ULTRUS™ | Windnavigator

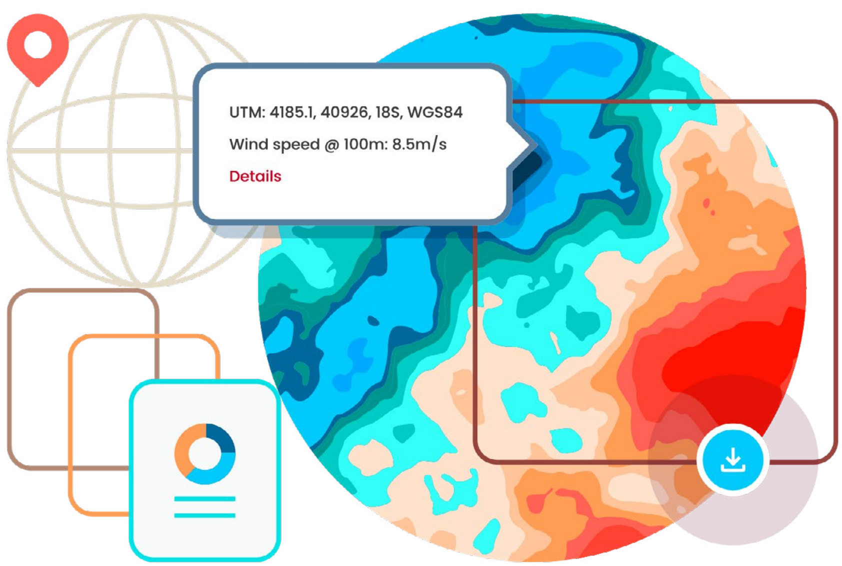
WHITE PAPER

2025 Europe Wind Map

Methods and Validation

Date: November, 2025

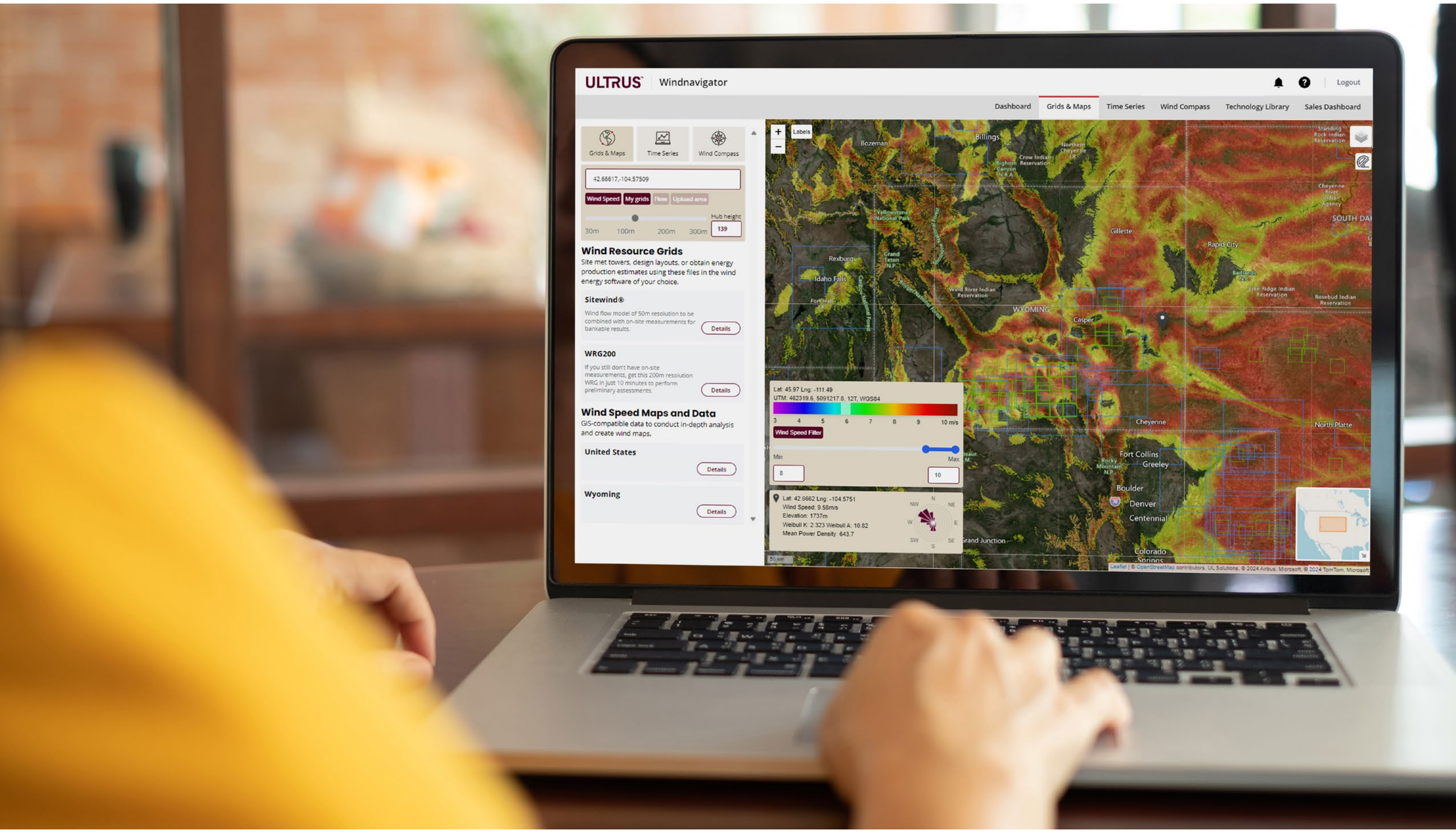
Authors:
José Vidal — Product Manager
Philippe Beaucage — Lead Research Scientist
Rahul Bhosale — Software Development Senior Manager
Yagnesh Yakkala — Research Scientist
Reviewer: José Javier Ripa — Head of Product Management.



UL Solutions

UL.com/Windnavigator

Table of contents



UL Solutions

UL.com/Windnavigator

1. Introduction

The 2025 Europe wind map released on UL Solutions' ULTRUS™ Windnavigator Resource Data and Maps software is a major update to the original map which dates from 15 years ago. The 200-meter resolution means wind speed maps are created with UL Solutions' proprietary wind flow modeling system, consisting of a coupled mesoscale and microscale model. The model outputs are subsequently fine-tuned with wind measurements from UL Solutions' large database of met stations. The new wind map not only provides more accurate data and at higher heights (up to 300m) but also leverages the latest advancements in wind modeling technology, offering enhanced insights when analyzing and prospecting greenfield sites and assessing competing projects. More specifically, the enhancements designed to help wind developers make more informed decisions include:

- Expanded met data coverage
  - Provides 2.3 times more observations compared to the original map
  - Includes met data from longer periods of record and higher measurement heights
  - Features more representative and spatially diverse met data in Europe
- Enhanced wind map heights
  - Wind maps now available up to 300m, accommodating taller turbines
- Improved wind modeling and accuracy
  - Based on the latest mesoscale modeling and reanalysis dataset

This report describes the methods and models behind the 2025 Europe wind map.

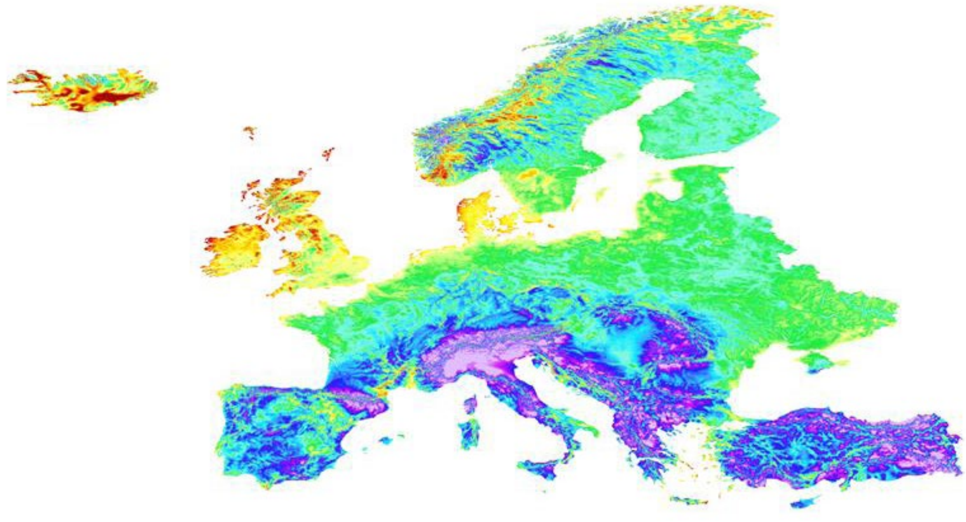


Figure 1.1: Europe mean wind speed map at 100 m a.g.l.

2. Methodology for wind resource mapping

The Europe wind map was created using UL Solutions' coupled mesoscale numerical weather prediction (NWP) model and a microscale model to estimate the wind resource. UL Solutions has extensive experience running NWP models such as MM5, MASS, ARPS and WRF over the last four decades. In the late 1990's, UL Solutions and the Technical University of Denmark (DTU) independently pioneered a method to couple a mesoscale NWP model with a microscale wind flow model. They are respectively known as MesoMap or SiteWind (Brower 1999) and KAMM/WAsP (Frank and Landberg 1997) systems. Over the years, the coupled mesoscale-microscale modeling system has become the preferred approach for generating mean wind speed maps over large regions (e.g. AWST 2012, Dörenkämper et al. 2020, Davis et al. 2023).

Figure 2.1 provides an overview of the wind mapping process. While a robust wind flow modeling system is key to creating an accurate wind resource map, a large database of good quality wind monitoring stations is just as important. The wind measurements are used to anchor the model outputs to ground truth. The last step when creating wind resource maps is to adjust the mean wind speed maps to wind measurements from met stations.

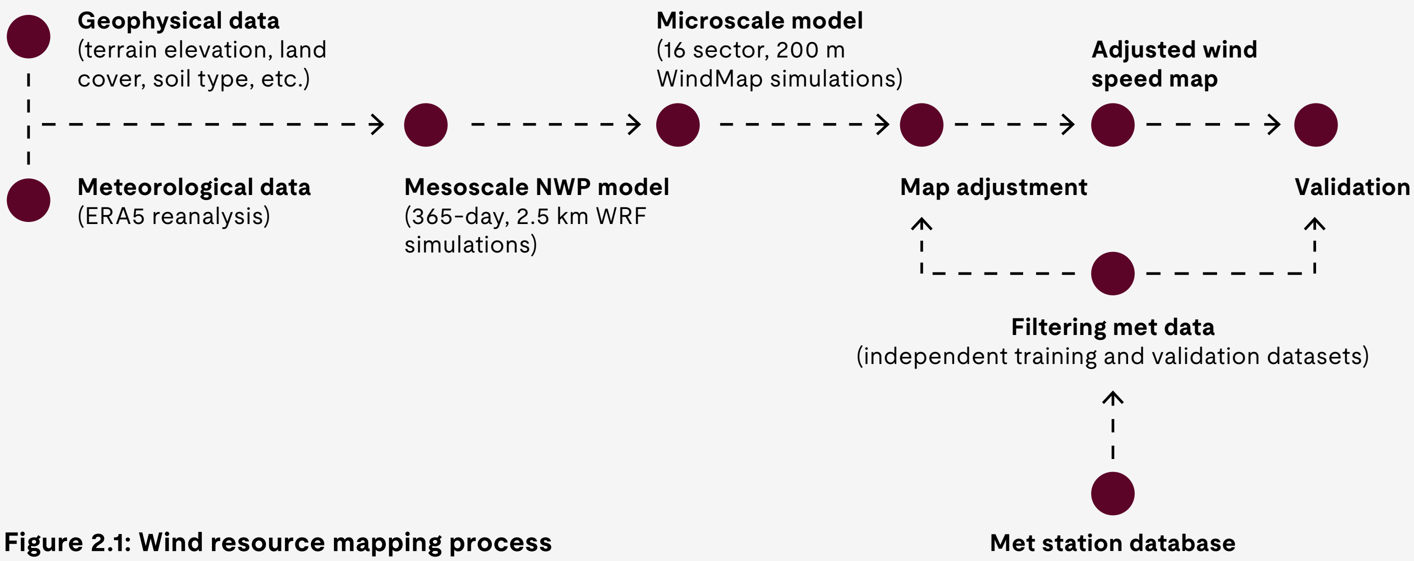


Figure 2.1: Wind resource mapping process

2.1 Wind Flow Modeling

The ULTRUS™ Windnavigator wind flow modeling system is a combination of two atmospheric models: a mesoscale NWP model and a microscale wind flow model. The mesoscale model simulates weather conditions for a representative meteorological year (365 days sampled from a recent 15-year period) on a horizontal grid of 2.5 km. The microscale model then refines the wind fields from the mesoscale model to capture the local influences of topography and surface roughness changes at a resolution of 200 m.

UL Solutions relies on a state-of-the-art mesoscale NWP model: the Weather Research and Forecasting (WRF) model (Skamarock 2004). WRF solves the fully compressible, non-hydrostatic Navier-Stokes equations and includes a complete suite of physics parameterization schemes. Accurate initial and boundary conditions are crucial for NWP simulations. UL Solutions relies on the ERA5 reanalysis, the fifth-generation climate reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). It incorporates weather observations from many thousands of platforms around the world, including surface stations, rawinsonde stations, satellites, aircraft and others. ERA5 provides hourly data for many atmospheric, land-surface and sea-state parameters on a 0.25-degree resolution grid (~30 km resolution). NWP models like WRF are highly effective in simulating the evolving atmospheric conditions, especially the synoptic scale and mesoscale.

The 2.5-km resolution WRF model outputs are then coupled to the microscale model, WindMap, which is run with a grid spacing of 200 m. WindMap, developed by UL Solutions, is a mass-conserving model that adjusts an initial wind field, here supplied by WRF, in response to local variations in topography and surface roughness. Thus, WindMap preserves as much information as possible from the mesoscale model fields while adjusting the microscale wind flow to the finer resolution topography and surface roughness maps.

2.2 Wind Observations

A large database of good-quality wind observations is crucial to produce accurate wind resource maps. Thanks to UL Solutions' long history of providing renewable energy advisory going back to the 1980s, we can rely on approximately 1,000 met stations in Europe, most of them coming from private sources. For this wind mapping exercise, we had roughly 2.3 times more wind observations than for the original map, and with longer periods of record and higher measurement heights. The UL Solutions database of long-term mean wind speed observations mostly comes from numerous met masts and remote sensing devices instrumented for wind resource assessment, often provided by customers of Windnavigator and is used only with permission. Where possible, the mean speeds from short-term measurement programs are adjusted to represent long-term conditions; stations with periods of record of less than one year are not considered. As can be seen in Figure 2.2, a majority of the met stations are in France, Italy, Spain, Turkey and the U.K.

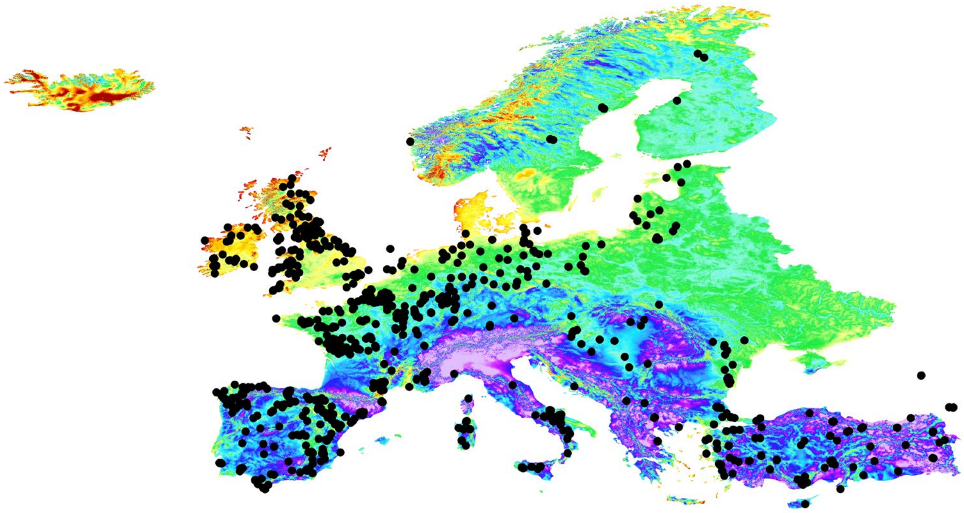


Figure 2.2: Met station database for Europe

To minimize the deviation between the mean wind speed map and the measurements, a regional — rather than local — bias correction is preferred (see next section). The met station database is filtered to find the most representative met station within a radius of about 40 km. To do so, the met stations were grouped by clusters, and one met station per cluster was selected. The most representative met station in a cluster is the one with the longest period of records and the highest top measurement height. This filtering allows for the representative met stations to be more equally spaced over the entire region. After filtering, 384 representative met stations were selected, as shown in Figure 2.3.

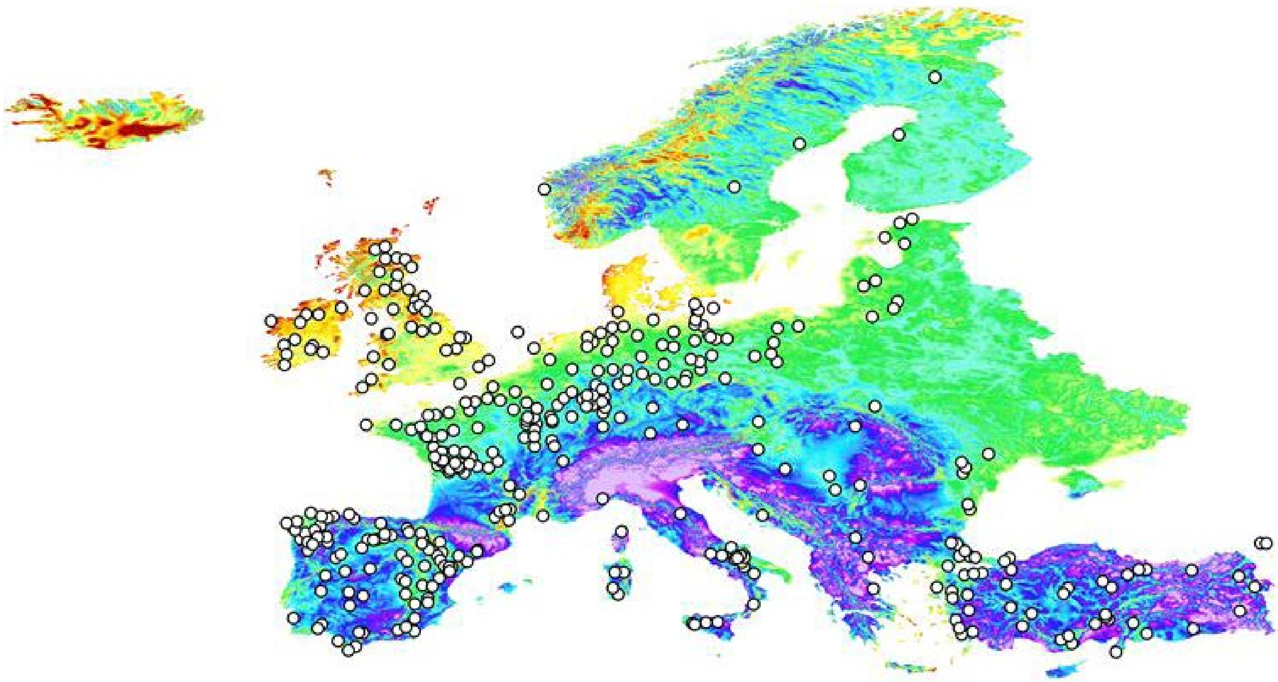


Figure 2.3: Representative met stations in Europe

2.3 Map Adjustment

In the map adjustment process, the wind observations in UL Solutions' database serve to reduce the mean wind speed bias of the map. The mean wind speed map is adjusted using the available wind observations. The objective of this map adjustment is to minimize discrepancies between modeled and observed mean wind speeds.

The first step is to calculate the wind speed bias between the raw (unadjusted) wind map and the observed mean wind speed for each met station. An in-house software program interprets the mean wind speed biases at all the met stations to generate a speed bias map. This speed bias map is then applied to the raw (unadjusted) wind map to create the adjusted wind speed map. Given our approach to select one representative met station within a radius of about 40 km, we are effectively applying a regional bias correction rather than a local bias correction. A local bias correction generally leads to bull's-eye patterns around the measurement locations and may lead to overfitting in surrounding areas without measurements. Instead, the smoother regional bias correction is designed to eliminate spatially correlated biases affecting regions of a significant size, roughly the mean spacing between representative met stations, although this is variable across the continent. In the end, this map adjustment approach does not eliminate the wind speed bias at every met station. However, it does help to significantly reduce the mean bias error (MBE) and root mean square error (RMSE) while improving the coefficient of determination (R^2). In fact, the scatterplots in Figure 2.4 demonstrate the advantages of adjusting the raw mean wind speed maps with good quality observations. The error statistics listed for the raw map (left panel) are satisfactory but are improved by a wide margin when using a leave-one-out cross-validation (center panel) that corresponds to adjusting the raw map with all but one met station at a time in a round robin fashion. It effectively removes the mean bias. Lastly, the adjusted map shows the most suitable error metrics because it is evaluated with the same met data used in the map adjustment. Notice that the RMSE is not equal to 0 m/s and the R^2 is not 1.0 for the adjusted map, although it is not that far on the R^2. It is indicative of a regional bias correction as opposed to a local bias correction. A local bias correction would yield an MBE and RMSE of 0 m/s and a R^2 of 1.0.

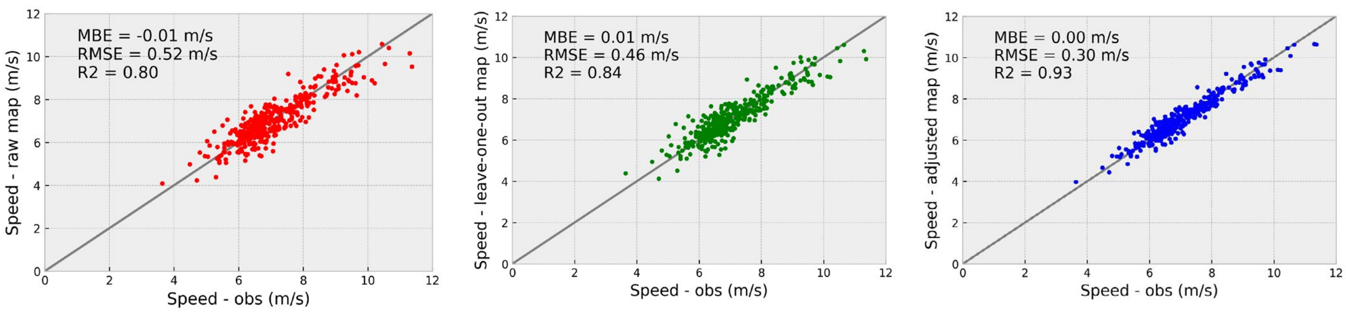


Figure 2.4: Scatterplots of 100 m a.g.l. mean wind speeds at the 384 representative met stations. The X axis represents the observed mean wind speeds, while the Y axis corresponds to the raw map (left panel), leave-one-out (center panel) and adjusted map (right panel).

3. Validation of Europe map

The primary goal of the validation is to provide an objective estimate of the map accuracy. To accomplish that goal, we use a leave-one-out cross-validation where each station in UL Solutions' database of representative masts is withheld in turn from the fine-tuning procedure, and the difference between the map speed and the observed speed at that station is determined. Then all the deviations are analyzed, and error statistics are derived. The 2025 Europe wind map was also compared to UL Solutions' original wind map (AWST 2012), as well as the publicly available New European Wind Atlas (NEWA, Witha et al., 2019) and Global Wind Atlas, version 3 and 4 (Davis et al. 2023).

The validation statistics are provided in Table 3.1. The 2025 Europe wind speed map is performing better than UL Solutions' original map, the NEWA and the GWA maps with regards to the mean bias error (MBE), the standard deviation (STDEV), the mean absolute error (MAE), the root mean square error (RMSE) and the coefficient of determination (R^2). It is worth pointing out that the mean bias of the 2025 map is very close to 0 m/s. In addition, UL Solutions' original map is performing well, which could be inferred given prior validation exercises (AWST, 2012 and UL Solutions, 2024). Our original map had an acceptable spatial coverage of met stations at the time. The New European Wind Atlas and the Global Wind Atlas maps are not performing as well, but they are doing a reasonable job in the absence of any met stations to adjust their map. In short, the NEWA and the GWA maps for Europe are effectively raw (non-adjusted) wind speed maps.

Map	MBE (m/s)	STDEV (m/s)	RMSE (m/s)	R^2	Sample size
Global Wind Atlas 3	0.60	0.65	0.88	0.71	384
Global Wind Atlas 4	0.43	0.60	0.74	0.74	
New European Wind Atlas	0.53	0.67	0.85	0.67	
UL Solutions original map	0.16	0.65	0.67	0.71	
UL Solutions 2025 map	**0.01**	**0.46**	**0.46**	**0.84**	

Table 3.1: Comparison of 2025 Europe wind map against UL Solutions' original version, the New European Wind Atlas and the Global Wind Atlas

The error statistics in Table 3.1 above do not convey much information about the spatial variations between the original and 2025 Europe. The two maps deviate from one another substantially in some regions, mainly in complex terrain like the Alps, the Apennines, the Armenian Highlands, the Carpathians or the Scandinavian Mountains, while they remain somewhat similar in simple terrain like the North and East European Plains, as shown in Figure 3.1.

Table 3.2 provides a closer look at the validation results for some European countries. All maps exhibit error statistics that tend to be worse in regions where the orography and land cover are more complex. By and large, UL Solutions' 2025 Europe map performs better than the other four maps in each European country, with one exception: Germany. In Germany, our previous map was as good or even slightly better than the new one, but the 2025 Europe map is still better than the other three alternatives.

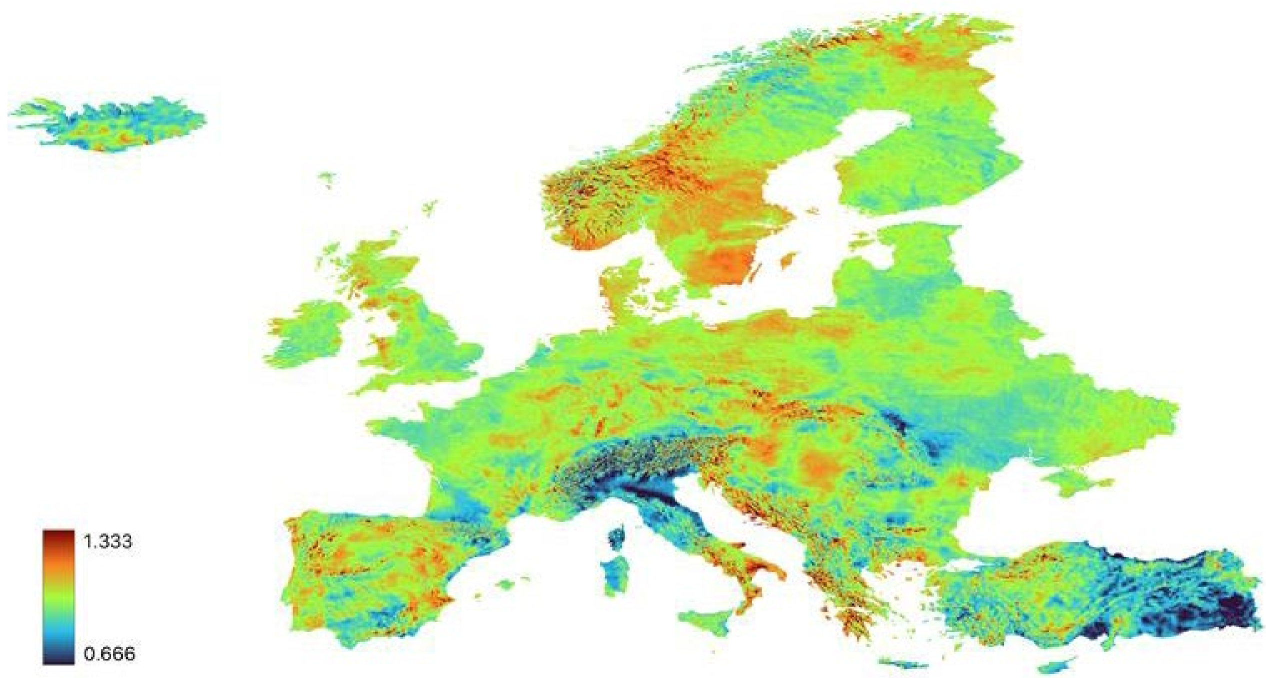


Figure 3.1: Wind speed ratio at 100 m a.g.l. between the 2025 and original map

Country	Map	MBE (m/s)	STDEV (m/s)	RMSE (m/s)	R^2	Sample size
Spain	Global Wind Atlas 3	0.32	0.55	0.63	0.61	83
	Global Wind Atlas 4	0.40	0.53	0.66	0.61	
	New European Wind Atlas	0.42	0.65	0.77	0.46	
	UL Solutions original map	-0.06	0.66	0.66	0.43	
	UL Solutions 2025 map	**0.00**	**0.37**	**0.37**	**0.78**	
France	Global Wind Atlas 3	0.82	0.47	0.94	0.61	74
	Global Wind Atlas 4	0.51	0.41	0.65	0.72	
	New European Wind Atlas	0.77	0.57	0.95	0.45	
	UL Solutions original map	0.13	0.45	0.46	0.65	
	UL Solutions 2025 map	**0.02**	**0.39**	**0.38**	**0.74**	
Germany	Global Wind Atlas 3	0.73	0.54	0.91	0.69	61
	Global Wind Atlas 4	0.39	0.44	0.59	0.78	
	New European Wind Atlas	0.60	0.47	0.76	0.74	
	UL Solutions original map	0.03	0.38	0.38	0.84	
	UL Solutions 2025 map	**0.02**	**0.43**	**0.42**	**0.81**	
Turkey	Global Wind Atlas 3	0.68	0.92	1.14	0.52	48
	Global Wind Atlas 4	0.51	1.00	1.11	0.43	
	New European Wind Atlas	0.53	0.99	1.11	0.51	
	UL Solutions original map	0.75	0.85	1.12	0.51	
	UL Solutions 2025 map	**0.06**	**0.67**	**0.66**	**0.65**	
UK	Global Wind Atlas 3	0.45	0.60	0.75	0.70	38
	Global Wind Atlas 4	0.36	0.57	0.67	0.73	
	New European Wind Atlas	0.18	0.56	0.58	0.77	
	UL Solutions original map	0.14	0.66	0.66	0.64	
	UL Solutions 2025 map	**-0.07**	**0.52**	**0.52**	**0.79**	
Italy	Global Wind Atlas 3	0.48	0.73	0.86	0.61	23
	Global Wind Atlas 4	0.37	0.66	0.74	0.59	
	New European Wind Atlas	0.57	0.75	0.93	0.61	
	UL Solutions original map	0.20	0.69	0.70	0.47	
	UL Solutions 2025 map	**0.01**	**0.57**	**0.55**	**0.68**	

Table 3.2: Same as Table 3.1 but by country

4. Conclusion

UL Solutions generated a new Europe mean wind speed map to replace the original version. The new wind map leverages the latest advancements in wind modeling technology and provides wind data at higher heights, up to 300 m. Notable differences can be found between the original and 2025 Europe wind map, especially in complex terrain. An objective estimation of the map accuracy was conducted using a met mast dataset. The accuracy of the 2025 Europe wind map was compared to UL Solutions' original wind map, the New European Wind Atlas and the Global Wind Atlas version 3 and 4 maps. Overall, the 2025 Europe map performs better than the other maps in terms of the standard error metrics, i.e., mean bias, RMSE and R^2. In all cases, these results suggest that the wind resource should be measured on-site before committing funds to a wind energy project of a substantial size.

References

AWS Truepower (2012). "Wind Resource Maps & Data: Methods and Validation." Technical report from AWS Truepower, 4 pp.

Brower, M. (1999). "Validation of the WindMap Program and Development of MesoMap." Proceeding from AWEA's WindPower conference. Washington, DC, USA. 10 pp.

Davis, N.N., et al. (2023). "The Global Wind Atlas: A high-resolution dataset of climatologies and associated web-based application." Bull. Atmos. Met. Soc., vol. 104, pp. E1507-E1525, DOI: https://doi.org/10.1175/BAMS-D-21-0075.1.

Dörenkämper M. et al. (2020). "The Making of the New European Wind Atlas – Part 2: Production and evaluation." Geosci. Model Dev., vol. 13, pp. 5079–5102, DOI: https://doi.org/10.5194/gmd-13-5079-2020.

Frank, H.P. and L. Landberg (1997). "Modeling the wind climate of Ireland. Boundary Layer Meteorology," vol. 85, pp. 359-378.

Hersbach, H. and co-authors (2019). "Global reanalysis: goodbye ERA-Interim, hello ERA5." ECMWF Newsletter, No. 159, p. 17-24.

Skamarock, W. C. (2004). "Evaluating Mesoscale NWP Models Using Kinetic Energy Spectra." Mon. Wea. Rev., vol. 132, pp. 3019-3032.

UL Solutions (2024). "Validation of the Wind Resource Maps Across Europe." Technical report from UL Solutions.

Witha, B., Hahmann, A., Sile, T., Dörenkämper, M., Ezber, Y., García-Bustamante, E., González-Rouco, J. F., Leroy, G. and Navarro, J. (2019). "WRF model sensitivity studies and specifications for the NEWA mesoscale wind atlas production runs." Retrieved November 2023 from Zenodo: https://doi.org/10.5281/zenodo.2682604.

ULTRUS™ | Windnavigator

UL.com/Windnavigator

3096824