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Wind and Photovoltaic Large-Scale Regional Models for Hourly Production Evaluation

Mattia Marinelli, *Member, IEEE*, Petr Maule, Andrea N. Hahmann, Oliver Gehrke, *Member, IEEE*, Per B. Nørgård, *Member, IEEE*, and Nicolaos A. Cutululis, *Member, IEEE*

Abstract—This work presents two large-scale regional models used for the evaluation of normalized power output from wind turbines and photovoltaic power plants on a European regional scale. The models give an estimate of renewable production on a regional scale with 1 h resolution, starting from a mesoscale meteorological data input and taking in account the characteristics of different plants technologies and spatial distribution. An evaluation of the hourly forecasted energy production on a regional scale would be very valuable for the transmission system operators when making the long-term planning of the transmission system, especially regarding the cross-border power flows. The tuning of these regional models is done using historical meteorological data acquired on a per-country basis and using publicly available data of installed capacity.

Index Terms—Large-scale integration, modeling, photovoltaic (PV) power systems, renewable energy sources, wind energy.

I. INTRODUCTION

THE INCREASING penetration of renewable sources in the electrical grid is posing new challenges to the management and the control of power systems [1], [2]. Among renewable sources, fastest increases are from wind turbines and photovoltaic plants (PV). The installed capacity achieved at the end of 2012 is given to the reader in order to paint a clearer picture of the level reached in Europe: 106 GW of installed wind power and 69 GW of photovoltaic corresponding, respectively, to 11% and 7% of the overall electric generation pool [3], [4]. In terms of energy, the impact on the European consumption is lower, due to the smaller capacity factors of these sources, compared to conventional generation. Nevertheless, in some countries like Germany and Italy, PV accounts for 5% and 6% of produced energy, and the amount provided by wind is 9% and 4%. Denmark is still in a leading position in wind integration and reached, at the end of 2012, an astonishing amount of 30% electric energy covered by wind [5].

The rapid growth of renewable energy penetration results in the displacement of conventional power plants, and eventually, in their shutdown [6]–[8]. Therefore, transmission system

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operators (TSO) need to incorporate renewable energy sources into their long-term planning tools. An evaluation of the hourly forecasted energy production on a regional scale will be necessary for the planning of the transmission system development, especially regarding the expected cross-border flows. The long-term planning timescale concerns the investment decisions to develop the transmission system's power transfer capability. The implementation of these decisions takes at least several years, often more than a decade, and investment costs are typically very high so that they have to be amortized over several decades.

Thus, there is a need to define properly tuned large-scale models which take in account the specific characteristics of the different power plants technologies, the spatial distribution, and also the behavior of their respective “prime mover”: wind and solar irradiation. Such models should be able to capture, with an acceptable level of accuracy, the annual energy production and also the variability induced by the stochastic nature of the energy source. Especially in the case of variable renewable generation, such as wind and PV, an important aspect is the correlation between them. One way of ensuring this is by using the same dataset of historical meteorological data for both wind and PV models.

In Europe, the European Network of Transmission System Operators for Electricity (ENTSO-E) is responsible for ensuring coordinated and sufficiently forward-looking planning and sound technical evolution of the transmission system in the European Community, including the creation of interconnection capacities. As part of this process, ENTSO-E is publishing a biannual Ten-Year Network Development Plan (TYNDP) [9].

This paper aims at describing and tuning regional models for the evaluation of hourly wind and solar production. It is structured as follows. In Section II, a description of the meteorological input data is provided. Section III reports description of the generation model realized for the wind and photovoltaic. In Section IV, the evaluation process is described and results regarding variability and correlation are given. Section V reports the conclusion and the future works.

II. METEOROLOGICAL INPUT

The meteorological data are produced using a mesoscale reanalysis method, which uses a numerical weather prediction model to fill space and time gaps among observations. The method thus obtains high-resolution temporal and spatial climate or climate change information from relatively coarse-resolution global general circulation models or reanalysis. The

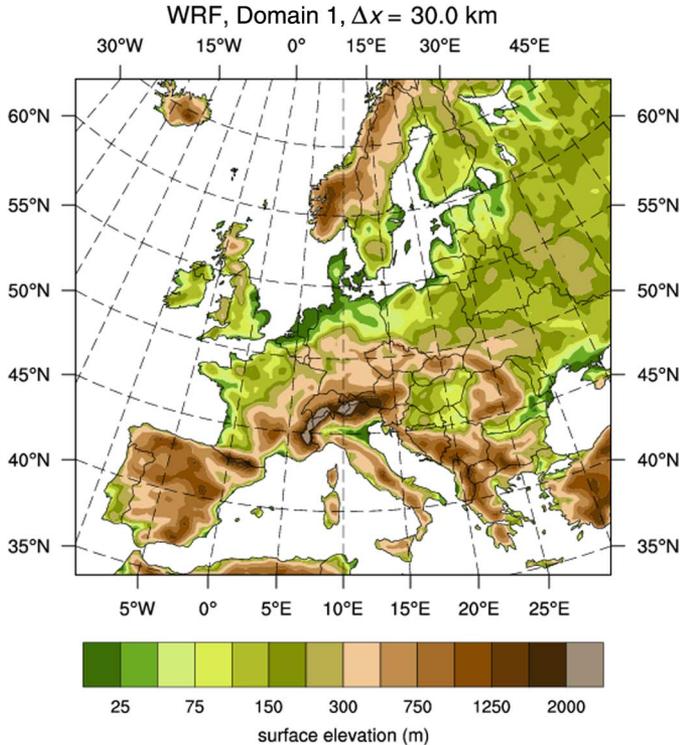


Fig. 1. Domain configuration and terrain elevation used in the simulations for domain (30 km).

strength in using the models to fill the observation gaps is that the fields are dynamically consistent, and they are defined on a regular grid. Additionally, the models respond to local forcing that adds information beyond what can be represented by the observations. Similar downscaling procedures are used for wind power prediction systems [10].

In the solar power sector, images taken by geostationary satellites may be used to estimate solar irradiance fluxes at the earth's surface [11]. The Heliosat method is based on the empirical correlation between a satellite-derived cloud index and the irradiance at the ground. While the methods in [10] and [11] used alone might individually outperform the one presented in this manuscript, the use of both wind and solar power from a single source provides an added degree of confidence to the analysis.

The mesoscale reanalysis used to generate the meteorological time series uses the National Center for Atmospheric Research Weather Research and Forecasting (WRF) model [12]. The version used is v3.2.1 released on August 18, 2010. The model forecasts use 41 vertical levels from the surface to the top of the model; 12 of these levels are placed within 1000 m of the surface. The model is integrated within the domain shown in Fig. 1; it has a horizontal spacing of 30 km, on a polar stereographic projection with center at 52.2°N, 10°E. The elementary cell of 30 km² is named MetCell (or Tile), and the domain has dimensions of 115 × 108 MetCells. A similar method was used and verified in [13]. Initial, boundary, and grids for nudging are supplied by the ERA Interim Reanalysis [14].

The size of the MetCell has been chosen equal to 30 × 30 km², due to computational and data storage constraints,

since the overall study has been conducted over the whole Europe. In this paper, the validation of the methodology, performed on the German area, is described.

The historical meteorological data provided are averaged values over time and space, i.e., over the hour and over the MetCell area. The following meteorological parameters are provided and used in the models to evaluate the normalized output of wind and photovoltaic production.

- 1) t : timestamp (date and time);
- 2) y_{lon}, x_{lat} : longitude and latitude (center of the MetCell);
- 3) $U_{10\text{ m}}$ (m/s): average wind speed at 10 m height level;
- 4) $U_{80\text{ m}}$ (m/s): average wind speed at 80 m height level;
- 5) p (hPa): average air pressure;
- 6) T_{air} (°C): average air temperature at 2 m height level;
- 7) I_{hor} (W/m²): average solar irradiation on the horizontal plane.

III. POWER GENERATION MODEL

A. Wind-to-Power Conversion Model

The Wind-to-Power (W2P) conversion model is performing the conversion of the wind speed kinetic energy into electrical energy. One method of doing this conversion is by using a dynamic model of the energy conversion chain: wind speed—rotor—mechanical shaft—electrical generator. This approach is used when the detailed dynamics of the W2P process is of interest. For long-term transmission system planning purpose, the aggregation level—large areas, i.e., countries and hourly resolution—is rather high, making use of a steady-state model, i.e., power curve, sufficient.

A power curve is an experimental characterization of the relation between wind speed and power. It is typically defined for individual wind turbines. For the aggregation level used in large-scale regional models, the wind turbine power curve is not very useful. An aggregated wind power curve is used instead. Calculating an aggregated wind power curve can be done by using the multiturbine power curve approach presented in [15] or by using multilevel aggregation, starting from individual wind turbines in a wind power plant and aggregating up to large areas [16]. The latter method has been developed to properly capture the dynamics of high wind speed shutdown, implementing a so-called storm controller. The details of the storm controller can be found in [17].

In this context, the power curve is a representation of the aggregated wind capacity and includes area smoothing and wind power availability. In general, the shape of the power curve is influenced by the wind power technology (i.e., fixed or variable speed wind turbines), the area size, and operating availability (i.e., technology availability, scheduled maintenance, and outages). Availability is usually expressed in a static manner, influencing the maximal value of the power curve. The W2P includes technology-type generic power curves, and the total power production is calculated according to the weighted wind technology mix in that area, i.e., fixed speed versus installed variable speed wind turbines. The module is part of the CorWind software model developed at Technical University of Denmark (DTU) Wind Energy [18].

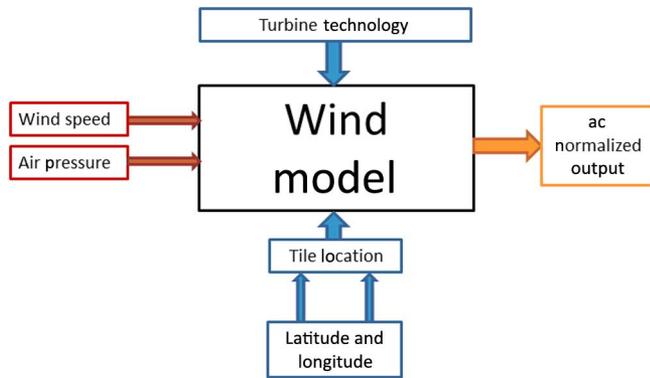


Fig. 2. Block diagram of the wind model.

TABLE I
GERMANY METCELLS

Region code	Region name	Number of MetCells (30 × 30 km ²)	Installed wind at the end of 2011 (GW)	Installed PV at the end of 2011 (GW)
DE 01–BB	Brandenburg	23	4.60	1.50
DE 02–BE	Berlin	1	0.00	0.05
DE 03–BW	Baden-Württem.	29	0.49	3.58
DE 04–BY	Bavaria	60	0.68	8.07
DE 05–HB	Bremen	1	0.14	0.02
DE 06–HE	Hesse	15	0.69	1.21
DE 07–HH	Hamburg	1	0.05	0.02
DE 08–MV	Meck.-Vorp.	19	1.63	0.52
DE 09–NI	Lower Saxony	35	7.04	2.28
DE 10–NW	Nordrhein-West.	28	3.07	2.81
DE 11–RP	Rheinland-Pala.	16	1.66	1.18
DE 12–SH	Schleswig-Hol.	10	3.27	0.95
DE 13–SL	Saarland	3	0.13	0.22
DE 14–SN	Saxony	15	0.98	0.89
DE 15–ST	Saxony-Anhalt	14	3.64	0.86
DE 16–TH	Thuringia	13	0.80	0.52

The inputs to the region-wide W2P are the wind speed, the air pressure, the technology mix, and the availability, as shown in Fig. 2. The evaluation is performed using meteorological data of Germany, whose land area corresponds to 283 MetCells, which are grouped into 16 regions, listed in Table I.

B. Photovoltaic Model

Several blocks make up the PV model, illustrated in Fig. 3, in which the equations for the description of the movement of the sun and the energy conversion chain are implemented. The latter takes in account the conversion process used to evaluate the AC power injected in the grid starting from the DC power produced by the PV modules [19], [20].

Three blocks make up the PV model, illustrated in Fig. 3, in which the equations for the description of the movement of the sun and the energy conversion chain are implemented. The latter takes in account the conversion process used to evaluate the AC power injected in the grid starting from the DC power produced by the PV modules [19], [20].

Three main inputs can be seen in the left part of Fig. 3: the horizontal irradiance, the air temperature, and the wind speed, given on hourly basis. By the knowledge of the geographic coordinates of each MetCell, it is possible to evaluate the movement of the sun and thus to evaluate the incidence irradiance on the panel. The panels can be installed with different orientations (or azimuth), south, east or west facing, and different inclination (or tilting), in the horizontal plane, on a pitched surface or vertical.

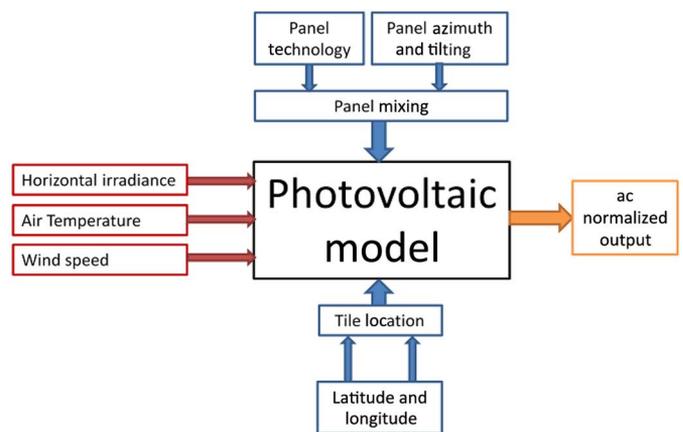


Fig. 3. Block diagram of the photovoltaic model.

TABLE II
PV LAYOUT CLASSES

Class	Azimuth (−90 east; 0 south; +90 west)	Tilting (0 horizontal; 30 optimal; 90 vertical)	Weighting factor (%)
Horizontal	0	0	50
Optimal – south	0	30	30
Vertical – south	0	90	2
Optimal – east	−90	30	13
Optimal – west	90	30	2
Vertical – east	−90	90	2
Vertical – west	90	90	1

The relative distributions between the different compass orientations and tilt angles are given by weighting factors for seven representative classes, listed in Table II. For each combination of layouts, the output is evaluated. The choice of the values has been done taking in account which are the most common installation criteria and also considering the ratio between ground and roof installation.

The panel model has been tuned in accordance with the data provided by manufacturers and considering the experience acquired from the PV systems installed at the SYSLAB laboratory at DTU Risø Campus [21], [22]. Once the panel dc output is evaluated, it is normalized by taking in account the nominal power of the module and the energy conversion chain, which includes several electrical and nonelectrical losses, such as panel contamination, dc cable losses, strings mismatch, panel shadowing, and inverter efficiency curve (including an optional insulation transformer). Finally, given the mixing of the different panel layouts, listed in Table II, the AC normalized output for the MetCell is calculated. As previously listed in Table I, the 283 MetCells which form the land area of Germany are considered. At the present stage, it is assumed that the previously described layout mix of Table II is the same for all regions, while the different PV penetration is taken in account by weighting the regional output by the installed capacity at the end of 2011. Per unit output for the whole Germany is therefore evaluated.

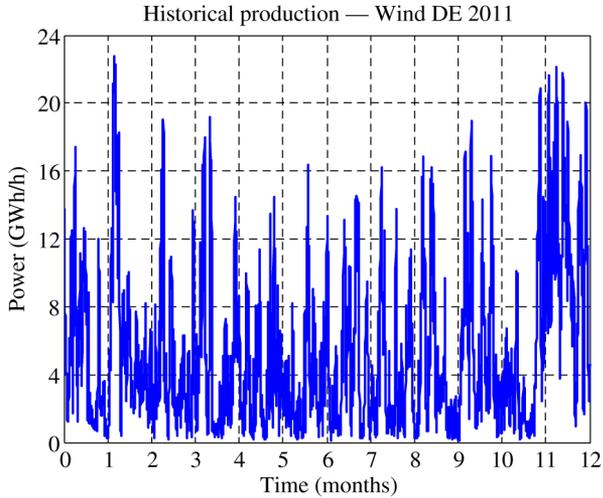


Fig. 4. Historical wind power production in Germany in 2011.

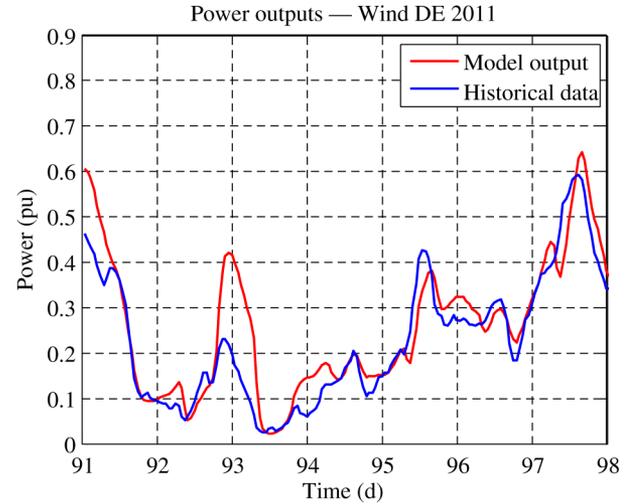


Fig. 5. Comparison of the normalized wind powers: model output (red curve) and historical data (blue curve) for the first week of April 2011.

IV. EVALUATION PROCESS

A. Wind Model Evaluation

The performance of the model is evaluated by comparison with publicly available data. The historical data are collected from the European Energy Exchange (EEX) and are compared to the output of the model [23]. In doing so, several hypotheses were made. First of all, in order to evaluate the hourly normalized wind power production in Germany, 2011 data for the installed capacity are needed. When trying to evaluate normalized annual time series, using the total installed capacity at the end of a year could lead to possible overestimation of the installed capacity in the first part of the year. A second assumption made is related to the technology mix of wind power installed in an area. For Germany, it is assumed that the ratio between stall and pitch-controlled wind turbines is 1:2. Finally, one has to keep in mind that the data published are a mix of actual measurements and estimations, since not all wind power is directly measured.

Using these assumptions, the evaluation is done for a full year. The year chosen is 2011: the historical wind power production is shown in Fig. 4. The installed amount of wind power at the beginning of the year was 27 191 MW, with less than 2 GW installed during the year. For the normalization process, it has been assumed a constant installation rate along the year.

The comparison between the normalized historical wind power production and model output, for the first week of April, is presented in Fig. 5. There are some deviations, but overall the model manages to capture most of the dynamics of the wind power production aggregated over a large region such as Germany. The match between the model and the historical data is good during midday: when comparing the average wind power production on an hour-by-hour basis, reported in Fig. 6, the average error, shown in Fig. 7, is close to 0.01 of the installed capacity. During night time, the error is significantly higher, going up to 0.05 pu of the installed capacity.

The distribution of the wind power production, given in the first plot of Fig. 8, indicates that the model tends to correctly estimate the produced power at lower output levels, i.e., up to

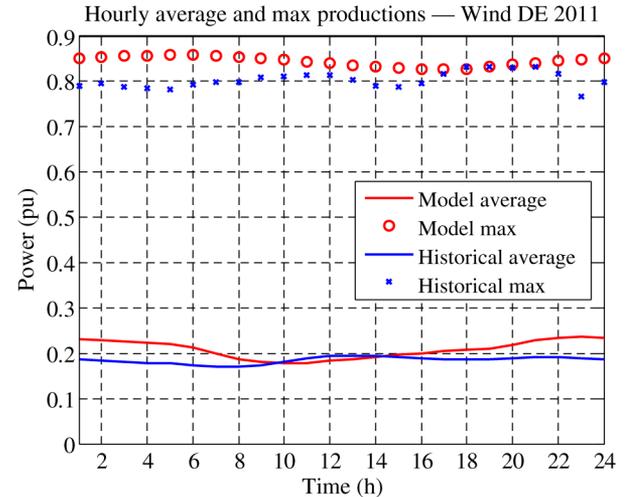


Fig. 6. Hourly average production and hourly maximum production over the year (red circle marker: model; blue star marker: historical).

20% of the installed capacity, while for high outputs, the model overestimates. It should be mentioned that the model cannot capture the periods of time when wind power is downregulated, due to TSO requests or negative power prices. This could, for instance, contribute to the fact that the model maximum output level is larger than the one from the historical data. The distribution of the hourly ramping, expressed as the difference between two consecutive wind power production values, shows that the model manages to capture the hourly variability of the wind power production, as shown in the second plot of Fig. 8. It can be noted that the hourly ramping is never greater than ± 0.1 pu/h, and most of the time (around 98% of the year), it is smaller than ± 0.05 pu/h.

The correlation between the model and the historical data is shown in Fig. 9. The correlation is rather well defined with a limited amount of values very far from the ideal matching. The correlation coefficient is equal to 93.0%.

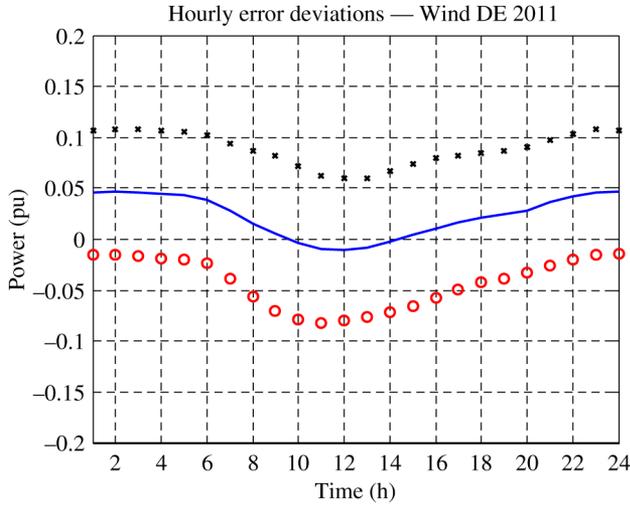


Fig. 7. Hourly error deviation (blue line: average value; black star marker: average plus standard deviation; red circle marker: average minus standard deviation). A positive error implies production overestimation.

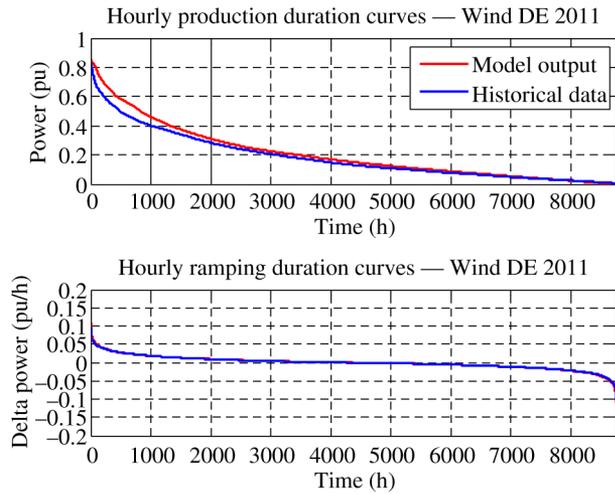


Fig. 8. First plot: production duration curve. Second plot: ramping duration curve (hourly production increase and decrease).

B. Photovoltaic Model Evaluation

Several assumptions have been made in order to evaluate the PV model output. The first one comes from the comparison of the aggregated normalized output of Germany with the historical production of the country. In order to evaluate the hourly normalized PV output, both installed power and hourly output are required. As for the wind, PV historical data have been collected from the database provided by EEX [24]; however, three important issues have to be taken in account when performing this evaluation.

- 1) The PV-installed power in Germany at the beginning of 2011 was 17 300 MW, and the value at the end of 2011 was 24 785 MW. This leads to an average installation rate of 20.5 MW/day.
- 2) The average installation rate was not constant during different months: it spans from 3.56 MW/day of February and gets to 96.23 MW/day of December, as depicted from the first plot of Fig. 10.

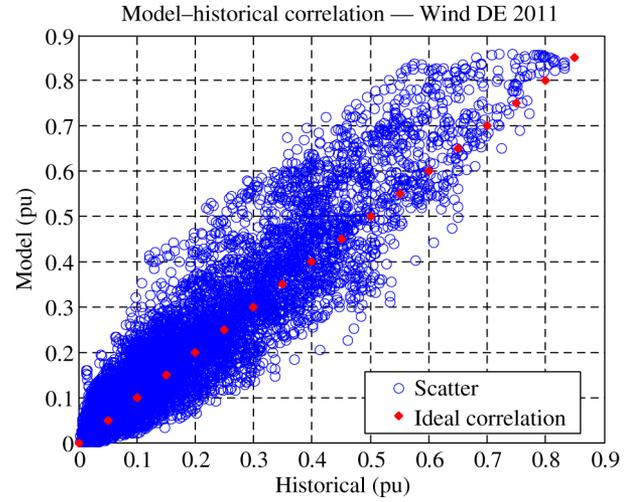


Fig. 9. Correlation between wind model and wind historical output.

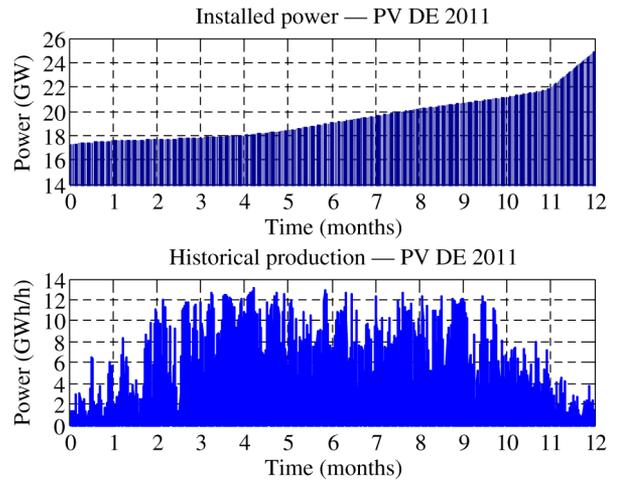


Fig. 10. First plot: cumulated installed PV power in Germany on monthly basis for 2011. Second plot: historical PV production during 2011.

- 3) PV output, illustrated in the second plot of Fig. 10, is also estimated and is not a precise measure of the hourly production of each single PV plant.

Having said that, the comparison is done for the whole year, and the results are reported subsequently. Fig. 11 shows the comparison between model output and historical data for the same period, first week of April, analyzed for the wind. The model describes quite well the behavior of the historical available data; some deviation can be observed but it has to be stressed that the model assumes a uniform layout distribution of the PV plants across Germany.

As reported in the wind evaluation section, also for the PV the hourly average and the maximum production over the whole year are reported. Fig. 12 shows the hourly average and maximum production, while the hourly error deviations are reported in Fig. 13. The model slightly overestimates the production during afternoon hours when the average errors get nearly to 5%.

The production duration curve is reported in the first plot of Fig. 14: it is possible to appreciate that, on such regional scale, the maximum power gets never above 0.7 pu, and for

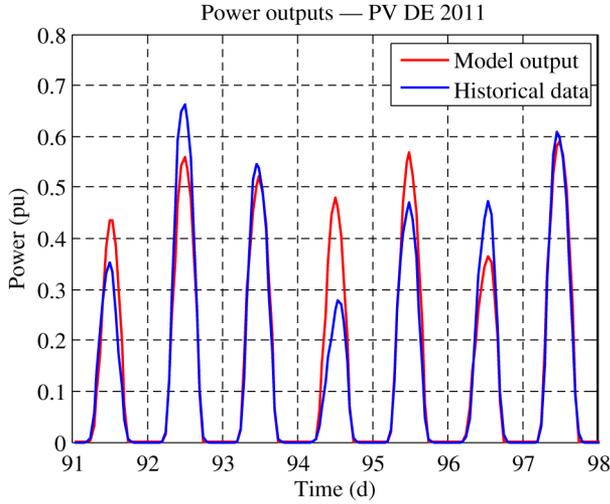


Fig. 11. Comparison of the normalized photovoltaic powers: model output (red curve) and historical data (blue curve) for the first week of April 2011.

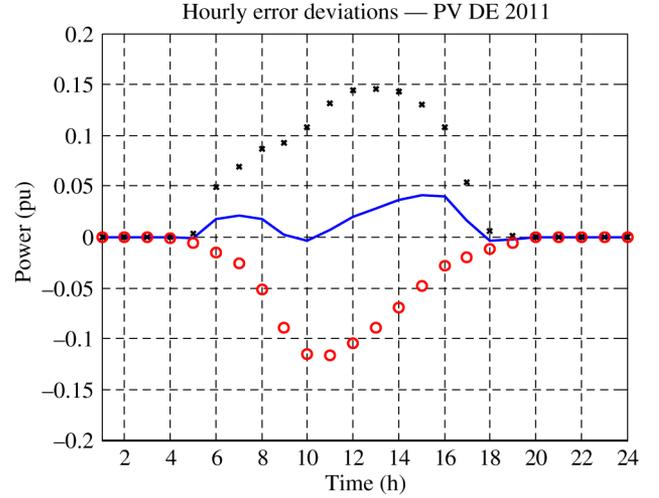


Fig. 13. Hourly error deviation (blue line: average value; black star marker: average plus standard deviation; red circle marker: average minus standard deviation). A positive error implies production overestimation.

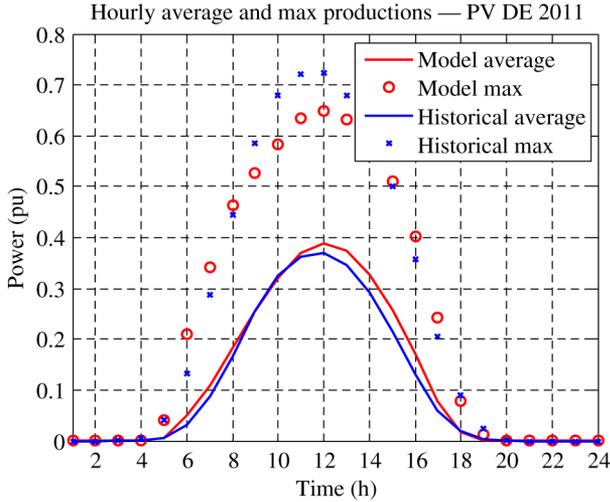


Fig. 12. Hourly average production and hourly maximum production (red circle marker: model; blue star marker: historical).

more than 4500 h per year, the production is zero. The hourly ramping curve, shown in the second plot of Fig. 14, reports the power change in 1 h, highlighting that the maximum changes are always within ± 0.2 pu/h, and for 90% of the time, it is smaller than ± 0.1 pu/h. It is interesting to note that the ramping rate is much higher for the PV compared to the wind.

The correlation between the model output and the historical data is reported in Fig. 15. It is possible to observe that there is a good correlation even if the model is little bit overestimating the production in the low-mid power range.

C. Summary Data Evaluation and Wind-PV Correlation

The relevant evaluation data are reported in Table III. As mentioned, the wind model is overestimating the capacity factor by about 12.5%, while the correlation factor is equal to 93.0%. Also the PV model overestimates, and the capacity factor is 8.9% greater than the historical one. The correlation coefficient is slightly higher and equal to 93.4%.

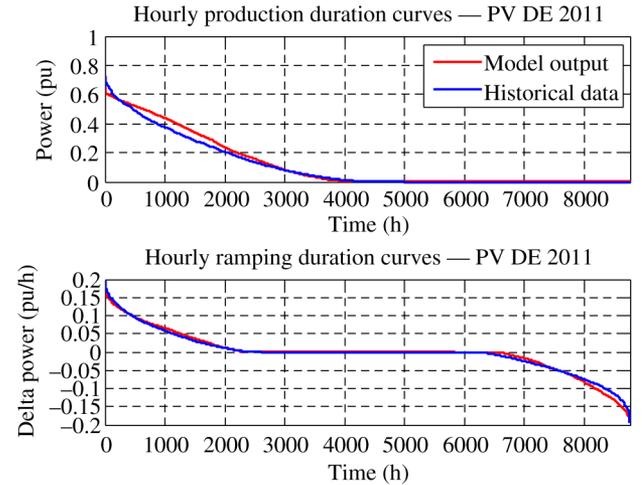


Fig. 14. First plot: production duration curve. Second plot: ramping duration curve (hourly production increase and decrease).

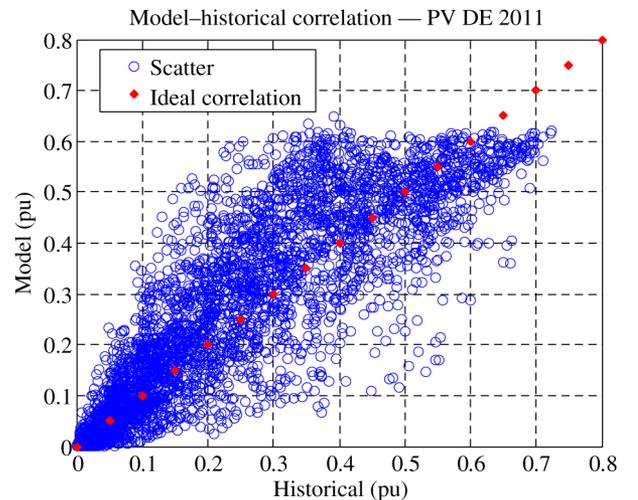


Fig. 15. Correlation between PV model and PV historical output.

A correlation analysis between the historical production of wind and PV across Germany is also reported. The graphical

TABLE III
WT AND PV SUMMARY EVALUATION DATA

Capacity factors (h/year)	
Wind model	1822
Wind historical	1619
Wind: Model–historical difference	+203 (+12.5%)
PV model	1061
PV historical	974
PV: Model–historical difference	+87 (+8.9%)
Correlation coefficients	
Wind Model vs. historical (see Fig. 9): 93.0%	PV Model vs. historical (see Fig. 15): 93.4%
Wind vs. PV historical (see Fig. 16): –12.8%	Wind vs. PV model (see Fig. 17): –22.9%

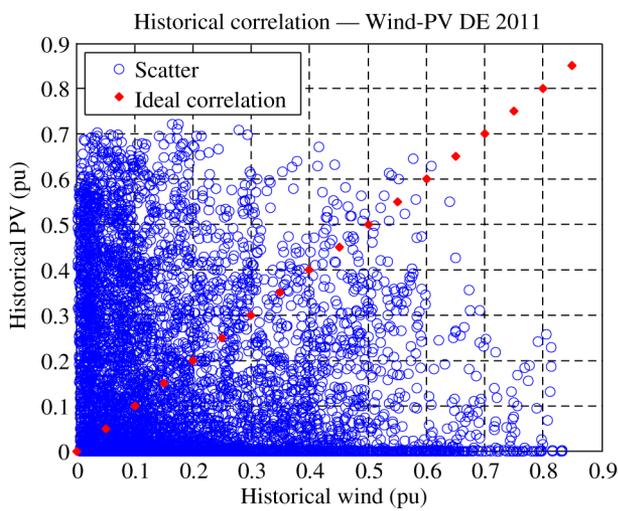


Fig. 16. Correlation between PV and wind historical outputs.

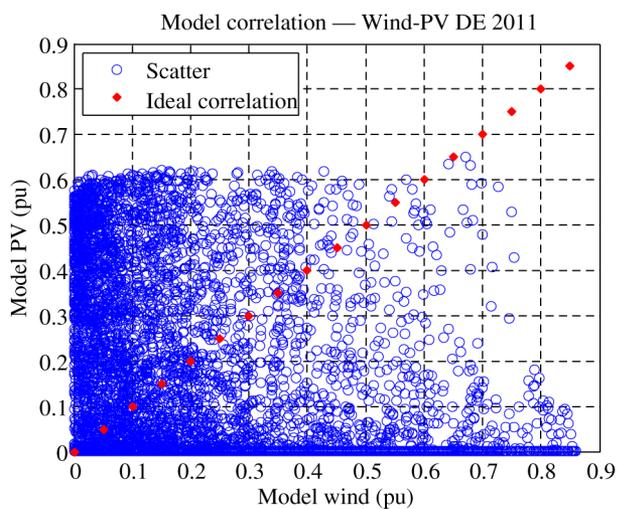


Fig. 17. Correlation between PV and wind model outputs.

results are shown in Fig. 16 for the historical values and in Fig. 17 for the model estimations. It is interesting to observe that wind and PV productions are rather uncorrelated: the coefficients are equal to -12.8% and -22.9% , respectively.

V. CONCLUSION AND FUTURE DEVELOPMENTS

Large-scale models, covering large areas or even countries, able to estimate the hourly production from renewable power sources such as wind and solar PV are very useful for the long-term coordinated planning of the pan-European transmission systems. The requirements for such models are to be able to reproduce the expected annual energy produced by RES and evaluate the correlation between the two energy sources. Using the same meteorological model for the relevant inputs, mainly wind speed, solar irradiation, and temperature, wind and solar models can ensure this. Furthermore, the models should reproduce as accurate as possible the variability in the power produced by RES.

The work presented two large-scale regional models used for the evaluation of the normalized output coming from wind turbines and photovoltaic power plants on a European regional scale perspective. The overall idea was to have an estimation of hourly production of these renewable sources on a regional scale starting from a mesoscale meteorological data input and taking in account the characteristics of the different plant technology and spatial distribution. The evaluation has been performed for the whole Germany using data of year 2011. The correlation between the production patterns of two sources has also been analyzed.

Evaluation of such models is not straightforward. The main obstacle is the lack of publicly available data regarding the historical energy production from RES. Such data would help not only for comparing the results but also for further calibration and tuning of the models. The evaluation presented in the paper has shown that the proposed models manage to reproduce the annual energy production from wind and PV. Furthermore, they manage to capture the hourly variability in a good manner and show a very good correlation with the measured data.

Finally, improvements should target the ability of the models to better capture the smoothing effect of geographical dispersion on extreme values. Of course, in the case of wind power, issues other than smoothing effects, such as control actions, availability, and/or transmission constraints, can influence the magnitude of the production maxima. All these factors can be hardly reproduced by the models without a more detailed knowledge regarding the frequency of occurrences.

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