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EMHIRES dataset
Part II: Solar power generation

European Meteorological derived HIgh resolution RES generation time series for present and future scenarios.

Part II: PV generation using the PVGIS model

GONZALEZ-APARICIO Iratxe
HULD Thomas
CARERI Francesco
MONFORTI Fabio
ZUCKER Andreas

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Contact information
Name: Iratxe GONZALEZ-APARICIO
Address: European Commission, Joint Research Centre, P.O. Box 2, NL-1755 ZG Petten
Email: iratxe.GONZALEZ-APARICIO@ec.europa.eu
Tel.: +31224565251

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EMHIRES dataset: Solar Power generation. European Meteorological derived High resolution RES generation time series for present and future scenarios

EMHIRES is the first publically available European solar power generation dataset derived from meteorological sources that is available at country, bidding zone, NUTS-1 and NUTS-2 level. It was generated applying using the validated and robust PVGIS model to estimate the solar electricity potential capturing local geographical information to generate meteorologically derived solar power time series at high temporal and spatial resolution, validated with transmission system operators' data

Contents

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Executive summary

Renewable energy sources for the generation of electricity (RES-E) directly relates to three of the five pillars of the Energy Union: the fully integrated energy market, climate action and emission reduction as well as research and innovation [1]. The deployment of large capacities of wind and solar energy impacts the electricity markets and challenges existing market designs, both at the wholesale and the retail level. At the same time it poses technical challenges resulting from the need to ensure a smooth operation of the European power system. Methodologies for assessing the adequacy need to be adapted in the presence of more RES-E [2]. Finally, investments are taking place into new technological solutions for improving the flexibility options to help to integrate RES-E.

Power system models are the tool of choice for assessing options along the three policy dimensions (market design, RES-E integration, research and innovation). High quality wind power and PV time series for long time periods and at different aggregation levels (countries, regions and power market zones) are needed in order to produce model results that translate into robust policy advice. Moreover, data should be publically available if impact assessments are to be transparent and reproducible. However, no such dataset currently exists for Europe. The EMHIRES dataset addresses this need and provides a publically available time series for the generation of intermittent RES-E derived from meteorological data.

EMHIRES applies an innovative approach trying to reproduce wind and solar power time series at both national and regional levels covering the whole Europe with a homogeneous methodology avoiding the use of artificial or on-purpose tuned correction factors. EMHIRES is able to capture the variability of wind and solar energy, in particular peaks and ramps, in a much more accurate way than previous meteorologically derived time series. The purpose is to develop an *ab-initio* methodology for wind and solar power production simulation and apply homogeneously to all Europe. The methodology has provided results ranging between good and excellent for all countries for which reliable TSOs data are available, regardless their sometimes huge geographical diversity. Using EMHIRES for power system analysis will increase the accuracy of generation adequacy assessments, renewable energy integration studies and market studies for flexibility technologies such as storage.

This report details the second part of EMHIRES, covering solar energy production. Further publications are planned on future RES-E deployment scenarios, hydropower and temperature corrected power demand. The datasets can be reviewed and readapted to new situations in the power system (e.g. the commissioning of new installations).

Chapter 1 explains the nature and cope of the work. The primary data sources used for creating EMHIRES and the methodology used for deriving solar power time series from meteorological data and information on solar power technology is described in Chapter 2. In Chapter 3, the generated time series are compared with other data sources. Possible applications and possible future work are also explained in Chapter 3.

1 Introduction

The global energy markets are changing due to the clean energy transition. According to the International Energy Agency the renewable energy already exceeded coal as main source of power capacity in 2015 [3]. In the recent ""Clean for Energy for All Europeans" package [4], the European Commission has defined three main goals to keep the European Union (EU) competitive and to lead this transition: putting energy efficiency first, achieving global leadership in renewable energies and providing a fair deal for consumers. Thus, placing the renewable energy in a central position, Europe has set itself a target to collectively reach a share of at least 27% renewables in the final energy consumption by 2030. This could be translated as about half of the EU's electricity generation will come from renewables [4].

However, the rapid growing share of electricity production from intermittent renewable sources (wind and solar) increases the stochastic nature of the power system introducing instability to the system and high uncertainties to the market design. As a consequence, planning and scheduling tools for the power sector have been updated and the study of power systems with a high share of intermittent RES-E has become an established field in Power System Analysis. In particular, the adequate modelling of high RES-E penetration systems crucially depends on the accurate representation of the spatial and temporal characterisation of the wind and solar sources. RES-E data inherently bears the risk of being imperfect, inappropriate or incomplete which might lead to errors in power system studies which could be either overstating or downplaying the possible role of solar and wind energy in the future energy mix [5].

The Knowledge Management Unit at the directorate for Energy, Transport and Climate, DG-Joint Research Centre (JRC) has developed the EMHIRES dataset (European Meteorological HIgh resolution RES time series) using the in-house PVGIS model [6] to fill this gap. This is the second part of the EMHIRES dataset, describing the development of EMHIRES Solar Power Generation database. This database is released as open-source according to the JRC data Policy.

1.1 Scope of EMHIRES

EMHIRES provides RES-E generation time series for the EU-28 and neighbouring countries. The solar power time series are released at hourly granularity and at different aggregation levels: by country, power market bidding zone, and by the European Nomenclature of territorial units for statistics (NUTS) [7] defined by EUROSTAT; in particular, by NUTS 1 and NUTS 2 level.

The time series provided by bidding zones include special aggregations to reflect the power market reality where this deviates from political or territorial boundaries, such as in Ireland (Republic of Ireland and Northern Ireland forming one market zone), Norway, Sweden, Denmark and Italy (separated in 5, 4, 2 and 6 different zones, respectively). In the case of Greece, the time series are released for the interconnected zone, i.e. the islands that are not connected with the mainland power system, are excluded.

The overall scope of EMHIRES is to allow users to assess the impact of meteorological and climate variability on the generation of solar power in Europe and not to mime the actual evolution of solar power production in the latest decades. For this reason, the hourly solar power generation time series are released for meteorological conditions of the years 1986-2015 (30 years) without considering any changes in the solar installed capacity. Thus, the installed capacity considered is fixed as the one installed at the end of 2015. For this reason, data from EMHIRES should not be compared with actual power generation data other than referring to the reference year 2015.

The Part I of the EMHIRES dataset comprises the wind power generation hourly time series with the same rationale and therefore, the EMHIRES wind and solar dataset make possible to prepare coupled wind –PV modelling and impact assessments.

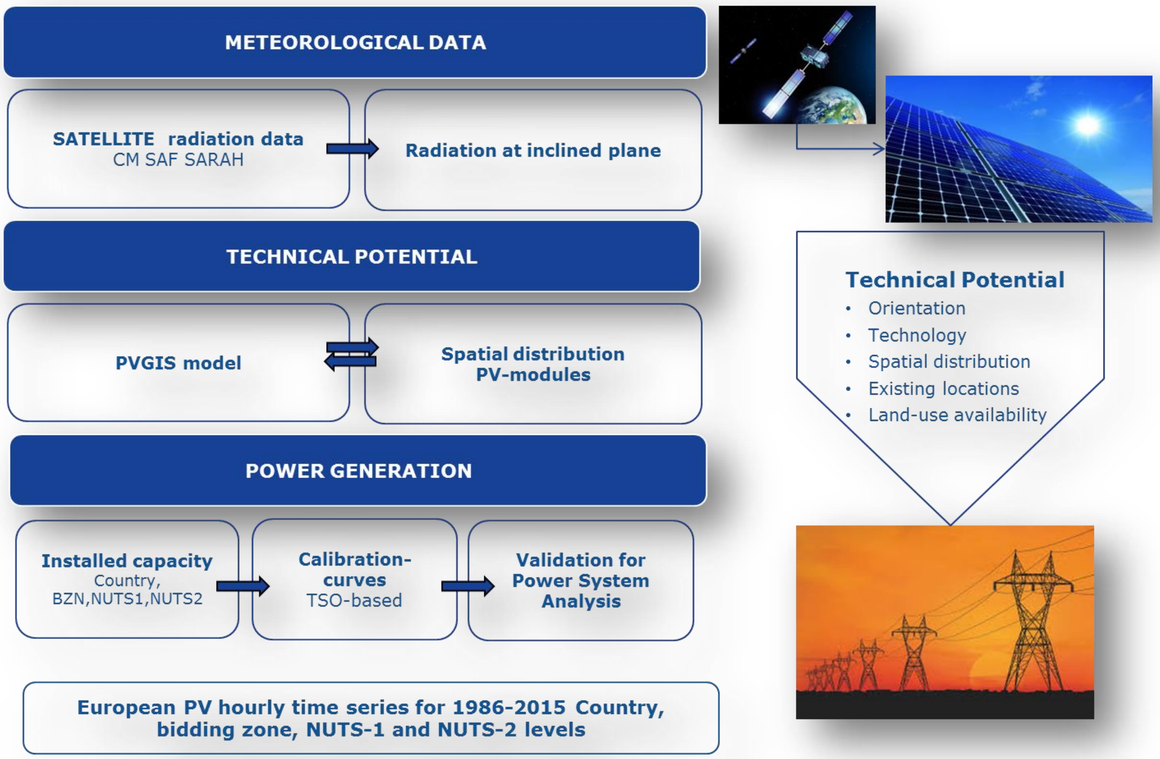
2 Description of data, tools and methodology

In this study, the general approach applied to convert solar resources into power generation consists in converting satellite-based radiation data using the PVGIS model (**Figure 1**).

The first step of the methodology is the meteorological data treatment; in this case, it is necessary to calculate solar radiation satellite-based data into radiation on inclined planes. Then, the radiation data is converted into theoretical potential; i.e. the solar electricity generation in each area given by kW generated from each kW peak of a typical PV System. In this approach, a sensitivity analysis is carried out to assess the impact of the spatial distributions of the PV-modules at country and regional levels. Thus, the quality of the assumptions is also gauged to estimate the locations of the PV farms for each region.

Finally, to obtain the power generation the installed capacity of each region is calculated and then, the time series are corrected with the TSO actual generation and statistically validated for power system analysis, by assessing the power peaks and ramps, duration curves and capacity factors.

Figure 1. Summary of overall methodology to develop EMHIRES-PV dataset



2.1 Meteorological data treatment

The primary data used to calculate the PV power generation is the irradiance extracted from the Climate Monitoring Satellite Application Facility (CM-SAF) [8]. The CM-SAF is part of the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) ground segment and part of the EUMETSAT network of Satellite Application facilities. It contributes to the operational long term monitoring of climate system by providing Essential Climate Variables [9] related to the energy and water cycle of the atmosphere. The dataset used comes from CM-SAF SARAH (Solar surface Radiation Heliosat) data record as the retrieval method used. The SARAH data are retrieved based on radiative transfer modelling resulting in climate data of solar surface irradiance, direct (horizontal and direct normal) and clear sky irradiance covering three decades at a spatial resolution of about 5 km. The SARAH data is validated with surface measurements of the Baseline Surface Radiation Network and of the Global Energy and Balance Archive [10].

The data provided by CM-SAF SARAH include the global horizontal and the direct horizontal irradiance at hourly intervals and it is subtracted for the 30 year period (1986-2015) to get the diffuse horizontal irradiance following [11]. Then, the global irradiance on an inclined plane is calculated following [12].

The SARAH dataset contains some missing hours over the 30 years period. The total number of missing values in each year (numbers out of 8760/8784 hours in the year), before 1993 is between the 5% and 8% and in the years 1988 and 1999 16% and 15%, respectively. Between 1994 and 1999, the total number of missing values each year is reduced from 5% to 1% and from 2000 to 2015 hovers between the 0.05% and 2.5%. In some of the mentioned cases, missing hours are at night when the radiation is zero. For example, nearly all hours in September around midnight are missing. In this study, the missing values are reconstructed as the average of the same hour for the same calendar day (plus the day before and the day after) from the other years. This means the reconstructed values tend to be intermediate between sunny and overcast, but the long-term averages are well conserved. In addition, although the satellites have changed along the 30 years considered, the SARAH data set was explicitly made in order to make a homogeneous data set for climate studies so they took great care to make the transition from Meteosat First Generation to Second Generation as smooth as possible.

There are other well-known and common sources to extract the irradiance for the 30 year period; for example, the European Centre for Medium-Range Weather Forecasts (ECMWF) provides different reanalysis up to 6-hourly frequency at about 25 km spatial resolution (ERA-40 and ERA-interim reanalysis) [13]; or the NASA atmospheric reanalysis dataset which was generated within the Modern Era Retrospective-Analysis for Research and Applications (MERRA) project [14]. The MERRA dataset has an hourly temporal resolution with a spatial resolution of 0.66-degree longitude by 0.5-degree latitude (60x56 km in the south and 25x56 km in the north approximately). However, although NASA-MERRA reanalysis was selected as primary data to build the EMHIRES-wind dataset, the EMHIRES-PV dataset has been built with the CM-SAF SARAH dataset. The reasons of this selection are that CM-SAF SARAH dataset has considerably higher spatial resolution than NASA-MERRA (about 5km against 50km resolution), a resolution needed to estimate the solar variability over a region. Moreover, [15] compared ERA-Interim and MERRA reanalyses with measurements of daily solar irradiation at surface showing that MERRA tends to overestimate the total irradiation because it underestimates the presence of clouds. This means that this pattern could lead to an overestimation of the PV capacity factors for power system analysis. In fact, [16] made an interesting comparison of the mean European capacity factors between MERRA (and MERRA 2) and CM-SAF SARAH data demonstrating that MERRA generally predicts higher capacity factors than CM-SAF SARAH and the model errors between MERRA, MERRA2 and SARAH data were lower for SARAH than MERRA and MERRA2 in comparison with the TSO PV-capacity factors.

Thus, although CM-SAF SARAH dataset contains missing hours over the 30 year period, it was the preferred option to give results with lower errors for the 97% of the hours (including the night hours with zero diffuse horizontal irradiance) in the 3 decades than give results of the 100% hours with higher biases, in comparison with the PV capacity factors given by the TSOs.

In addition, this study intends to reproduce solar power time series at both national and regional levels covering the whole Europe with a homogeneous methodology avoiding the use of artificial or on-purpose tuned correction factors, at the highest possible resolution and reducing the uncertainty cascade. The purpose of this study is to develop an *ab-initio* methodology for solar power production simulation and apply homogeneously to all Europe.

2.2 Technical potential

2.2.1 The PVGIS model configuration

The Photovoltaic Geographic Information System (PVGIS) is a model developed at the Joint Research Centre since 2001 providing values of solar irradiance and the potential power production from PV modules for different choices of technologies, panel orientations ant other parameters. PVGIS is based on open data and software architecture, freely available climatic and geographic data at high spatial resolution and map-based interface providing easy-understandable information for the scientific and non-scientific community. PVGIS combines the long-term expertise from laboratory research, monitoring and testing with geographical knowledge. It is often used as a research tool for the performance assessment of the PV technology in different aggregation levels and as a support system for policy-making in the European Union. PVGIS is accessed through a web interface developed to provide interactive access to the data, maps and tools to other research and education institutes, decision-makers PV professionals and system owners as well as to the general public [17].

The general description of the model can be found in [18], [19], [20]. Those studies have lately improved the model including the effects of temperature, cooling of wind speeds for Europe and Africa. Basing on these latest improvements, in this study the PVGIS model is used to perform simulations to calculate the electricity generation in hourly intervals over 30 years (1986-2015) for Europe.

All the simulations with the PVGIS model have been performed using the hourly solar radiation data from the CM SAF SARAH solar radiation product. The configuration of the model has a spatial resolution of 3 arc-minutes (~5km) and the hourly PV power is calculated for each pixel taking into account the effects of shallow-angle reflectivity, temperature and low irradiance as well as cooling of the modules by wind [18]. The calculation is performed for PV arrays mounted on an open-rack mounting at 30°inclination south-facing (for additional explanations of the technology assumptions see section 2.2.2).

The output of the PVGIS model is converted into power generation by country, bidding zone, NUTS1 and NUTS2 taken into account the installed capacity at the end of 2015. Finally, the dataset is calibrated with the actual generation in 2015 provided by the national TSO over 28 MS and neighbouring countries.

2.2.2 Assumptions on the distribution of solar farms

Ideally, in order to convert the radiation into PV generation it would be necessary to have available technical information about the existing PV fleet such as module orientation, technology used, power curves, loss of performance and location of each farm, etc. There are databases registering similar information for PV portfolios; however, as the best of authors' knowledge, there is no complete database registering such information of all the PV modules over Europe.

For this reason, assumptions had to be taken about the main factors influencing the uncertainties of the total weather-derived PV generation over a country or a region: (1) the orientation and the inclination and (2) the technology of the PV modules; (3) the distribution of the PV fleet whether is homogenously or heterogeneously distributed over the area and (4) the locations of the installed PV fleet.

For a first approximation to generate the PV production time series, among the four drivers mentioned, here it is firstly assumed, for the PV fleet in Europe, an open-rack mounting at 30° inclination south-facing. In parallel to this work, it is evaluated the impact of the PV-module spatial distribution and suitability of the lad-use on the total solar generation at different aggregation levels [21]. For that, the PVGIS model has produced two types of datasets of the hourly PV potential for 2015 (given by the maximum solar energy output (watt hour) for each kilowatt of installed capacity averaged over a region) based on different land-use assumptions:

- Assumption 1): All type of land classes are used as potential sites for the installation of solar panels.
- Assumption 2): Some geographical areas are excluded for the installation of solar panels such as mines, dumps and construction sites, artificial, non-agricultural vegetated areas, forests, glaciers and perpetual snow, wetlands and water bodies and any Natura 2000 protected areas. All the remaining areas are defined as potential sites for the installation of solar panels. Those available areas are merged creating an exclusion mask that is implemented in the PVGIS model.
  To build the exclusion mask, different land-use databases and territorial administrative units are used: Nomenclature of Territorial Units for Statistics NUTS 2013 version, the 2006 CORINE Land Cover (CLC) and the 2015 version of Natura 2000 geographic layers sourced by, Eurostat [22], Copernicus [23] and European Environmental Agency respectively [24].

Note that the selection of the excludable areas is rather conservative approach since Natura 2000 areas or artificial, non-agricultural vegetated areas could be permitted for solar PV installation under several circumstances, evaluating the land-use competition with other use [25]. However, the scope of this sensitivity analysis is to investigate the maximum difference on the total generation between two extreme assumptions. Thus, it is possible to capture the entire range of sensitivity of the spatial distribution and the potential sites in the solar generation.

Nevertheless, it is also worth to remind that solar radiation shows a relatively small spatial and temporal stochastic variability compared, for instance, with than of the wind speeds.

2.3 PV generation hourly time series for 30 years at different aggregation levels

2.3.1 PV installed capacity, TSO time series and statistics

The output of the PVGIS model (that is, the technical potential hourly time series given by W for each kW of installed capacity) is converted into generation by considering the installed capacity as of 31st December 2015 by country, bidding zone, NUTS 1 and NUTS 2 regions.

Actual PV generation: the main source for TSOs hourly time series is the Transparency Platform provided by the European Network of Transmission System Operators for Electricity [26] in agreement with Regulation 543/2013 [27]. This database has been consulted last time in February 2017: in case data were not available on the ENTSO-E transparency platform (e.g. Croatia or Italian bidding zones) or contained significant amount of missing values (e.g. United Kingdom, Republic of Ireland, Cyprus), data from the corresponding TSO is preferred as a source. Regardless this, for Bulgaria, Luxemburg, Slovenia and Slovakia data were not available (**Table 1**).

To crosscheck the level of accuracy of the ENTSO-E and national hourly time series, the annual total generation (that is, the sum over all hours in 2015) is compared with the annual generation reported by the annual statistical factsheet from the same source. It is observed that there are mismatches for most of the countries between the total annual production reported and the sum of the hourly reported values.

The ENTSO-E time-series include hours that are not registered while the total annual generation could have been metered and reported separately. For the validation at NUTS 1 and NUTS 2 level, regional statistics have been searched but, for most of the countries, neither time series nor were monthly or annual statistics available for 2015.

Installed capacity: the installed capacity data by country is collected from the statistical annual factsheet from ENTSOE (**Table 1**) and the installed capacity by bidding zone, NUTS1 and NUTS 2 has been collected from the national TSO, whenever the statistics are available. However, as most of the solar capacities on a regional European level are not available, an alternative approach is chosen to proxy the regional distribution capacities. Following the [28] study, it is assumed that the share of solar generation for the nth NUTS2 depends on the geographical size of the regional area valued over the solar potential on a NUTS2 level, derived from the PVGIS model (The table in the annexes shows the resulted installed capacities by NUTS 2 considered). The calculated installed capacity factor is then adjusted by additional weight to ensure that the sum of all shares per country is equal to 1 and consistent with the national installed capacity given by the ENTSOE platform.

$$(Installed\ Capacity)_n = \frac{\left(\frac{Potential_{NUTS2n}}{AvgPotential_{Country(n)}}\right)^2 Size_n}{Size_{Country(n)}} * Installed\ Capacity_{Country(n)}$$

Table 1. PV installed capacity (MW) as of 31st of December 2015 and annual generation (GWh) by country

COUNTRY	Installed capacity as of 31/12/2015 (MW)	Net Generation (annual report) GWh	Net Generation (hourly time series) GWh
Austria	404	400	820
Belgium	3068	3000	3038
Bulgaria	1041	1400	NA
Switzerland	756	0	NA
Cyprus	85	0	NA
Czech Re	2067	2200	2198
Germany	38411	35200	34746
Denmark	781	600	NA
Estonia	6	0	NA
Spain	6967	8263	4232
Finland	11	0	NA
France	6192	7400	7175
Greece	2444	3665	3583
Croatia	44	0	NA
Hungary	29	0	NA
Ireland	1	0	NA
Italy	19100	23900	19673
Lithuania	69	100	NA
Luxemburg	116	100	NA
Latvia	2	0	NA
Netherlands	1429	100	981
Norway	14	0	NA
Poland	87	0	NA
Portugal	429	800	759
Romania	1249	2000	1239
Slovenia	263	200	375
Slovakia	532	500	NA
Sweden	104	0	29
United Kingdom	9000	7500	7655

2.3.2 Calibration curve and correction of the PV generation time series

The calculated PV generation time series are corrected with the actual generation outputs provided by the TSOs for the year 2015. Before that correction the actual hourly time series from the TSO are upscaled using an annual factor to match the net generation from the annual statistics and to avoid the differences found (see **Table 1**).

Then, a calibration curve is obtained for each country and by bidding zone where data from TSO are available for the year 2015. The calibration curve (**Figure 2**) is calculated by the difference between the simulated and the corrected-TSO PV durations curves (named as delta in **Figure 2**). This figure shows the calibration curves for some of the countries where the TSO data are available. The table below indicates the difference in percentage of the delta distribution (with respect to the installed capacity of each country) to compare among the differences of the countries. It is shown as the main percentiles (minimum, 25 percentile, 50 percentile, the mean, the 75 percentile and the maximum). In the table, the extreme differences (minimum and maximum) can be related to the solar power peaks differences between the simulations and the TSO data.

From the figure and the **Table 2**, it is observed that the difference between the simulations ranges between -2% and 5% from the minimum to the 75 percentile. The difference between the countries is more variable when the maximum generation is reached. At maximum generation, that is, solar power peaks during 2015; Germany has the maximum difference (20%), correlated with the highest installed capacity in this country. France and Austria has a 17% difference while the lower difference is in Portugal.

Table 2. Descriptive statistics of the delta for the countries selected

Delta (%)	AT	BE	CZ	DE	ES	FR	IT	PT	UK
MIN	-1.7	-0.3	-0.5	-0.18	-4.18	-1.8	-0.1	-7	-1.2
25 p	-1	0	0	0	-1.95	-0.5	0	-5	0
50p	0	0	0	0	0	-0.35	0	-0.5	0
mean	0.2	0.65	0.4	2	-0.92	1	2.1	-2.4	1.6
75p	0	0.39	0.4	3.9	0	1.6	5.1	0	4.4
MAX	16.2	8.4	6.9	20.62	4.3	17	14.5	0	11.8
installed capacity (MW)	715	2904	2067	39332	4664	6192	19100	429	9000

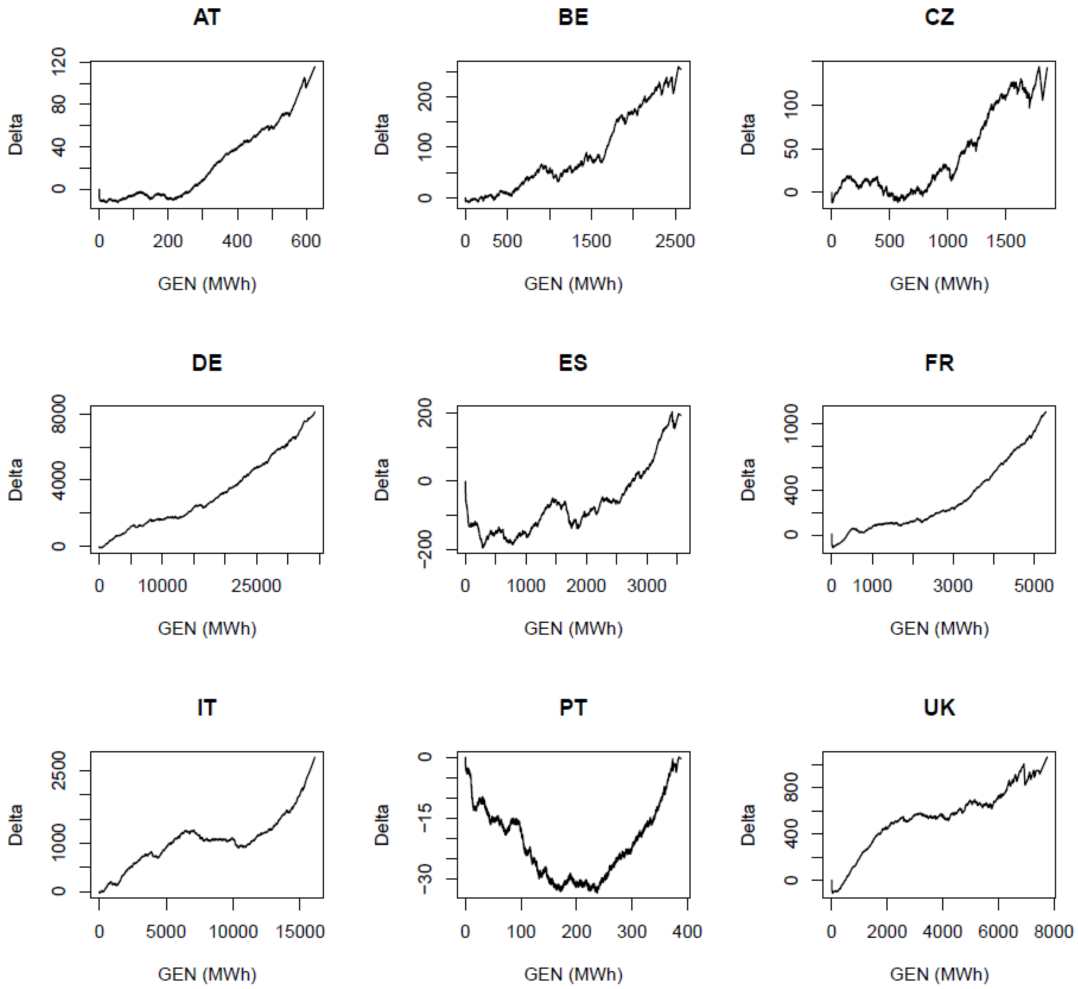
The delta obtained in most of the cases is positive (except in Portugal, but the difference between the simulations and the TSO data is very small, up to 2%), indicating an overestimation of the TSO data. The calibration curves show positive slopes suggesting that the overestimation is proportional to the power production and roughly giving a linear systematic bias.

This pattern of overestimation may be due to the uncertainties accumulated in the theoretical process of the conversion of radiation into generation and the idealised assumptions considered. That is, small biases in the extraction and reconstruction of the satellite data, the calculation of the diffuse radiation at inclined plane, the assumptions made on the technology, module orientation, spatial distribution, and existing locations and in the actual time series themselves contributed to the accumulated overestimation in the time series.

To reduce the uncertainties cascade, on-going and future work is devoted to analyse PV generation output under different assumptions. For example, analysing the impact of the land-use availability on the aggregated PV potential in market areas (Moustafelou et al. 2017), or evaluating the difference between the PV generation assuming East-West facing of the PV module orientation.

For the countries were TSO data are not available the calibration curves used for the correction corresponds to a country with similar latitude, normalised with respect to the installed capacity of each country. That is, the calibration curve of Austria is applied to Switzerland, Hungary and Slovakia; the curve of United Kingdom to Ireland, Nordic countries; Estonia, Latvia and Lithuania and Poland; Italy to Croatia and Belgium to Luxemburg. At bidding zone, NUTS1 and NUTS 2 levels the correction is applied using the calibration curve corresponding to the country of the aggregation level. Finally, the calibration curve is used to correct the 30 years of the time series.

Figure 2. Calibration curves used for correcting any systematic bias of PV generation time series with TSO data



3 Results and discussions

The results of the corrected PV generation time series for 2015 are compared with the actual generation provided by the TSO data. The validation is first statistically assessed by country. Then, the robustness and quality of the results are quantified using statistical and energy parameters such as the PV duration curves, power peaks, ramping rates and capacity factors, at country, bidding zone, NUTS 1 and NUTS 2 aggregation levels, crucial for the estimation of the flexibility needs and storage capacities.

3.1 Statistical indicators

The quality of agreement between the corrected PV generation time series derived from the PVGIS and the TSO data is shown in the **Figure 3** in the form of Taylor diagram [29], for the countries with TSO data available. Those diagrams assess comparatively the modelled and observed data by the use of the sample Pearson correlation coefficient (r), the root mean square error (RMSE) and the standard deviation (SD), giving a concise statistical summary of how well patterns match each other.

The sample Pearson correlation coefficient (equation 1) assesses the internal consistency of the modelled dataset and to gauge the statistical significance, the Student's t is applied. The significance measured by the p-value indicate the probability of obtaining the result equal to or more extreme than is actually observed and is considered statistically significant when $p<0.05$. In all cases the datasets follow a Student's t-distribution under the null hypothesis.

The RMSE (equation 2) and the difference between the modelled and the TSO standard deviations (equation 3) gauge the simulations accuracy. High values of RMSE indicate a high level of non-systematic (i.e. random) discrepancy between the simulations and the TSO data.

$$r=\frac{\sum_{i=1}^{n}X_iY_i-\frac{(\sum_{i=1}^{n}X_i)(\sum_{i=1}^{n}Y_i)}{n}}{\sqrt{\left(\sum_{i=1}^{n}X_i^2-\frac{(\sum_{i=1}^{n}X_i)^2}{n}\right)\left(\sum_{i=1}^{n}Y_i^2-\frac{(\sum_{i=1}^{n}Y_i)^2}{n}\right)}} \tag{1}$$

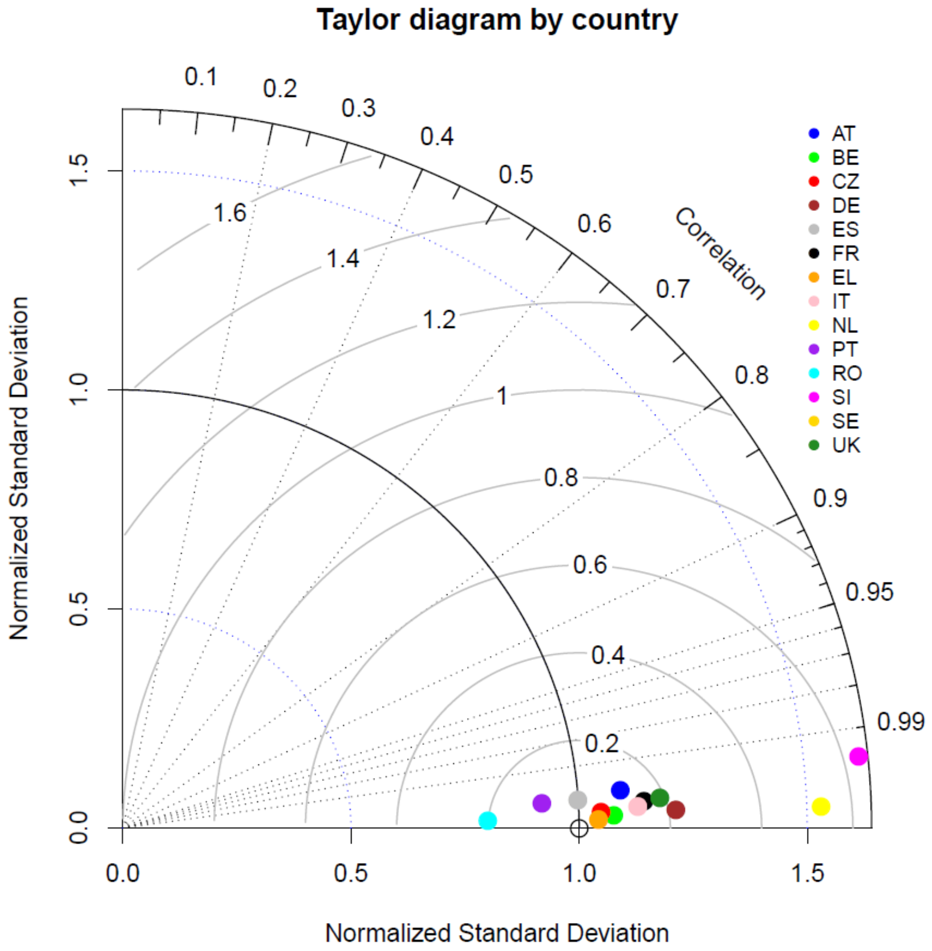
$$\mathrm{RMSE}=\sqrt{\frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}(X_{\mathrm{i}}-\mathrm{Y_i})^2}{\mathrm{n}}} \tag{2}$$

$$\mathrm{SD}=\sqrt{\frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}(X_{\mathrm{i}}-\bar{X})^2}{\mathrm{n}-1}} \tag{3}$$

The statistical indicators show that the simulations'pattern correlations with the TSO data are higher than 0.99 for all counties analysed. The centred RMS errors between the simulated and the TSO data are up to 0.2 for all the countries except for Netherlands and Slovenia that are 0.5 and 0.6, respectively. The standard deviations of the simulated patters are proportional to the radial distance from the origin. Most of the countries are characterised by standard deviations between 1 and 1.2 except for Netherlands and Slovenia that are 1.5 approximately and Romania and Portigal hovers around 0.8. In summary, the relative merits of the model shows that all of the countries agree well with the TSO data lieing nearest the reference point on the x-axis with high correlations and low RMS errors. Romania and Portugal have less spatial variability and Slovenia and

Netherlands have too much spatial variability with respect to the TSO data. The case of Spain show the best variability with the same standard deviation than the TSO data, low RMSE and high correlations.

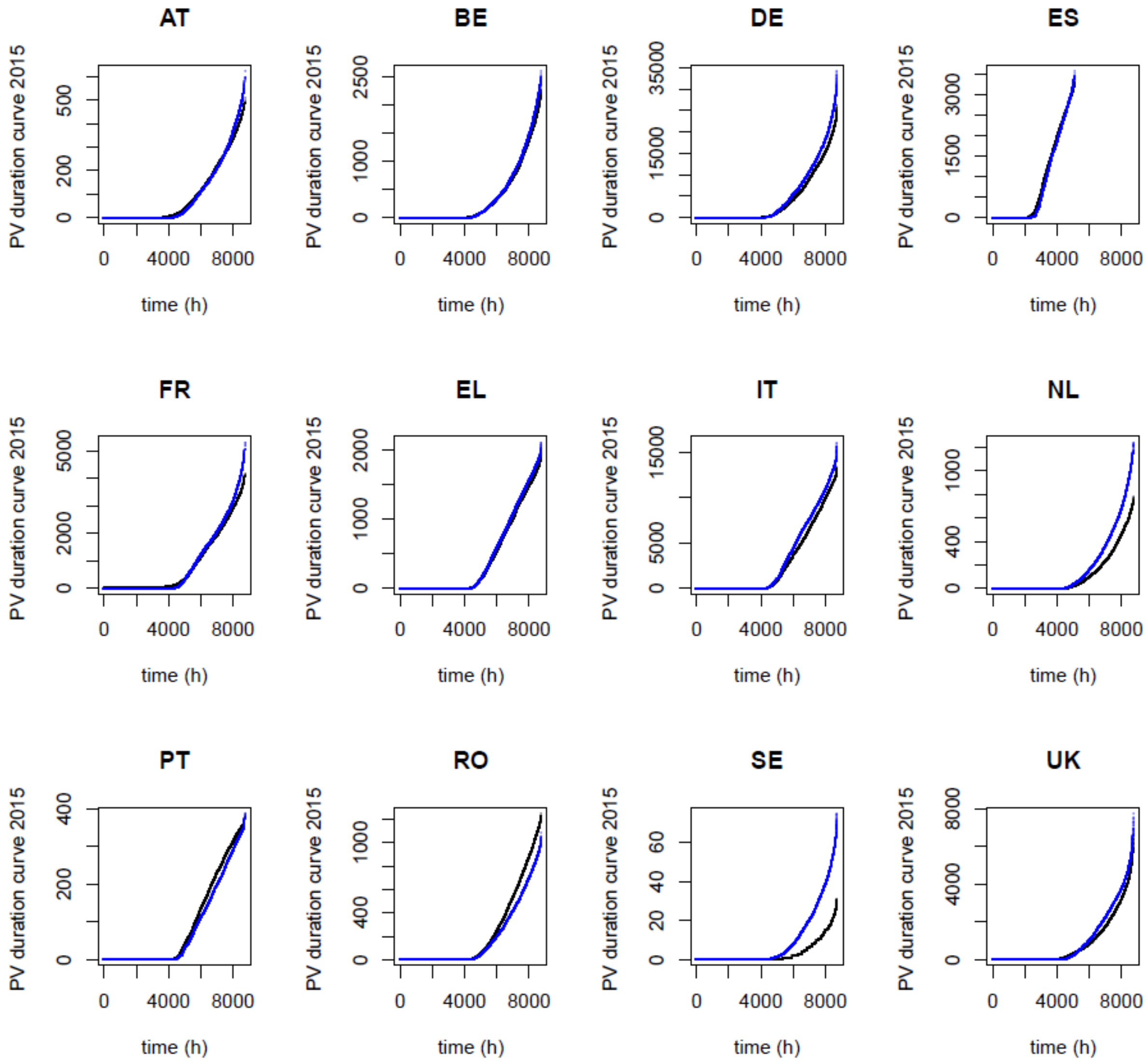
Figure 3. Taylor diagram for the countries with TSO data available.



3.2 Duration curves

The PV power duration curves for the simulations and the TSO data are shown in the **Figure 4**. It is shown that for all countries with TSO data available, the simulations follow similar pattern of the TSO data. Assessing the extremes of the curves it is observed that the simulations reproduce higher values than the TSO data in most of the countries as previously mentioned and accounting for the inconsistencies of the actual generation hourly time series themselves. In this stage, it is observed that the time series selected from ENTSO-E for the case of Sweden are omitted and the country is corrected with the calibration curve of other country.

Figure 4. PV duration curves for countries with TSO available data. The blue colour represents PVGIS derived generation and the black colour the TSO data.



3.3 Time series and ramping rates

The overall statistical performance shows good results, which means that simulations are able to reproduce the PV power generation with similar errors. The direct comparison of the modelled and TSO time series can provide further useful information on the suitability of EMHIRES in reproducing actual data. For instance, the **Figure 5**, the **Figure 6** and the **Figure 7** show the PV power generation time series for the PVGIS-derived, PVGIS-corrected and the TSO datasets for Belgium, Germany and United-Kingdom.

In order to assess the quality of the PV-corrected time series in capturing the sudden increase or decrease of power characterised by large positive or negative hour by hour differences, the series of the ramping values in absolute terms of the modelled and TSO datasets are analysed. The TSO and corrected time series are normalised with the installed capacity of each country and shown in the **Figure 8**. The standard deviations are represented by the bars and the extreme values are depicted with the black lines (error bars) over the bars. It is observed that, where the TSO data are available, both modelled standard deviation and the extreme values are similar to the TSO values.

Figure 5. PVGIS-derived (blue), PVGIS-corrected (red) and TSO (black) power generation hourly time series for Belgium 2015

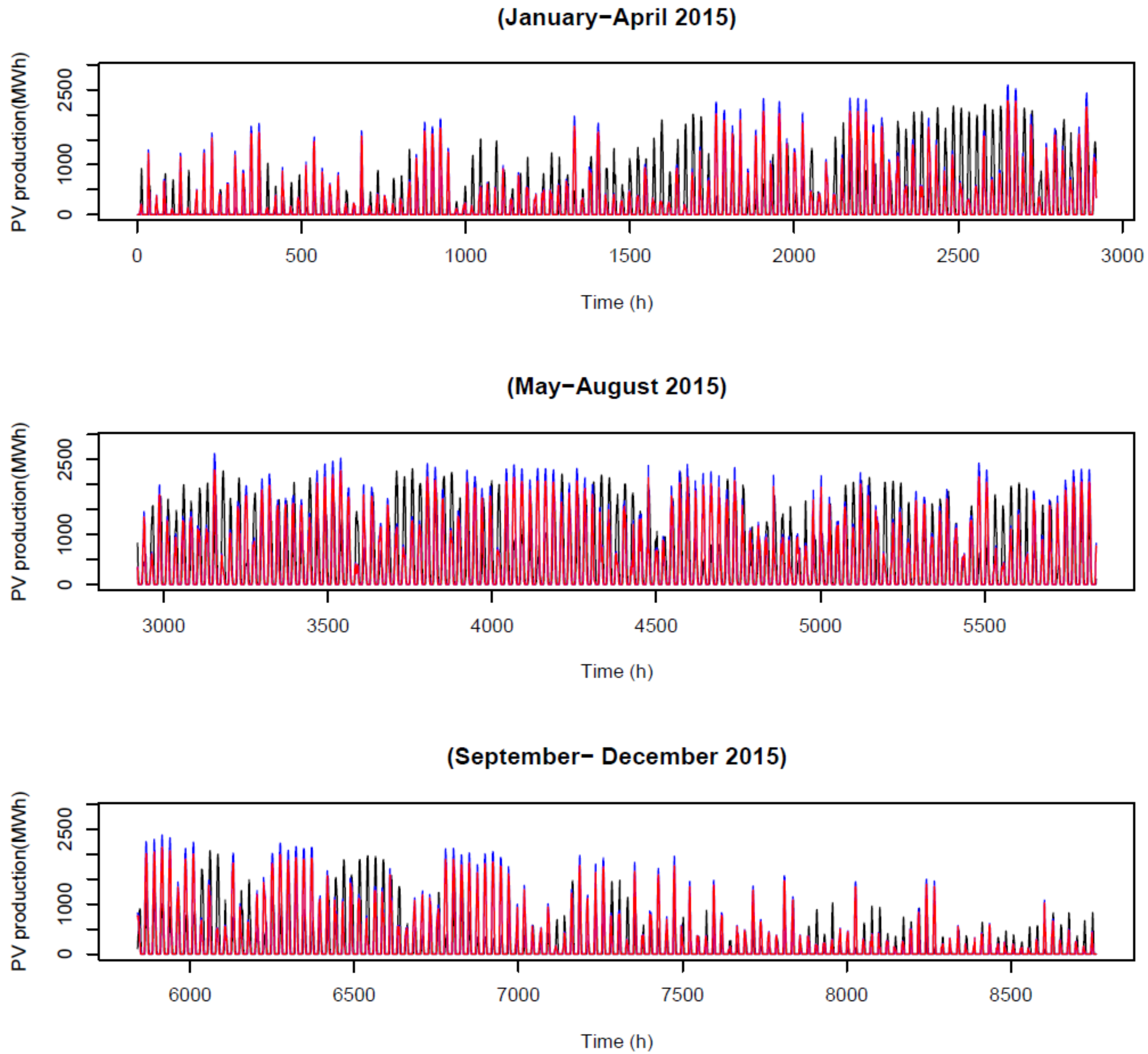


Figure 6. PVGIS-derived (blue), PVGIS-corrected (red) and TSO (black) power generation hourly time series for Germany 2015

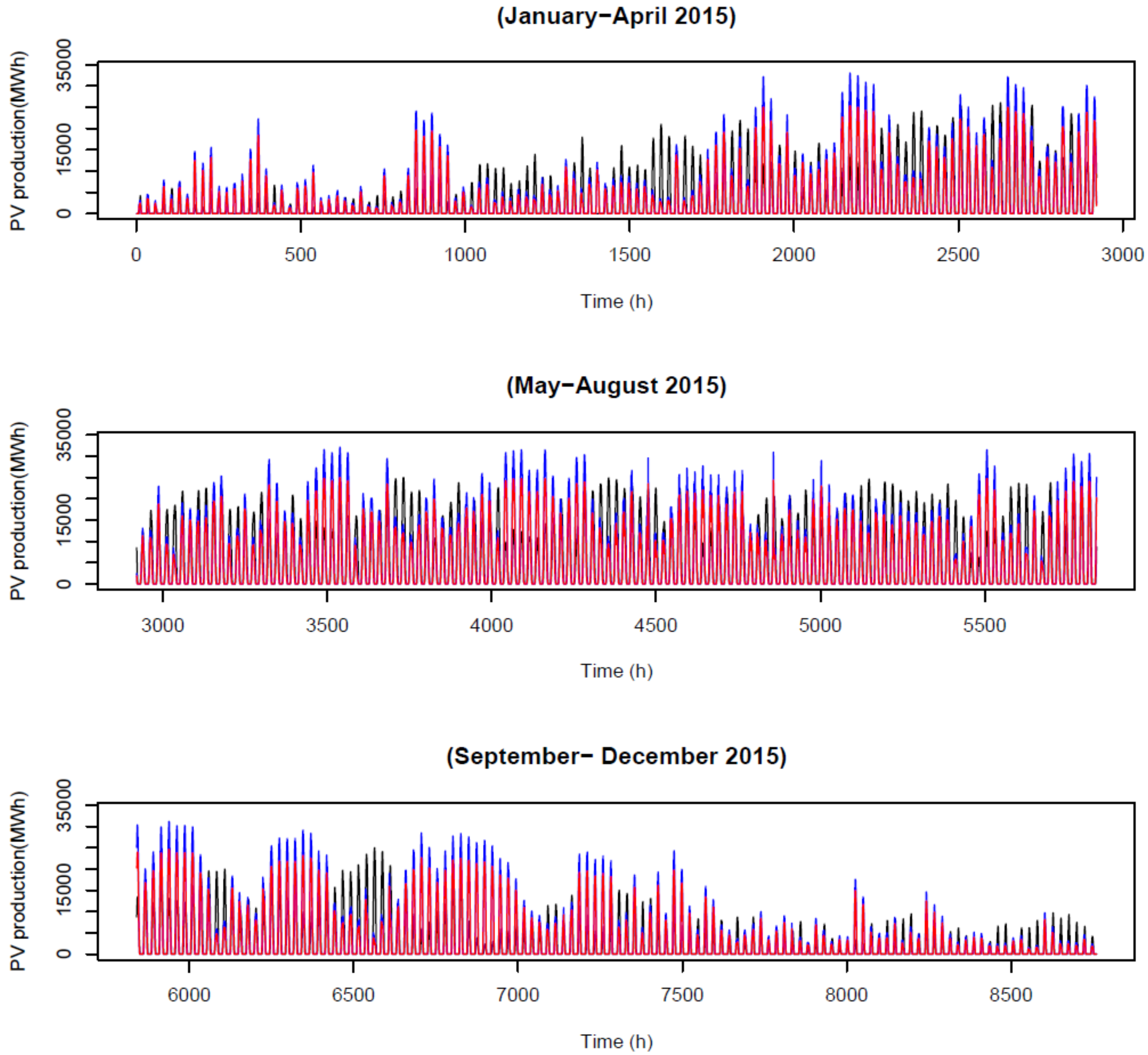


Figure 7. PVGIS-derived (blue), PVGIS-corrected (red) and TSO (black) power generation hourly time series for United-Kingdom 2015

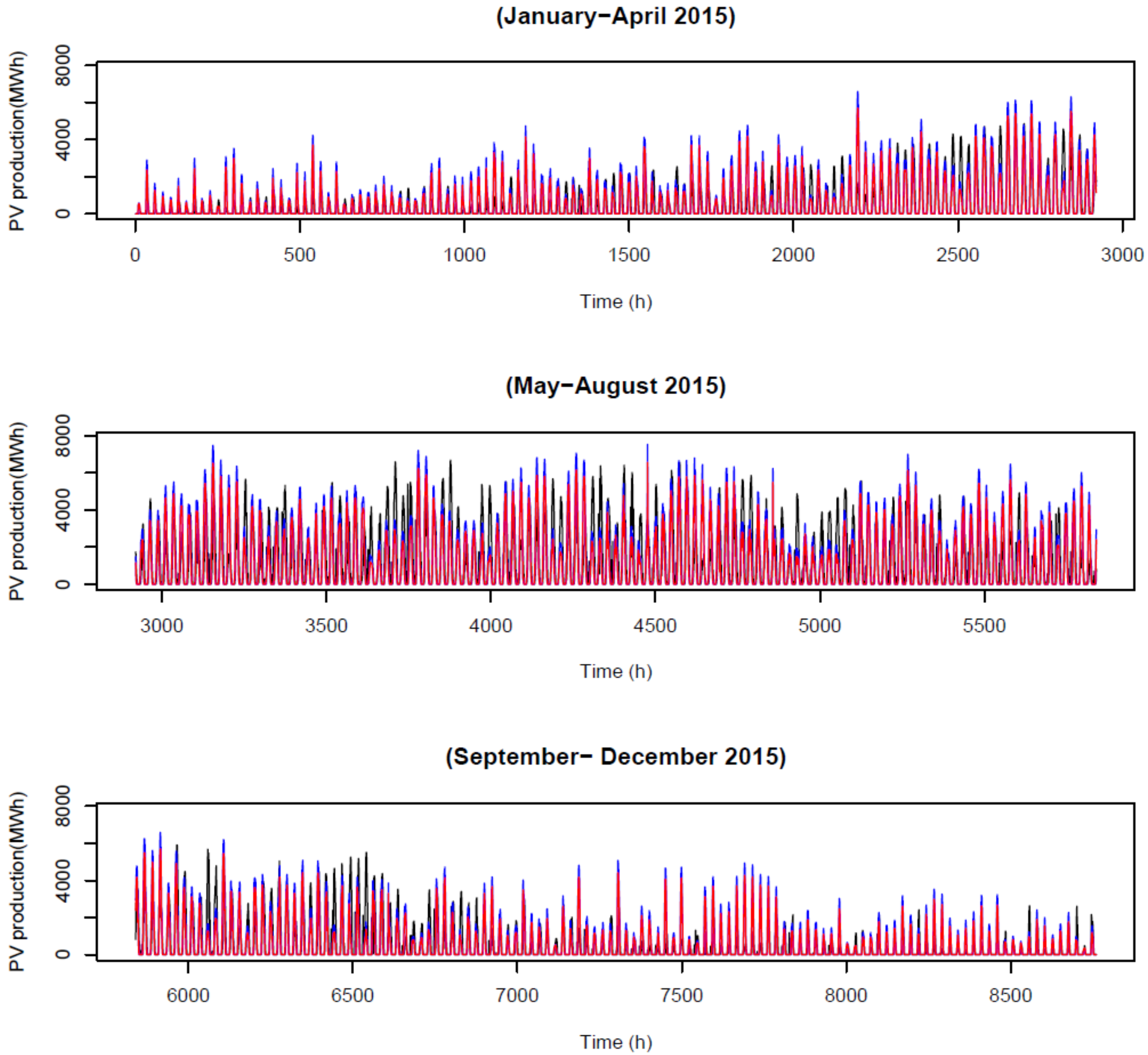
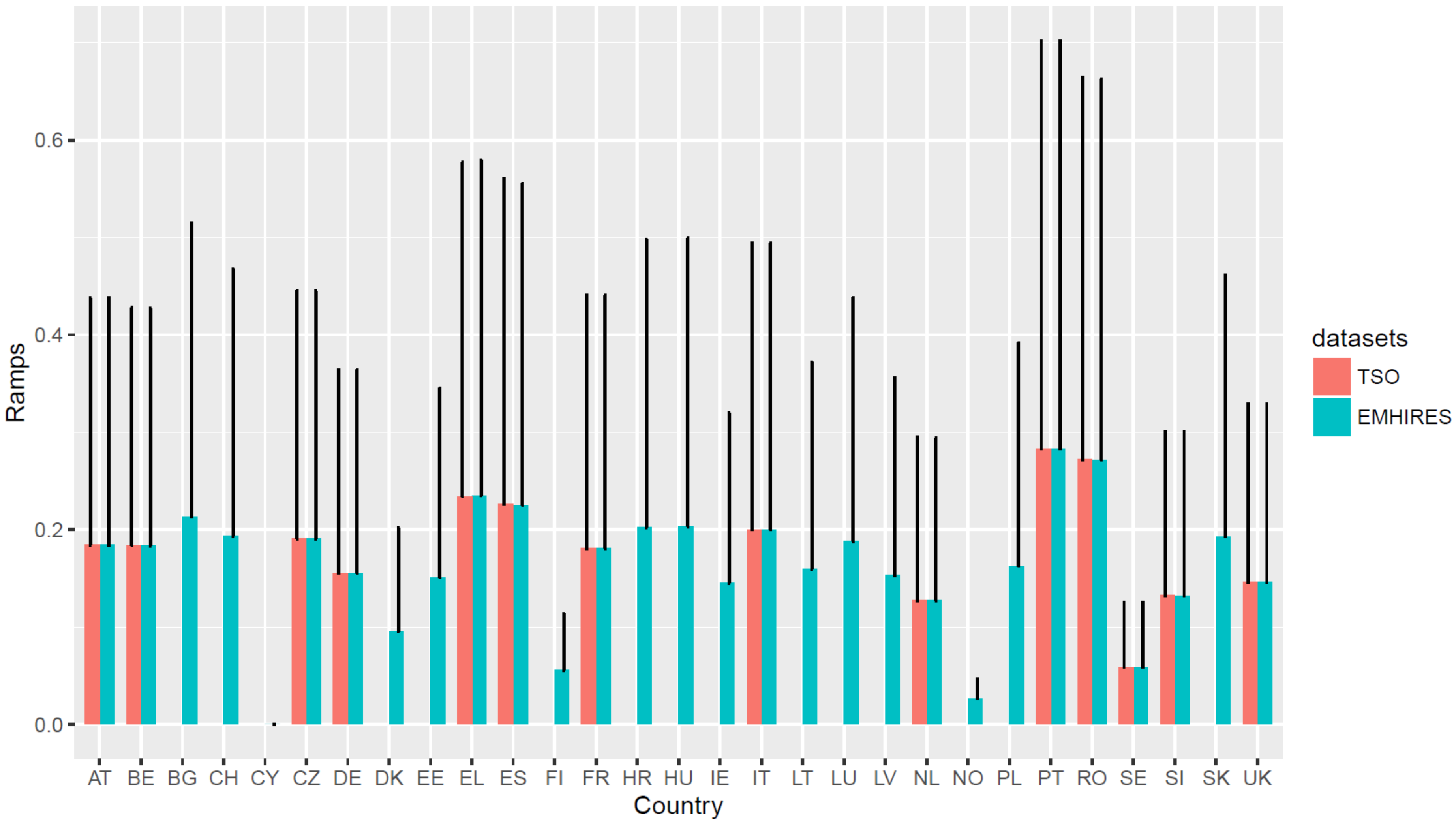


Figure 8. Absolute standard deviation and extremes of the normalised hourly time series for the TSO and EMHIRES (PVGIS-corrected) datasets for all the countries with TSO data available



3.4 Capacity factors and regional statistics

Additional comparison of the EMHIRES dataset with the TSO time series is done by calculating the capacity factors; that is, the ratio between the sums of the energy produced (GWh) and the maximum possible generation (installed capacity (GW)*8760) per country.

Note that the generation has been calculated accounting for the installed capacity at 31st of December 2015 and then, it has been corrected with the calibration curve (including the generation during the 2015). However, for this comparison, the installed capacity considered is the averaged capacity as for 31st of December 2014 and 2015. The **Table 3 Table 3.** Installed capacity as of 31st of December 2014 and 2015 and the % increased during 2015.includes the increase of the installed capacity during 2015, showing that for several countries the growth in the share is significant, for example for United-Kingdom and Netherlands and therefore, it has been considered the distribution over the year.

Table 4 depicts averaged and maximum capacity factors for the direct output of the PVGIS model, the TSO data and the EMHIRES dataset, calculated with the averaged installed capacity of 2015. For the countries where the hourly time series are not available, the capacity factors have been calculated based on the total annual generation. Once again, the TSO capacity factors for some countries show very low or extreme values (such as the case of Sweden, Slovenia and the Netherlands, in the table coloured in red) suspecting inconsistencies in the TSO time series.

In general, it is observed that the averaged values are very similar among the datasets but the PVGIS model output tends to overestimate the maximum capacity factors. The corrected time series with the TSO data (EMHIRES) – both with the annual generation and the hourly time series - show that the mean and maximum capacity factors are closer to the TSO data.

The **Figure 9** shows the boxplots for the hourly capacity factors by country for the 30 year period and the **Figure 10** shows the mean PV capacity factors for each NUTS 2 classified by countries. Although in the comparison between EMHIRES and the TSO data the results were highly correlated, it would be necessary to validate the data at regional scale with actual hourly time series. Therefore, the validation by NUTS 2 region will continue once the data is released by the national TSO.

Table 3. Installed capacity as of 31st of December 2014 and 2015 and the % increased during 2015.

	Installed capacity (MW) as of		
COUNTRY	**31/12/2014**	**31/12/2015**	**% increased**
Austria	324	404	20
Belgium	2986	2904	3
Bulgaria	1039	1041	0
Switzerland	437	756	42
Cyprus	NA	85	NA
Czech Re	2061	2067	0
Germany	37981	39332	1
Denmark	606	781	22
Estonia	NA	6	NA
Spain	6902	6967	1
Finland	NA	11	NA
France	5292	6192	15
Greece	2436	2444	0
Croatia	30	44	32
Hungary	6	29	79
Ireland	NA	1	NA
Italy	18620	19100	3
Lithuania	69	69	0
Luxemburg	109	116	6
Latvia	NA	2	NA
Netherlands	1000	1429	30
Norway	NA	14	NA
Poland	23	87	74
Portugal	396	429	8
Romania	1162	1249	7
Slovenia	260	263	1
Slovakia	531	532	0
Sweden	79	104	24
United Kingdom*	5400	9000	40

* In United-Kingdom the main increase of installed capacity occurred during the first quarter of the year.

Table 4. Capacity factors for each country given by the direct output of PVGIS, EMHIRES and the TSO data for 2015.

Country	Av. TSO	Max. TSO	Av. EMHIRES	Max. EMHIRES	Av. PVGIS	Max. PVGIS
AT	13.08	71.18	13.04	71.18	13.36	87.39
BE	11.59	78.33	11.78	79.65	12.44	88.40
BG	15.38	NA	14.30	87.40	15.38	87.44
CH	NA	NA	13.69	72.90	14.01	86.37
CZ	12.14	82.82	12.12	82.82	12.55	89.75
DE	10.21	66.47	10.21	66.47	12.34	87.09
DK	10.03	NA	10.43	79.01	11.28	87.75
EE	NA	NA	8.86	75.14	10.58	85.78
ES	17.81	72.27	17.51	74.32	16.64	78.69
FI	NA	NA	6.77	57.67	8.4	69.14
FR	14.35	67.57	13.37	68.06	14.60	85.93
EL	16.84	84.84	16.89	86.37	17.97	86.41
HR	NA	NA	13.08	73.08	15.28	87.62
HU	NA	NA	14.07	72.59	14.32	87.07
IE	NA	NA	9.02	76.20	10.72	87.15
IT	14.29	69.80	14.28	70.01	16.47	84.33
LT	NA	NA	9.70	73.46	11.41	84.54
LU	NA	NA	11.36	81.12	12.22	90.14
LV	NA	NA	9.29	74.63	11.00	86.43
NL	9.52	54.72	11.24	79.90	12.09	87.07
NO	NA	NA	5.16	48.41	6.86	60.20
PL	NA	NA	10.85	76.13	12.55	86.73
PT	21.26	90.54	21.25	90.54	18.84	90.45
RO	12.17	99.95	14.25	71.23	14.56	86.50
SI	16.46	56.14	12.25	73.56	14.45	88.10
SK	10.75	NA	10.7	85.46	13.4	85.97
SE	3.15	29.81	7.5	60.86	9.21	71.72
UK	9.51	74.36	9.48	74.36	11.17	86.16

Figure 9. Boxplot of the capacity factors by country for the 30-year period (1986-2015)

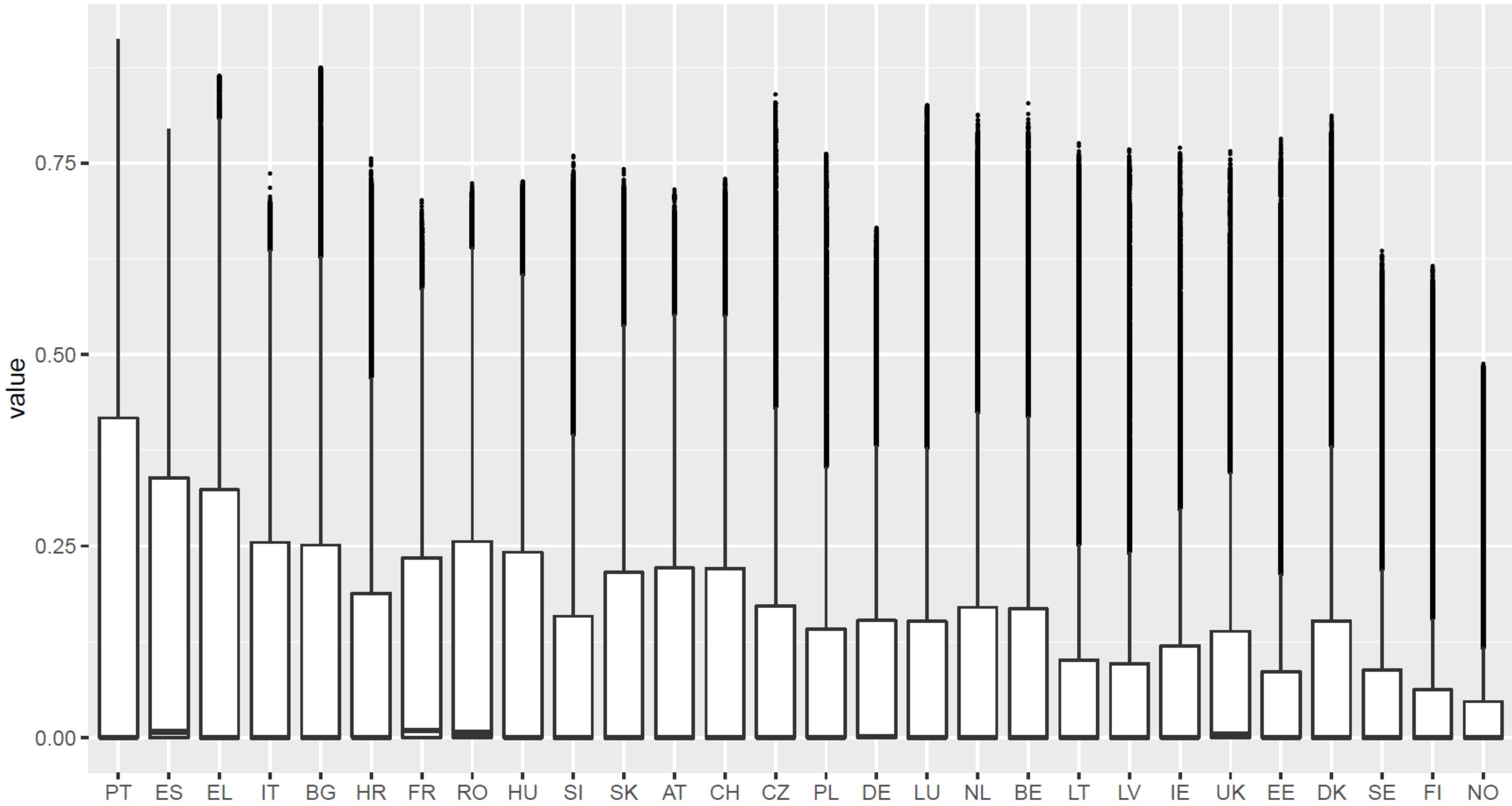
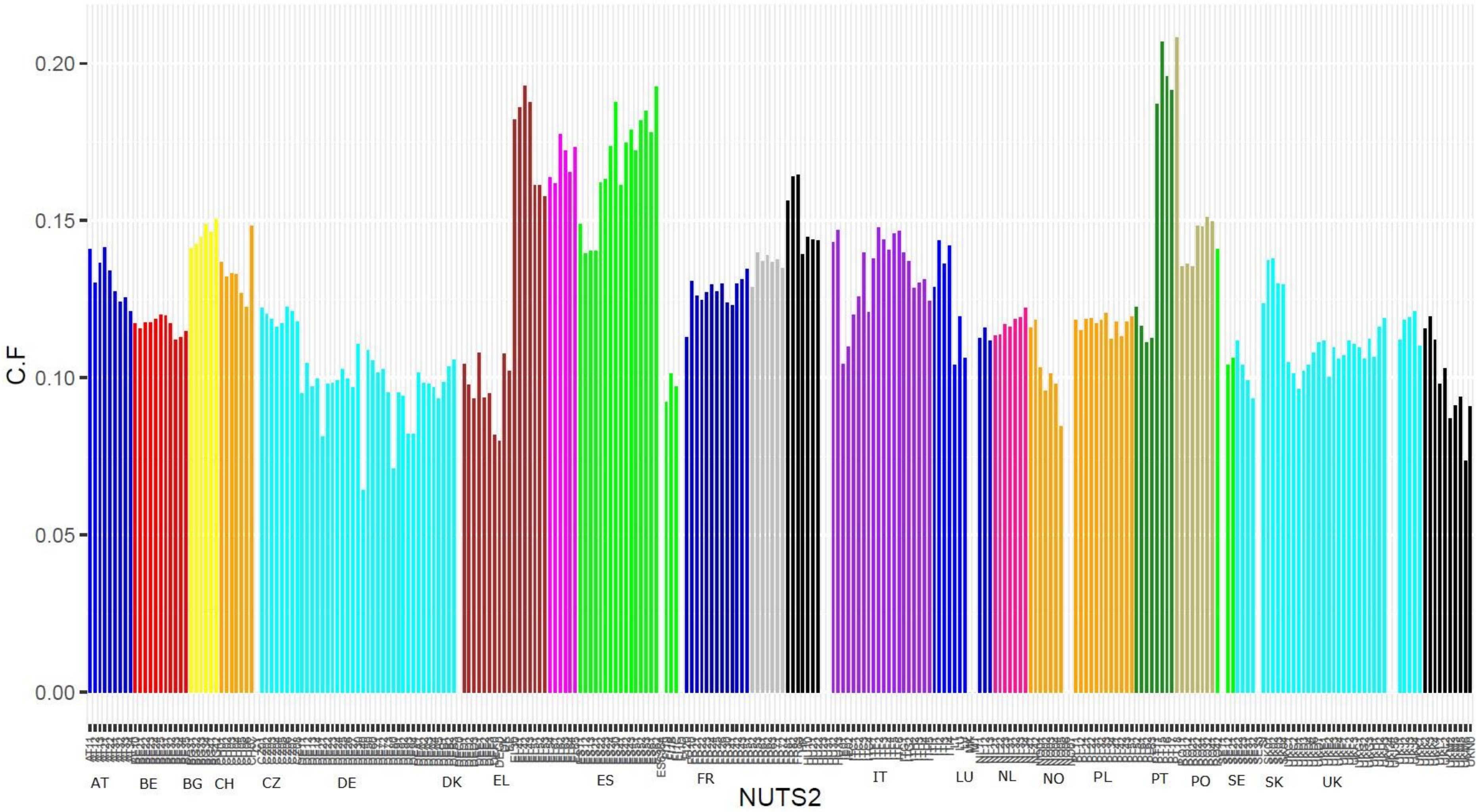


Figure 10. Example of the 1986-2015 averaged PV capacity factors for each NUTS-2 classified by countries.



3.5 Description of the files generated and platform used

The first version of EMHIRES dataset releases four different files about the PV power generation hourly time series during 30 years (1986-2015), taking into account the existing installed capacity at the end of 2015, for each country, bidding zone and by NUTS 1 and NUTS 2 region.

- 30 years of PV power capacity factors at country level.
- 30 years of PV power capacity factors at bidding zone
- 30 years of PV power capacity factors at NUTS 1 level
- 30 years of PV power capacity factors at NUTS 2 level

The time series are released as hourly capacity factors time series, taking into account the installed power by country, NUTS1, NUTS2, and bidding zone included in the annexes. The installed capacity (MW) by country has been extracted from ENTSO-E annual statistical factsheet; the installed capacity (MW) at NUTS1, NUTS 2 and NUTS 3 has been derived using the theoretical potential of NUTS2 and normalized according to the relationship between the ENTSO-E data by country.

A detailed description of the data obtained will be performed in future reports and publication. In the present report, some basic statistics of the PV power generation for the 30 years by country have been computed and are reported in the **Table 5**. Finally, the last figures include a visual sample of randomly selected NUTS 2 regions monthly and diurnal cycle averaged over the 30 year-period.

Terms of use:

This report describes the methodology used to generate EMHIRES and the approach followed to validate the data against the Transmission System Operators time series. It has been described the associate cascade of uncertainties. Therefore, the responsibility how to use, examine the quality of the data for the user's objectives and treat the data available relies on the user.

If you use EMHIRES data in publications, please acknowledge the Knowledge Management Unit, Directorate C Energy, Transport and Climate, Joint Research Centre, European Commission for the dissemination of EMHIRES.

And use the citation of the current JRC Science for Policy Report.

Link to download the dataset:

https://setis.ec.europa.eu/related-jrc-activities/jrc-setis-reports/emhires-dataset-part-ii-solar-power-generation

Table 5. EMHIRES-PV means, 3rd quartile and maximum capacity factor for the 30 year period by country.

Country	Mean	3d quantile	Maximum
AT	0.1262	0.2212	0.7153
BE	0.1122	0.1679	0.8275
BG	0.1433	0.2512	0.8740
CH	0.1284	0.2207	0.7290
CZ	0.1170	0.1722	0.8392
DE	0.0978	0.1527	0.6654
DK	0.1061	0.1523	0.8111
EE	0.0892	0.0856	0.7811
ES	0.1719	0.3390	0.7938
FI	0.0682	0.0622	0.6159
FR	0.1282	0.2347	0.7020
EL	0.1697	0.3234	0.8637
HR	0.1271	0.1880	0.7558
HU	0.1389	0.2420	0.7259
IE	0.0874	0.1196	0.7705
IT	0.1393	0.2548	0.7364
LT	0.0939	0.1009	0.7751
LU	0.1134	0.1516	0.8261
LV	0.0917	0.0967	0.7676
NL	0.1103	0.1700	0.8123
NO	0.0509	0.0471	0.4879
PL	0.1024	0.1415	0.7617
PT	0.2082	0.4171	0.9111
RO	0.1397	0.2558	0.7229
SI	0.1171	0.1584	0.7590
SK	0.1290	0.2154	0.7426
SE	0.0751	0.0880	0.6347
UK	0.0924	0.1387	0.7649

Figure 11. 30-year period average of monthly capacity factors over selected NUTS2 regions.

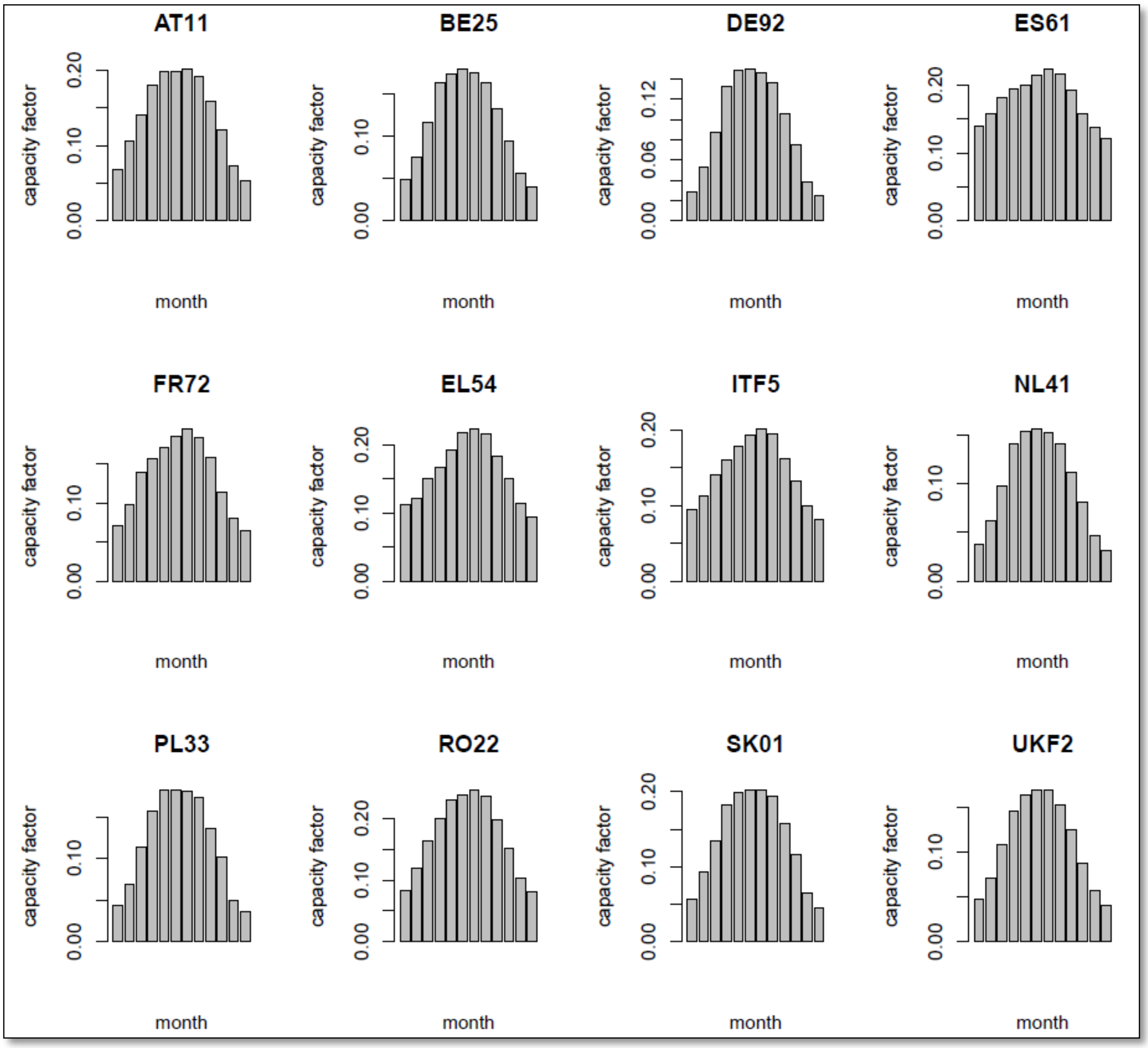
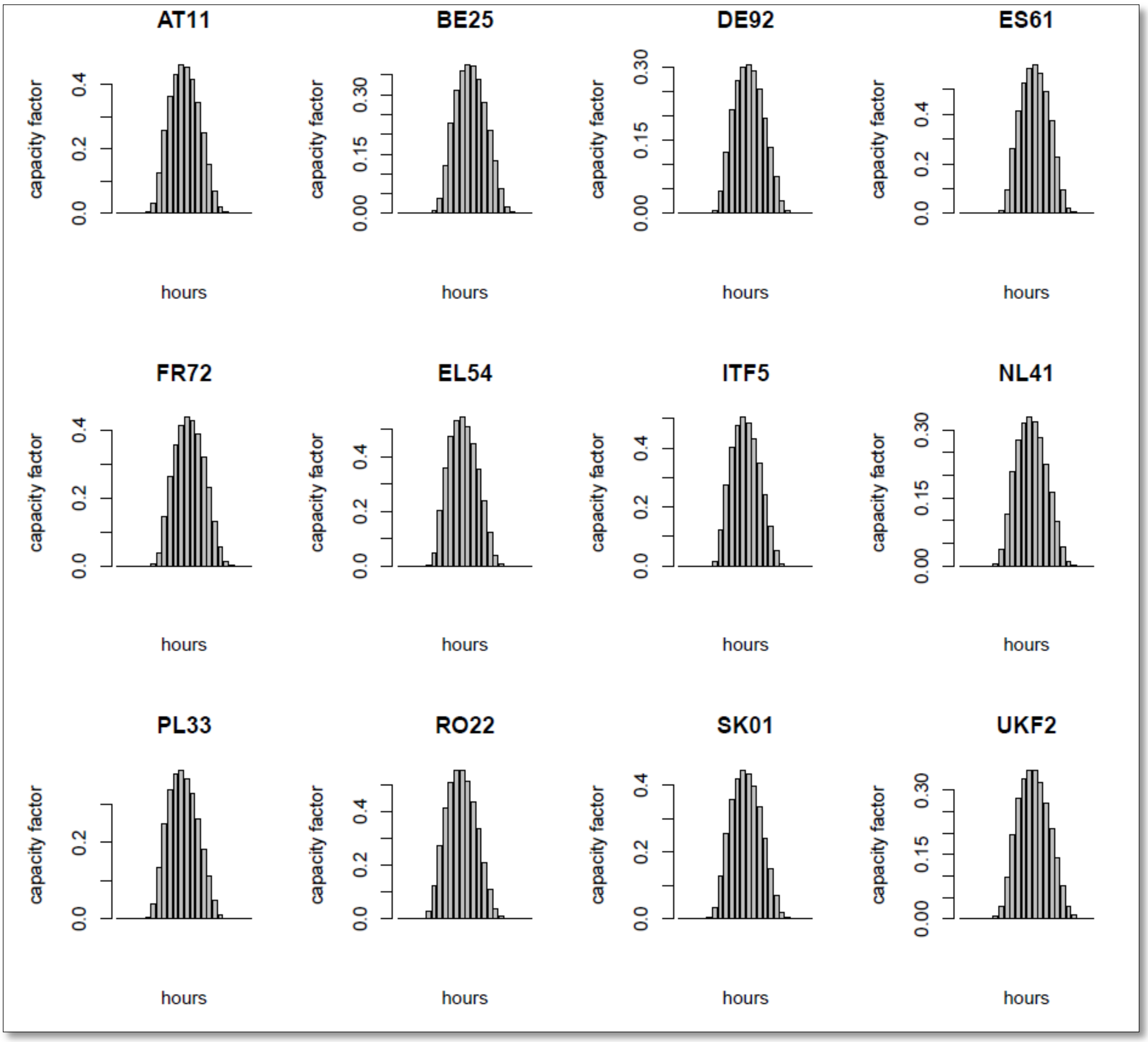


Figure 12. 30-year period average of hourly capacity factors over selected NUTS2 regions.



4 Conclusions and further steps

EMHIRES is the first publically available dataset of European solar power generation time series at high temporal and spatial resolution derived from meteorological sources covering up to NUTS-2 level. It was generated using the PVGIS model, a robust open source online tool to estimate the solar electricity production of a photovoltaic (PV) system.

The validation of EMHIRES against power system statistics and time series published by Transmission System Operators shows a very good performance over the countries analysed. EMHIRES is able to capture the variability of solar energy, the seasonality and diurnal cycles and also the peaks and ramps.

There is a general slight overestimation of the simulations due to the uncertainties accumulated in the theoretical process of the conversion of radiation into generation. That is, the extraction and reconstruction of the satellite data, the calculation of the diffuse radiation at inclined plane, the assumptions made on the technology, module orientation, spatial distribution, and existing locations and in the actual time series themselves. The limitation of EMHIRES (and consequently other meteorological derived time series) is that it does not account for effects of curtailment, outages such as maintenances and grid losses or network incidences. However, using EMHIRES for power system analysis will increase the accuracy of generation adequacy assessments, renewable energy integration studies and market studies for flexibility technologies such as storage.

Like the EMHIRES wind part, this is the only study, to the best of the authors' knowledge, trying to reproduce solar power time series at both national and regional levels covering the whole Europe with a homogeneous methodology avoiding the use of artificial or on-purpose tuned correction factors. Although it is possible to obtain high correlation values on more limited and homogeneous areas and/or using purposely tailored additional parameters to be set a posteriori through data fitting, the purpose of this study is to develop an *ab-initio* methodology for solar power production simulation and apply homogeneously to all Europe. The methodology has provided results ranging between good and excellent for all countries for which reliable TSOs data are available, regardless their sometimes huge geographical diversity.

Using EMHIRES wind and solar generation time series for power system analysis will increase the accuracy of generation adequacy assessments, renewable energy integration studies and market studies for power system flexibility options such as storage systems, electric vehicles and demand response.

In addition, further work will consist on performing new simulations with different technological assumptions and driven by different future scenarios. The EMHIRES dataset will be used for the analysis of current and future power systems. The capacity credit of wind and solar energy has an impact on the generation adequacy of a power system so that the capacity credits will be determined using probabilistic assessments. The datasets generated under the future scenarios will be open-access.

All datasets can be reviewed, updated and readapted to new situations in the power system (e.g. the commissioning of new installations) as well as to future RES-E deployment scenarios.

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List of figures

List of tables

Annexes

Annex 1. Calculated the PV installed capacity (MW) as of 31st of 2015 by NUTS 2 regions.

Country	NUTS2_code	Calculated installed capacity (MW)
AT	AT11	35.98
AT	AT21	98.42
AT	AT12	156.30
AT	AT31	91.76
AT	AT32	57.32
AT	AT22	147.91
AT	AT33	106.52
AT	AT34	19.93
AT	AT13	3.63
BE	BE21	266.80
BE	BE31	110.73
BE	BE32	371.38
BE	BE33	349.33
BE	BE22	237.10
BE	BE34	391.62
BE	BE35	348.09
BE	BE23	288.57
BE	BE10	15.52
BE	BE24	212.63
BE	BE25	312.23
BG	BG32	132.03
BG	BG33	133.24
BG	BG31	172.82
BG	BG34	190.52
BG	BG41	192.40
BG	BG42	220.01
CZ	CZ06	378.25
CZ	CZ03	443.98
CZ	CZ08	138.75
CZ	CZ01	13.63
CZ	CZ05	325.58
CZ	CZ04	223.21
CZ	CZ02	297.73
CZ	CZ07	245.88
DE	DEA5	775.72
DE	DE30	99.02
DE	DE40	3268.65
DE	DE91	805.45
DE	DE50	39.55

DE	DED1	208.99
DE	DE71	823.87
DE	DEE1	344.60
DE	DEA4	646.15
DE	DED2	923.27
DE	DEA1	559.95
DE	DE13	1255.44
DE	DE72	581.55
DE	DEE2	1230.09
DE	DE60	68.00
DE	DE92	889.74
DE	DE12	839.61
DE	DE73	856.38
DE	DEB1	839.22
DE	DEA2	789.43
DE	DED3	1246.56
DE	DE93	1423.47
DE	DEE3	1069.06
DE	DE80	2305.85
DE	DE25	821.54
DE	DEA3	702.00
DE	DE22	1211.96
DE	DE21	2153.80
DE	DE24	752.93
DE	DE23	1050.66
DE	DEB3	790.07
DE	DEC0	281.90
DE	DEF0	1445.32
DE	DE27	1225.74
DE	DE11	1267.18
DE	DEG0	1731.86
DE	DEB2	497.26
DE	DE14	1142.45
DE	DE26	950.60
DE	DE94	1419.27
ES	ES61	932.49
ES	ES24	453.98
ES	ES12	56.20
ES	ES13	27.35
ES	ES41	811.68
ES	ES42	835.38
ES	ES51	299.33
ES	ES63 ES64	0.00
ES	ES30	83.52
ES	ES52	230.61

ES	ES43	420.81
ES	ES11	191.96
ES	ES53	47.54
ES	ES23	36.74
ES	ES22	77.35
ES	ES21	38.05
ES	ES62	121.07
FI	FI20	0.09
FI	FI1C	1.28
FI	FI1D	7.08
FI	FI1D	0.00
FI	FI1B	0.42
FI	FI19	2.13
FR	FR42	83.63
FR	FR61	477.53
FR	FR72	302.68
FR	FR25	158.49
FR	FR26	334.27
FR	FR52	249.66
FR	FR24	409.36
FR	FR21	243.66
FR	FR83	134.63
FR	FR43	175.27
FR	FR23	111.29
FR	FR10	117.50
FR	FR81	424.52
FR	FR63	190.90
FR	FR41	209.80
FR	FR62	575.53
FR	FR30	104.65
FR	FR51	336.44
FR	FR22	175.07
FR	FR53	293.00
FR	FR82	535.08
FR	FR71	549.03
EL	EL51	240.94
EL	EL30	80.70
EL	EL63	226.64
EL	EL53	154.62
EL	EL62	47.95
EL	EL54	168.55
EL	EL52	326.90
EL	EL43	174.59
EL	EL42	123.16
EL	EL65	297.13

EL	EL64	276.04
EL	EL61	242.75
EL	EL41	84.05
HU	HU33	5.84
HU	HU23	4.63
HU	HU32	5.36
HU	HU31	3.99
HU	HU21	3.48
HU	HU10	2.15
HU	HU22	3.56
CH	CH02	186.55
CH	CH03	37.99
CH	CH05	200.15
CH	CH01	164.96
CH	CH07	65.76
CH	CH06	68.80
CH	CH04	31.80
IE	IE01	0.44
IE	IE02	0.56
IT	ITF1	644.53
IT	ITF5	655.23
IT	ITF6	1003.76
IT	ITF3	890.17
IT	ITH5	1321.08
IT	ITH4	454.11
IT	ITI4	1214.36
IT	ITC3	325.15
IT	ITC4	1440.04
IT	ITI3	552.46
IT	ITF2	280.54
IT	ITC1	1537.75
IT	ITF4	1388.76
IT	ITG2	1783.29
IT	ITG1	1972.90
IT	ITI1	1440.96
IT	ITH2	347.21
IT	ITI2	547.84
IT	ITC2	163.98
IT	ITH3	1136.12
NL	NL13	101.70
NL	NL23	60.74
NL	NL12	135.33
NL	NL22	205.32
NL	NL11	89.69
NL	NL42	97.62

NL	NL41	215.11
NL	NL32	119.03
NL	NL21	132.32
NL	NL31	59.40
NL	NL34	85.58
NL	NL33	127.17
NO	NO04	2.23
NO	NO02	4.50
NO	NO07	0.00
NO	NO01	0.55
NO	NO03	3.70
NO	NO06	0.00
NO	NO05	3.02
PL	PL51	5.90
PL	PL61	4.85
PL	PL31	7.63
PL	PL43	4.01
PL	PL11	5.31
PL	PL21	4.35
PL	PL12	9.91
PL	PL52	2.83
PL	PL32	5.14
PL	PL34	5.42
PL	PL63	4.48
PL	PL22	3.53
PL	PL33	3.54
PL	PL62	5.80
PL	PL41	8.70
PL	PL42	5.59
PT	PT18	163.70
PT	PT15	27.69
PT	PT16	132.23
PT	PT17	14.88
PT	PT11	90.49
RO	RO32	10.58
RO	RO12	168.05
RO	RO21	187.42
RO	RO11	161.82
RO	RO31	198.53
RO	RO22	185.23
RO	RO41	171.75
RO	RO42	165.62
SE	SE32	22.67
SE	SE31	24.69
SE	SE12	17.76

SE	SE33	0.00
SE	SE21	15.66
SE	SE11	3.18
SE	SE22	6.95
SE	SE23	13.09
SK	SK01	23.18
SK	SK03	173.02
SK	SK04	162.46
SK	SK02	173.35
UK	UKH2	126.32
UK	UKJ1	248.18
UK	UKD6	83.86
UK	UKK3	174.38
UK	UKD1	210.25
UK	UKF1	191.95
UK	UKK4	306.33
UK	UKK2	285.44
UK	UKH1	581.15
UK	UKE1	149.69
UK	UKL2	297.78
UK	UKM2	576.61
UK	UKH3	173.61
UK	UKK1	328.36
UK	UKD3	42.32
UK	UKJ3	195.33
UK	UKG1	252.48
UK	UKM6	1021.45
UK	UKI3, UKI4	14.13
UK	UKJ4	183.95
UK	UKD4	106.81
UK	UKF2	214.33
UK	UKF3	269.69
UK	UKD7	29.12
UK	UKM5	215.06
UK	UKE2	308.47
UK	UKN0	454.51
UK	UKC2	203.88
UK	UKI5, UKI6	34.87
UK	UKG2	246.83
UK	UKM3	411.58
UK	UKE3	62.31
UK	UKJ2	264.94
UK	UKC1	110.83
UK	UKG3	36.49
UK	UKL1	511.37

UK	UKE4	75.48
HR	HR	44.00
CY	CY	85.00
DK	DK	781.00
EE	EE	6.00
LV	LV	2.00
LT	LT	69.00
LU	LU	116.00
MK	MK	#ND
MT	MT	#ND
SI	SI	263.00

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