Does High-Resolution Hybrid Downscaling of ERA5 Improve Hub-Height Wind-Power Profiling in Complex Terrain?

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Motivation and core objective

For the accurate assessment of renewable energy resources, high-quality meteorological data with sufficient spatial- and temporal resolution is essential. Modern reanalysis products provide such data by combining observations from ground-based stations, remote-sensing platforms, and numerical weather prediction models into physically consistent, gap-free atmospheric fields.

The ERA5 reanalysis dataset, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), offers global hourly meteorological variables at ∼30 km resolution and has become widely used in energy-system modelling because of its long temporal coverage, open availability, and consistent methodology. Numerous studies have demonstrated the value of reanalysis data for renewable-energy applications, e.g. RenewablesNinja, Global Wind Atlas (GWA), WindPRO etc. Nevertheless, ERA5 also has important limitations: while it performs well on large spatial scales, its ability to represent wind conditions in regions with complex terrain remains restricted due to its coarse resolution [1][2].

Similar limitations have been reported for other reanalysis products as well. The study by Staffell and Pfenninger [3] validates the MERRA and MERRA-2 reanalysis datasets across 23 European countries. The validation shows systematic bias which must be corrected to obtain realistic power-generation profiles and to increase the accuracy in the estimation of the technical potential. Despite the good temporal resolution, the coarse spatial resolution of the resulting profiles requires additional correction. The GWA developed by the DTU, combines reanalysis data and microscale flow model WAsP, to generate highly resolved wind speed and mean power density maps. However, the GWA only provides long-term climatologies (multi-year means) at several hub heights rather than hourly time series. A validation study at two Austrian sites also shows that applying GWA information to statistically adjust ERA5 dataset does not yield noticeable improvements in the accuracy of the ERA5 wind-speed profiles [4]. A 2023 study from Hu et al. explores statistical downscaling to increase the accuracy of the ERA5 wind profiles [5]. The approach involves regression-based downscaling that aims to establish the relationship between the ERA5 wind-speed dataset, ground observations, and topographic effects. Although this approach improves the performance of ERA5 wind-speed data in complex terrain, the wind speeds are evaluated only at 10 m and not at specific hub heights or in terms of wind-power outputs, which limits its suitability for energy-system modelling.

The core objective of this study is to develop a hybrid wind-downscaling and correction framework that blends terrain-informed downscaling with physical and statistical correction methods, transforming coarse-resolution ERA5 data into highly resolved (preferably 500m x 500m), bias-corrected hourly wind-speed fields and wind-generation profiles suitable for energy-system modelling.

Methodology

To address the limitations of ERA5 wind-speed profiles, this study proposes a framework that combines physical and statistical methods to refine the ERA5 wind fields and generate high-resolution, hub-height wind speeds suitable for energy-system modelling. The ERA5 wind-speed components are obtained from the Copernicus Climate Data Store, together with meteorological variables including 2-m air temperature, surface pressure, surface roughness length, and turbulent fluxes. To account for terrain-induced wind variability, a 30m x 30m digital elevation model (DEM) of Austria is aggregated to the

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target grid (preferably 500m x 500m). The resulting grid is used to incorporate topographic effects into the coarse ERA5 fields.

A schematic overview of input variables and output wind profiles is depicted in Figure 1. The proposed hybrid model applies three methodological steps. First, ERA5 wind fields are spatially refined using high-resolution topographic information to represent terrain-induced modifications of the near-surface flow. Second, hub-height wind speeds are derived through a physically based vertical adjustment using the Monin–Obukhov Similarity Theory (MOST) wind-profile, which corrects the near-surface winds for surface roughness and atmospheric stability to produce height-resolved wind fields. This step yields height-resolved wind fields that reflect the influence of local surface characteristics and thermal stratification. In the third step, residual systematic deviations are reduced through a statistical correction informed by observations or the publicly available reference data. After the corrected hub-height wind speeds are derived, wind-power generation time series are computed using altitude-adjusted air density and turbine-specific power curves. The resulting hourly, bias-corrected wind and power fields at the target spatial resolution provide a consistent basis for detailed energy-system modelling, e.g. to assess the technical wind-power potential across the study region.

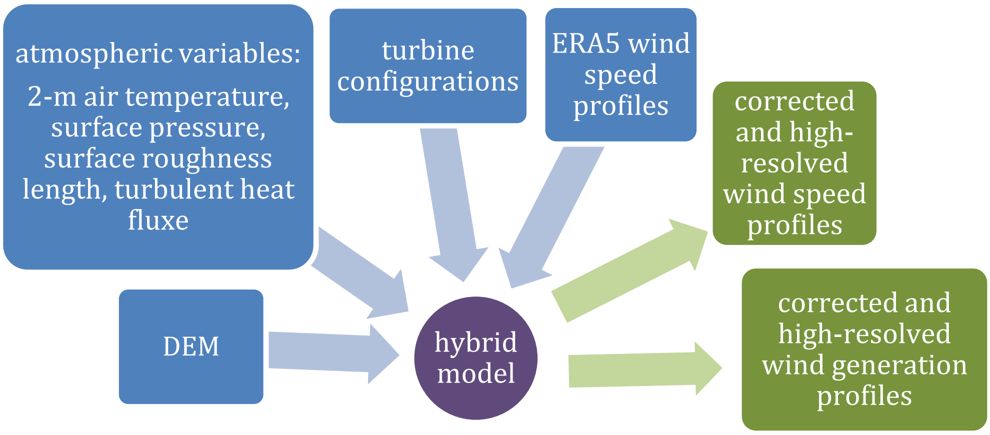

Figure 1: Structural representation of the methodology.

Preliminary results

The preliminary results indicate that the terrain-based downscaling approach modifies the spatial pattern of the ERA5 wind fields and leads to a noticeable reduction in variance. This indicates that part of the mesoscale variability (the intermediate-scale regional wind pattern) is smoothed during the interpolation and terrain adjustment. Applying atmospheric-stability corrections yields wind-speed profiles with a more realistic vertical structure. An initial validation is performed by comparing the mean, standard deviation and variance of the 100 m raw ERA5 winds and RenewablesNinja dataset with those of the downscaled and MOST-corrected fields. The statistical comparison shows that the corrected data performs best in terms of statistical characteristics. A comparison to the ground-based measurements indicates that further correction factors are necessary to reduce the remaining overestimation.

References

[1] I. Schicker, J. Ganglbauer, M. Dabernig, and T. Nacht, “Wind power estimation on local scale—A case study of representativeness of reanalysis data and data-driven analysis,” *Front. Clim.*, vol. 5, 2023, doi: 10.3389/fclim.2023.1017774.

[2] B. Jourdier, “Evaluation of ERA5, MERRA-2, COSMO-REA6, NEWA and AROME to simulate wind power production over France,” *Adv. Sci. Res.*, vol. 17, pp. 63–77, 2020, doi: 10.5194/asr-17-63-2020.

[3] I. Staffell and S. Pfenninger, “Using bias-corrected reanalysis to simulate current and future wind power output,” *Energy*, vol. 114, pp. 1224–1239, 2016, doi: 10.1016/j.energy.2016.08.068.

[4] K. Gruber and J. Schmidt, “Bias-correcting simulated wind power in Austria and in Brazil from the ERA-5 reanalysis data set with the DTU Wind Atlas,” *Int. Conf. Energy Econ. TU Wien*, pp. 1–15, 2019.

[5] W. Hu, Y. Scholz, M. Yeligeti, L. von Bremen, and Y. Deng, “Downscaling ERA5 wind speed data: a machine learning approach considering topographic influences,” *Environ. Res. Lett.*, vol. 18, no. 9, 2023, doi: 10.1088/1748-9326/aceb0a.