observations is then used for simulating a complete year. If this last verification also shows good forecast quality, the main simulation will be started continuously (> 20 years).

5. Statistical verification with wind measurements as preparation for remodelling

The most important task after running the main simulation is its intensive verification with various wind measurements. 45 measurements were used for verifying the **D-3km.M2**.

Through the verification the quality of the main simulation can be determined and systematic errors in the next step, the remodelling process (chap. 6), can be identified and the quality of the wind atlas can be improved. The verification includes statistical key parameters such as mean values, coefficient of determination (R^2) or correlation (R), bias, root mean squared error (rmse) and extreme values (QQ-plot). Additionally, vertical profiles, diurnal cycles, wind roses, and frequency distributions with Weibull parameters are checked.

6. Remodelling

After the complete verification of the main simulation with all available wind measurements, the wind atlas is optimized through a remodelling process. Based on the results of the verification in chap. 5, a sectorial training is conducted with 28 wind measurements. The remaining measurements are used for the subsequent independent verification of the remodelling process.

During the training process, scale parameters are developed by a multiple linear regression analysis, which will then be applied to the wind atlas time series. Dependencies between the scaling parameters and the sub grid topography are identified and applied if they show sufficient significance. Consequently, all grid cells can be corrected with the developed scaling parameters based on the sub grid information (orography, roughness, etc.). Eventually, remodelling improves the statistical key parameters as well as the frequency distribution with Weibull parameters and the vertical wind profile.

7. Site-specific time series of wind speed

Within the frame of the remodelling process, a site-specific elevation correction was developed based on CFD simulations at various complex measurement sites. The CFD model Meteodyn WT simulates the 3 km x 3 km grid cells of the test sites with a high spatial resolution. The orographic information is taken from the SRTM data set (3 arcsec ~ 90 m).

Since the elevation correction takes into account the difference in elevation between the grid cell and the measurement, the site-specific correction yields improvements in mean wind speed especially in complex regions. In flat terrain, the elevation correction has no significant impact because of the small height variations. The height correction function is applied to each time step of the time series. Due to the remodeling process with site-specific elevation correction and the intensive verification with measurement data, the new wind atlas represents currently the best data set for Germany.

8. Verification after remodelling

After remodelling, the wind atlas times series are verified with 45 wind measurements. In Fig. 3 the results of the verification are exemplarily given for a measurement height of 100 m. The bias of wind speed is calculated and displayed for 4 offshore and 41 onshore sites. Fig. 3 shows the percentage deviations for each measurement in comparison to the wind atlas before remodelling (WRF output, blue) and after remodelling (D-3km.M2, red). The graph shows that the significant positive bias at onshore sites and the small negative bias at offshore sites can be corrected through remodelling. Most sites exhibit a bias in the range of ± 5 % (71% of the measurements) after remodelling, which is a significant improvement. The mean hourly correlation (R) is 84.2% and the mean bias is -0.2%. The rmse of the deviation is 4.4% and thus, below the 5% threshold.

Additionally, an external verification was performed by Dr. Anselm Grötzner, CUBE Engineering GmbH – Part of Ramboll. Fig. 4 shows the results of this verification, for which relevant hub heights between 80 m and 140 m a.g.l. were investigated.

Fig. 4 shows the bias in wind speed and in energy density for 56 external wind measurements. The deviations in wind speed between the measurement and the D-3km.M2 data are in the range of ± 7% for the majority of the sites (88% of the measurements). The hourly correlation of wind speed averaged across all available measurements reaches a value of 84.8% for the wind atlas D-3km.M2. The bias (0.9%) and rmse (5.3%) show a significant improvement compared to the old wind atlas for Germany.

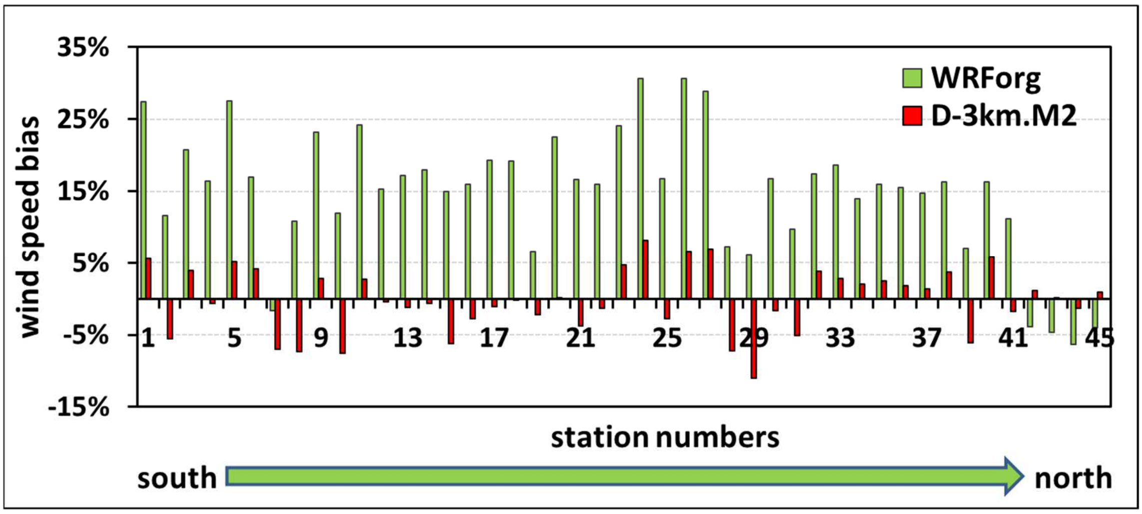

Fig. 3: Bias in mean wind speed between 45 internal wind measurements and the WRF output (blue) or the D-3km.M2 (red). The measurements are sorted from south (left) to north (right). The measurement height is 100 m and the measurement period covers one year.

The deviations in energy density are also very small (bias 0.7% and rmse 6.8%). Therefore, also the prediction of the energy density could be improved significantly compared to the former version of the wind atlas for Germany. This is especially important for the calculation of energy yields and market values. Through remodelling, in particular the Weibull distribution and the vertical profile of the wind speed are improved, such that the bias of the energy density is within the range of ± 10% for 93% of the sites.

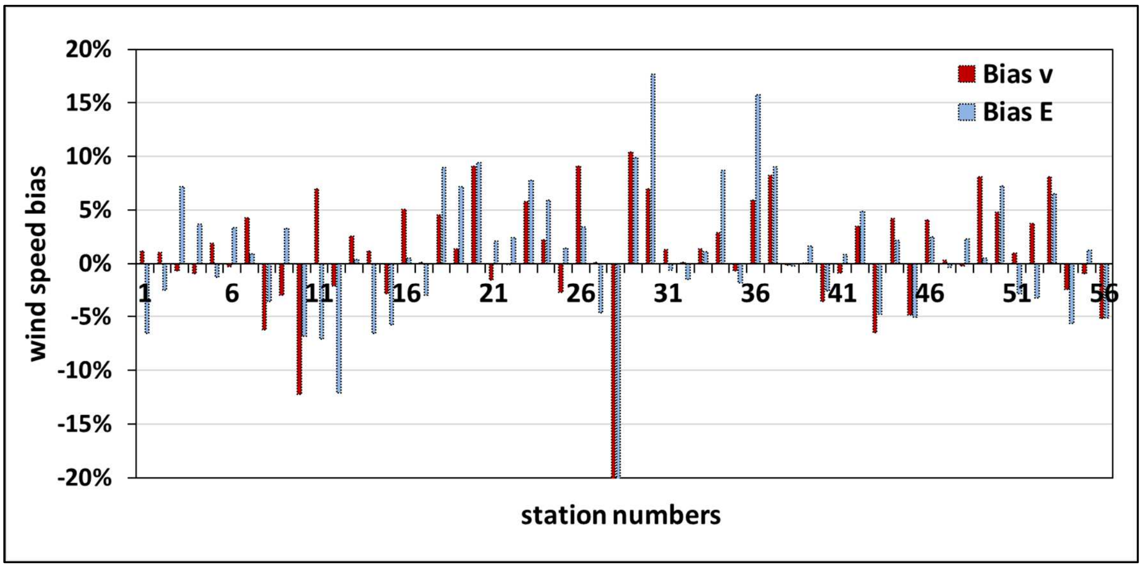

Fig. 4: Bias in mean wind speed (red) and mean energy density (blue) between 56 external measurements and the D-3m.M2. The measurement heights cover 80 m to 140 m a.g.l. and the measurement period covers one year. The verification was performed by Dr. Anselm Grötzner, CUBE Engineering GmbH – Part of Ramboll

An additional analysis (Fig. 5) was carried out by an anonymous wind farm developer. In this verification, 23 long-term wind speed measurements from heights between 100 m – 170 m are compared with the corresponding wind speed from the wind atlas. A slight underestimation of the wind potential was recorded (mean deviation of -0.6 %). The standard deviation is with a value of 4.8 % underneath the 5 % threshold. All in all, at more than 90 % of the locations, the wind atlas bias is less than 7 %. Furthermore, the measurements were classified as forest, farmland or rather grass locations. No significant difference of the bias is visible.

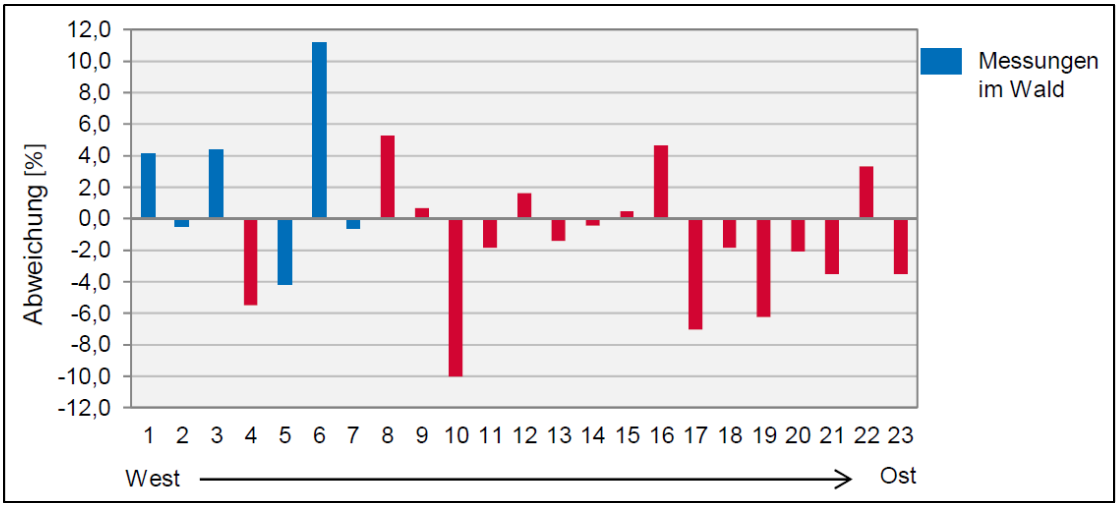

Fig. 5: Bias of mean wind speed (between anemos wind atlas and long-term wind speed from measurements) on a mean height of about 130 m. Forest locations are indicated by blue color, farmland or rather grass locations by red color.

TÜV Süd investigates the anemos wind atlas time series at one site with a height about 140 m. Fig. 6 shows the monthly average wind speed and the deviation between the measurement and the wind atlas time series. An average bias of around -3.6 % and a correlation (R^2 with hourly basis) of about 74.5 % was calculated. A significant deviation in wind speed was only found at one month. In addition, the time series shows satisfying simulation results for the diurnal cycle and the wind direction, which are both close to the measurement.

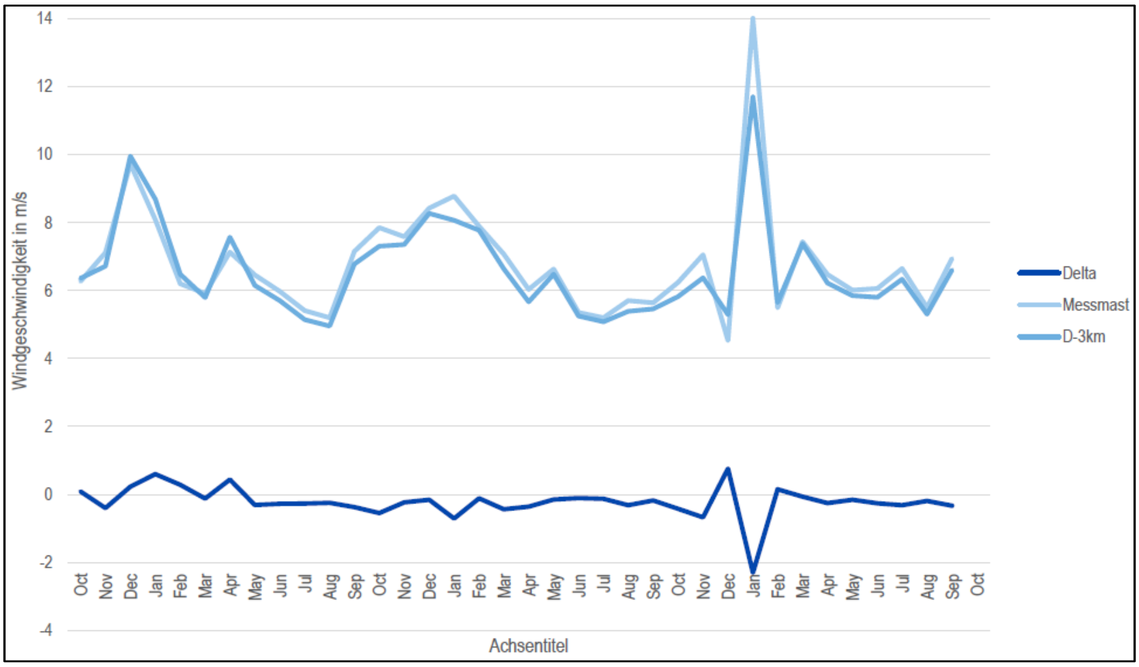

Fig. 6: Comparison of the monthly means of absolute values (top) and the deviation of the wind speed (bottom) between a measurement in Bavaria (height: 140 m a.g.l.) and the anemos wind atlas. (figure provided by TÜV Süd)

9. Verification with energy yield data

In this chapter, site-specific wind speed time series are transformed to energy yield (power production) time series and compared to SCADA-data from operating wind turbines. In order to realize this comparison in a consistent way, the atlas wind speed time series is corrected according to air density and in the next step, it is combined with the measured power curve. In addition, local information of the surrounding wind turbines is added. By applying the Jensen Wake model equations at every time step of 10 min under consideration of wind direction, it is accounted for the wake effects of surrounding wind turbines which are included in the SCADA-data of operating wind turbines. In contrast, the SCADA-data is filtered. All time steps are removed where the wind turbine was not in optimal operational mode. After that, the wake effects are the only source of energy yield loss which is left after the filtering. This is the reason why the wake model is applied to the wind atlas data. In the following, the wind atlas energy yield time series and the SCADA-data from operating wind turbines are prepared in order to carry out a consistent statistical analysis.

For this verification project, a data base of SCADA-data from 150 wind turbines located in 27 wind farms was established (minimum one year of data, see Tab. 1 for more information). Fig. 7 shows the hourly correlation (wind farm average) between the wind atlas (D-3km.M2) energy yield time series and the SCADA-data. The correlation coefficients are between 75 % and 85 % for the wind farm averages which is rated as good to very good. On total average, the correlation is 82.7 % (without wake model) and 81.8 % (with wake model). The lower correlation after applying the wake model is due to the use of the wind atlas wind direction time series, which includes an additional uncertainty in the calculation. In addition, a comparison of the SCADA-data with the ConWx time series was carried out. In general, the correlations with ConWx are lower than with the anemos wind atlas (D-3km.M2). This difference is small in flat terrain (North) and higher at locations with complex terrain (South). On total average, ConWx has a correlation of 80.2 %.

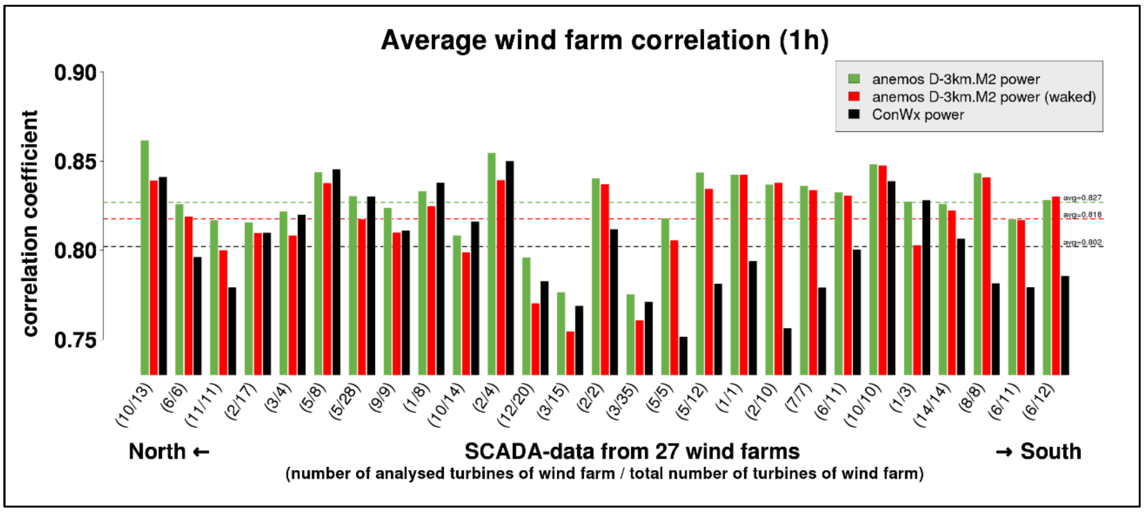

Fig. 7: Average correlation (1h) per wind farm between the energy yield time series from the D-3km.M2 wind atlas (with/without wake losses: green/red) and the SCADA-Data of 27 wind farms. The average correlation (1h) per wind farm between the ConWx energy yield time series and the same SCADA-Data of 27 wind farms is shown in black bars. Wind farms are sorted from North to South. The numbers under the bars indicate the number of analysed turbines of a particular wind farm to the total number of turbines in this wind farm. Dashed lines illustrate the total average of the correlations.

During the verification of the energy yield an adaptation was included. A first preliminary verification revealed that the wind atlas energy yield was too high in comparison to the turbines' SCADA data. This contradicts the verification results of the wind atlas with wind measurements (chapter 8). In this verification it was shown that there is a mean bias in wind speed very close to zero. The fact that wind turbines are not able to perfectly meet the power curve at many sites possibly leads to this discrepancy. Reasons could be flow inclination, an imperfectly-oriented gondola or increased turbulence. All these points are minimized during a power performance measurement.

For that reason, an adaptation factor was established that corrects the bias in energy yields. To this end, 27 wind farms were assorted from the North to the South and every third wind farm was taken out in order to have an independent verification data set. In the next step, an adaptation factor was selected that minimized the bias of the training data (Fig. 8). A factor of 0.9 turned out to be the best choice. It was decided not to use more decimal places. This factor was applied on the independent verification data set and it turned out that it improved the results of 7 out of 9 wind farms (Fig. 9). The total average of the verification data set shows an improvement as well. Before (after) the adjustment, the average bias was 12.4 % (-2.7 %). In summary there is a notable improvement of the wind atlas energy yield after the adaptation.

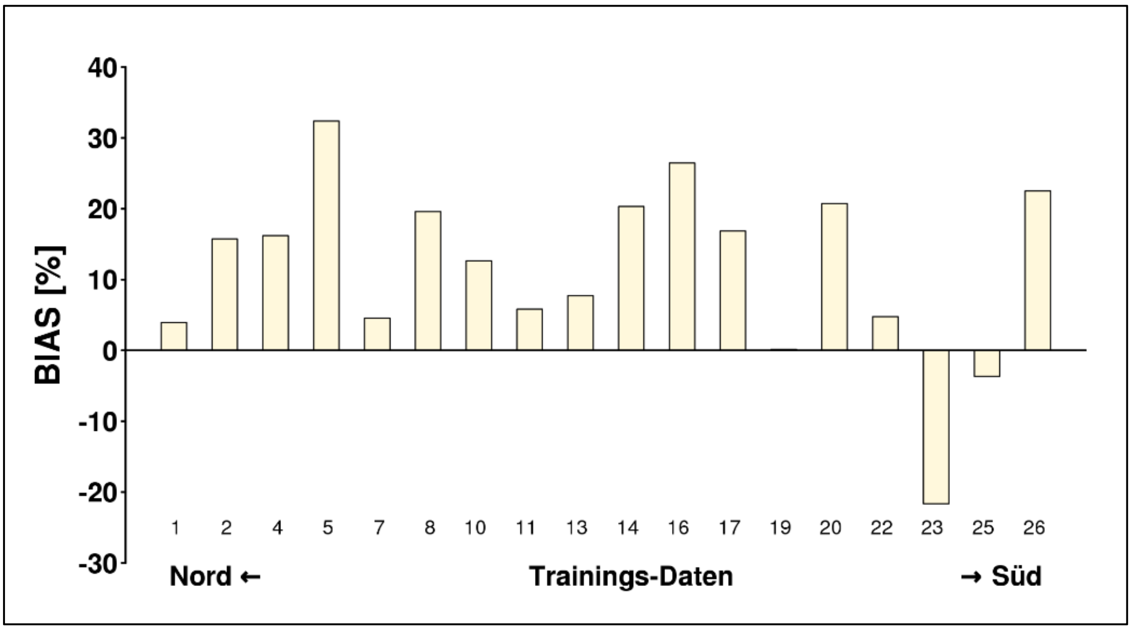

Fig. 8: Bias of the training data before the establishment of the adaptation factor. Wind farm averages are shown here. The wake model was applied.

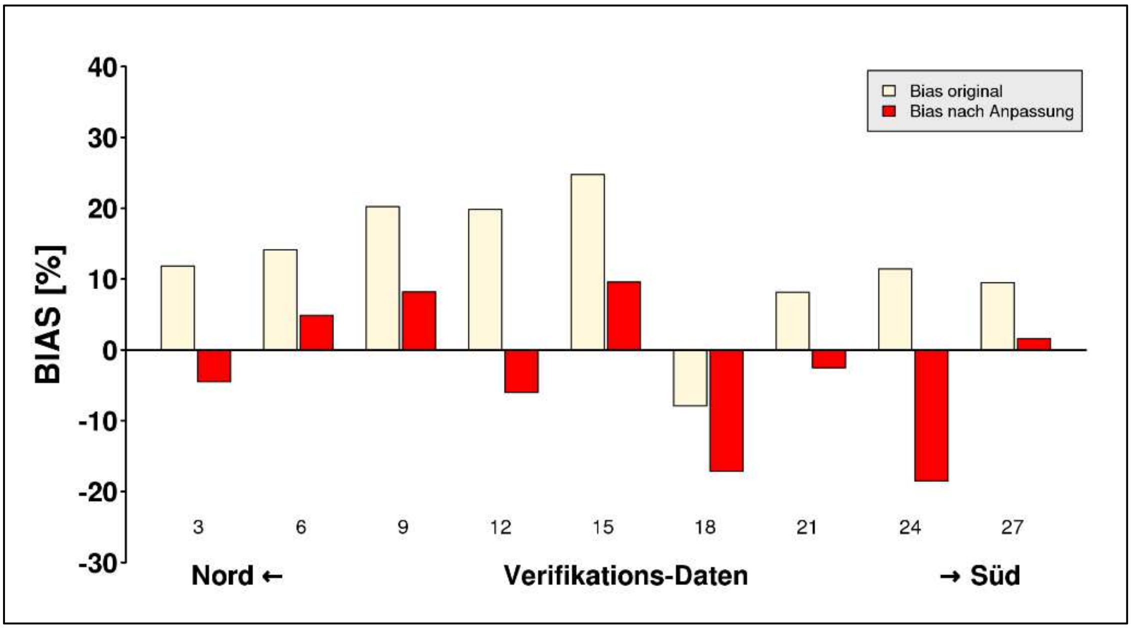

Fig. 9: Bias of the verification data before (beige) and after (red) the establishment of the adaptation factor. Wind farm averages are shown here. The wake model was applied.

Fig. 10 shows the average bias of the wind atlas (D-3km.M2) to the SCADA-Data for each wind farm after the adaptation. Regarding the D-3km.M2 without having applied a wake model, most of the wind farms are positively biased (green). The energy yield of the D-3km.M2 time series is reduced by the wake model and thus results in a distribution around the zero line (red). Consequently, 95 % of the locations shows a bias within the range of ±20 %. In contrast, ConWx energy yield time series show a large positive bias at all locations (black).

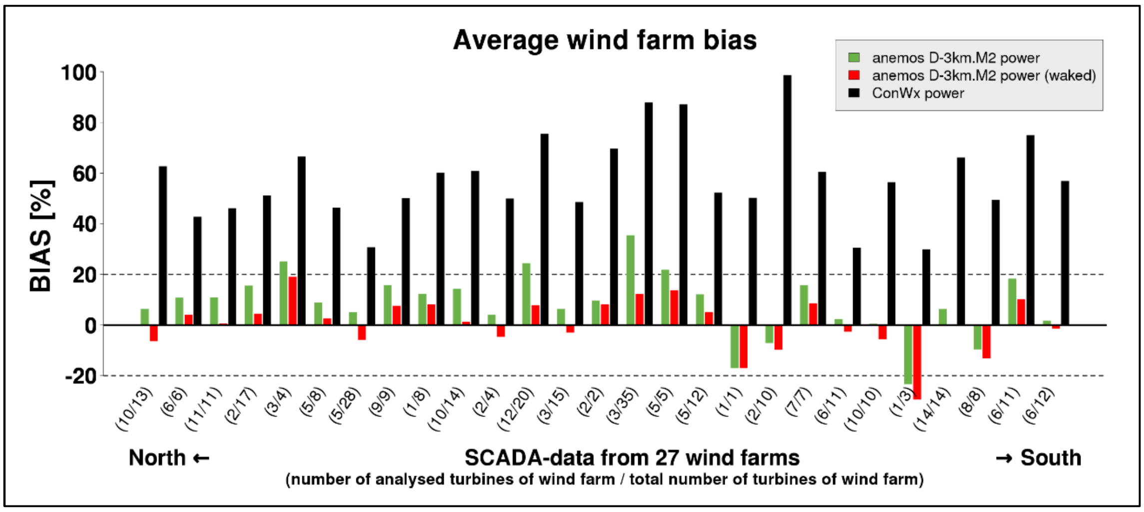

Fig. 10: as in Fig. 7, but here the average bias (%) per wind farm is presented. The black dashed lines mark the ±20 % threshold.

10. Uncertainty analysis of the wind atlas

For an estimation of the regional uncertainty, an additional analysis was carried out. Tab. 1 shows the measurements per federal state of Germany, Fig. 11 roughly indicates the locations. The measurements are not shown with the exact place of location, due to the privacy of the data. The deviation map for the wind speed was calculated with the verification results of the chapter ‘Verification after remodelling‘. All measurements shown in Fig. 11 were separated in different classes of orography and roughness. The deviation (bias) of the particular class (region) is the sum of the mean absolute bias plus the standard deviation of that particular measurement.

Tab. 1: List of all measurements and SCADA-Data farms per federal state

Federal states of Germany	Number		Federal state of Germany	Number	
	measurements	SCADA-data		measurements	SCADA-data
Baden-Württemberg	13	1	North Rhine-Westphalia	4	0
Bavaria	8	3	Rhineland-Palatinate	16	5
Berlin	0	0	Saarland	8	0
Brandenburg	6	6	Saxony	0	0
Bremen	0	0	Saxony-Anhalt	1	4
Hamburg	1	0	Schleswig-Holstein	0	1
Hesse	28	1	Thuringia	1	0
Mecklenburg-West Pomerania	0	2	Offshore	4	0
Lower Saxony	2	2	Borderlands	12	2

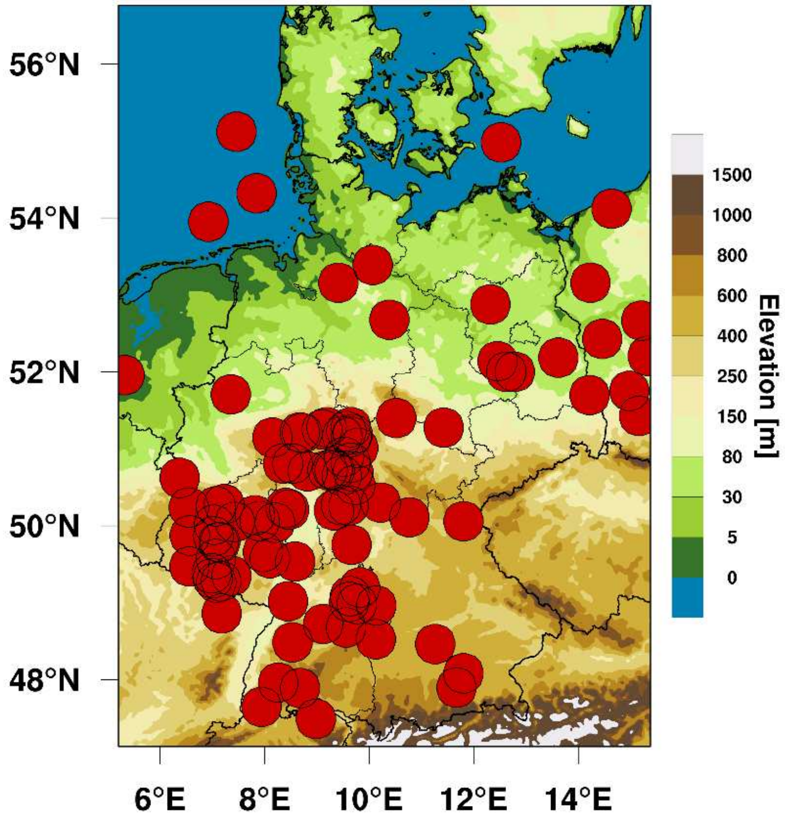

Fig. 11:Map of the measurements used in the verification

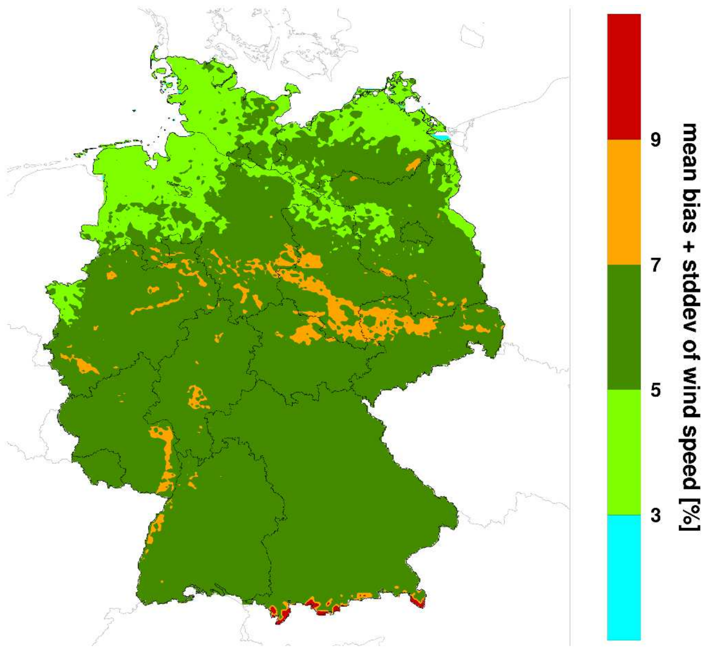

Fig. 12: Deviation map (mean absolute bias + one standard deviation) of the Germany 3 km wind atlas.

The deviation map for the wind speed shown in Fig. 12 is an estimate for the regional deviation. For most regions of Germany, the deviation is below 7%. The uncertainty analysis of the wind speed for the Germany 3 km wind atlas is shown in Fig. 13. The deviation (bias) to the measurements is separated into 1 % bins. With an average bias of 0.11 %, the majority of the deviations is within the range of ±5 %. The standard deviation of the Gauss distribution is 5.05 % (P68).

Analogue to the uncertainty calculation for wind speed, the same is carried out for the energy yield. Therefore, 27 wind farms with over 150 WTG from Chapter 9 are separated into bins of 2%. With an average bias of +1 %, the majority is within the range of ±15%. The standard deviation of the Gauss distribution for the energy yield is 13.56 %.

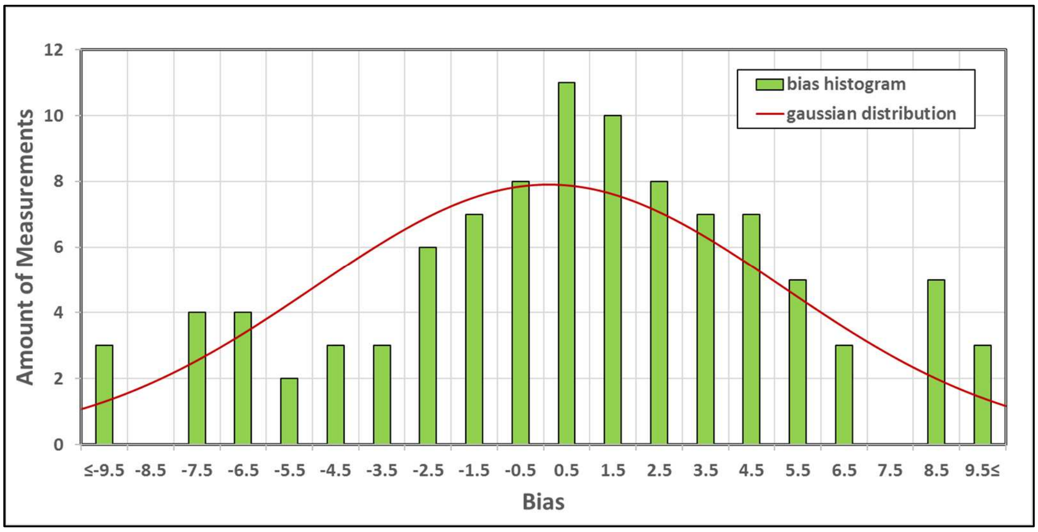

Fig. 13: Histogram of the deviations and uncertainty analysis using the gauss distribution.

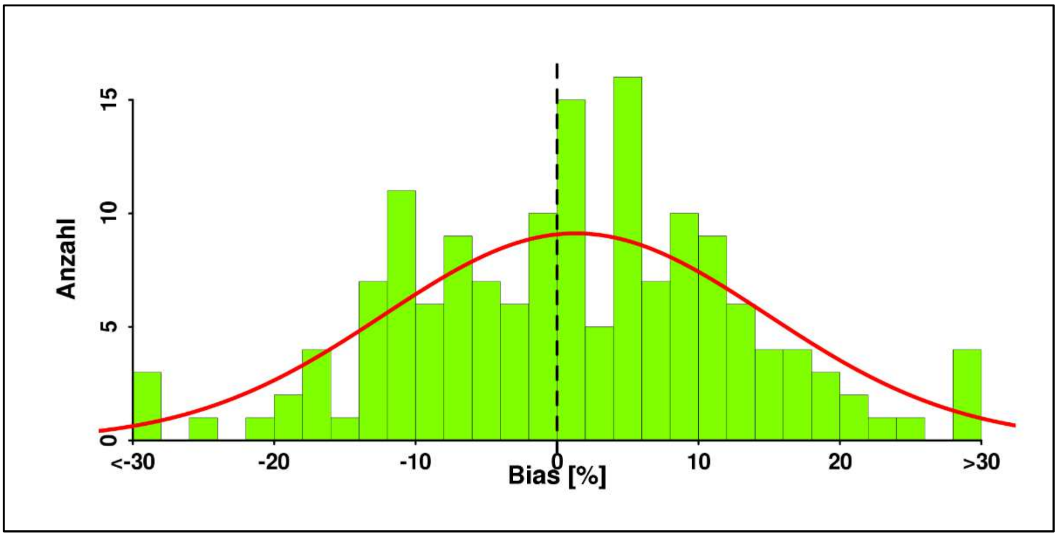

Fig. 14: Histogram of the deviations and uncertainty analysis for energy yield.

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