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Global temporal power data collection: electricity load and power generation from solar and wind

Hourly time series and representative daily profiles

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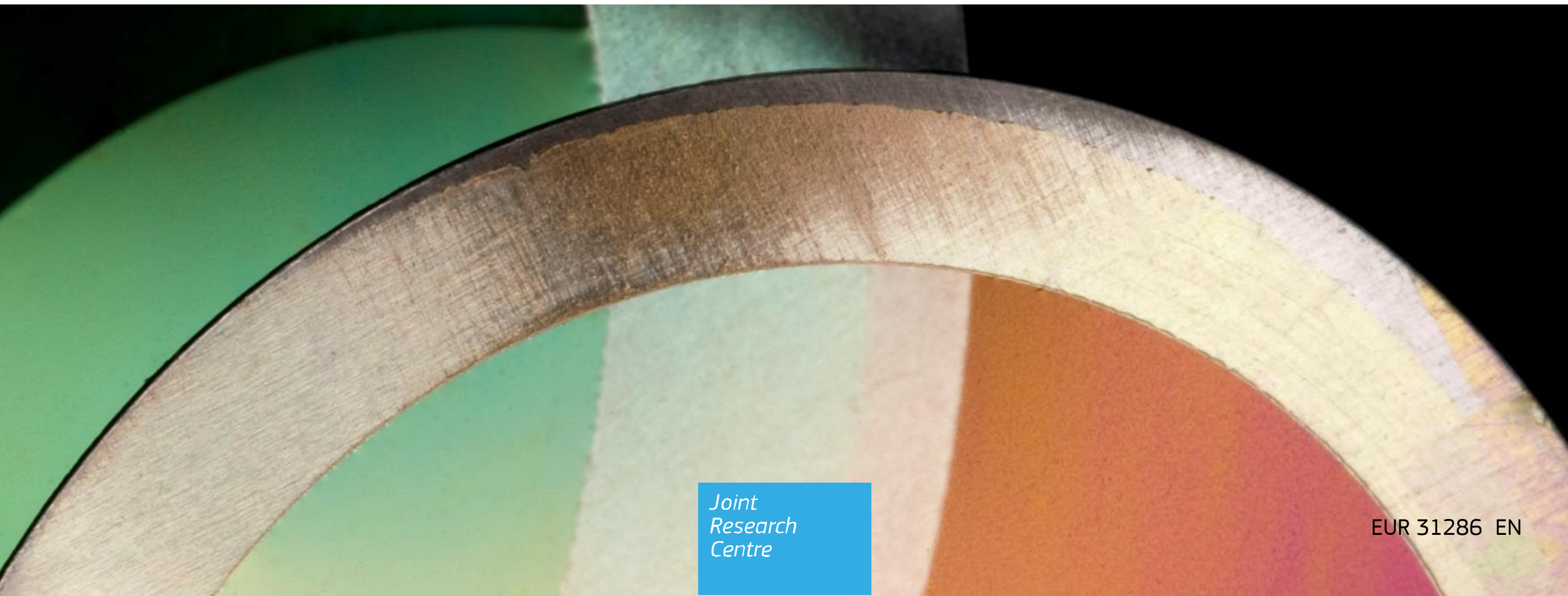

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Contents

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Authors

Schmitz, A., Després, J.

Abstract

This technical report provides a global collection of temporal data of the power sector covering about 60 countries and regions worldwide. This global collection makes available temporal data of electricity load as well as power generation from wind and solar. The temporal data consists of hourly time series and representative daily profiles. This wealth of data can be visualised in interactive data viewers publicly accessible online.

The *time series* for electricity load cover at least a period of one year and up to 10 years. The time series for wind and solar generation span from 2004 to 2018 and are derived from meteorological data provided by satellite reanalysis data. The *wind and solar time series* are provided for different spatial distributions of generator locations in order to examine the effect of spatial capacity distributions on the time series.

The *representative daily profiles* are calculated based on five different clustering methods. Different shares of wind and solar in the power mix are taken into account according to the 2°C scenario of *Global Energy and Climate Outlook 2018* for scenario years 2010 to 2100. As a result, *representative daily profiles* (electricity load, wind & solar, net load) for almost any country or region of the world are made available for a range of spatial capacity distributions, clustering methods, wind & solar shares and number of representative daily profiles.

1 Introduction

Energy system models allow simulating scenarios for decarbonisation pathways. These scenarios provide important insights for policymakers on the pathways to achieve the 2°C and 1.5°C temperature targets put forward in the UNFCCC Paris Agreement.
The power sector plays a crucial role in any decarbonisation strategy. Renewable power generation technologies are fundamentally changing the structure of the power sector. A major challenge for the power system is the integration of large capacities of intermittent wind and solar power generation.
On the demand side, the electricity load varies substantially throughout the day (e.g. morning and evening peak) and across power consuming sectors (e.g. residential, industry, services, etc.). Moreover, seasonal changes (e.g. heating and cooling demand) affect the variation of electricity load throughout the year. Additionally, fundamental changes will occur such as the spread of electric vehicles, battery storage but also demand side management (DSM) strategies.

In power sector models, these dynamic interactions have to be implemented. A crucial condition for modelling the power sector adequately is the availability of temporal data reflecting the dynamics of the power system.
Making available temporal data for the power sector with a high time-resolution is the objective of this technical report. This work provides temporal data with hourly resolution for electricity load and power generation from wind and solar.
Chapter 2 is dedicated to *time series* with hourly resolution with a *duration of at least one year* for electricity load and power generation from wind & solar. Electricity load time series were collected from various sources worldwide. The period covered by the electricity load time series is at least one year and up to 10 years depending on the country. The time series for power generation from wind & solar were calculated based on meteorological data from satellites. These time series cover the period from 2003 to 2018. The calculation of these time series took into account different renewable potentials based on the geographic distribution of power generators.

Chapter 3 deals with the concept of representative daily profiles. Reducing the complexity of the hourly time series (i.e. 8760 h per year) to several daily profiles (i.e. 24 h) which are sufficiently representative for capturing the dynamics of the time series is the objective. This in turn allows reducing computation requirements drastically when modelling the power system. The representative daily profiles are obtained by clustering calculation, of which 5 different methods are presented.

Interactive data viewer which are publicly accessible online allow to visualise the time series with hourly resolution as well as the representative daily profiles, covering the whole globe in countries or multi-country regions.

Indeed, this global collection of time series for the power sector and the concept of representative daily profiles were pursued with a view to enhance the global energy system model POLES-JRC. The POLES-JRC model is the European Commission in-house tool for global and long-term analysis of greenhouse gas (GHG) mitigation policies and evolution of energy markets. For the annual Global Energy and Climate Outlook [1] reports the POLES-JRC model provides long-term energy and GHG scenarios.
The modelling of the power system within POLES-JRC was substantially enhanced in recent years by taking into account the above-mentioned aspects of power systems [2]. The modelling of the power system in POLES-JRC uses *representative daily profiles* in order to simulate long-term scenarios (until 2100) for 66 countries and regions within a reasonable computation time.

This report also studies how representative daily profiles are affected by the tremendous expansion of wind and solar capacities projected in decarbonisation scenarios. To this end, wind and solar shares according to the 2°C scenario of Global Energy and Climate Outlook 2018 [3,4] are used for calculating representative daily profiles for scenarios years 2010 to 2100. For energy system modellers the provided representative daily profiles allow to analyse the impact of an expansion of wind and solar on the power system with a view to draw important conclusions for policy makers.

2 Time series with hourly resolution

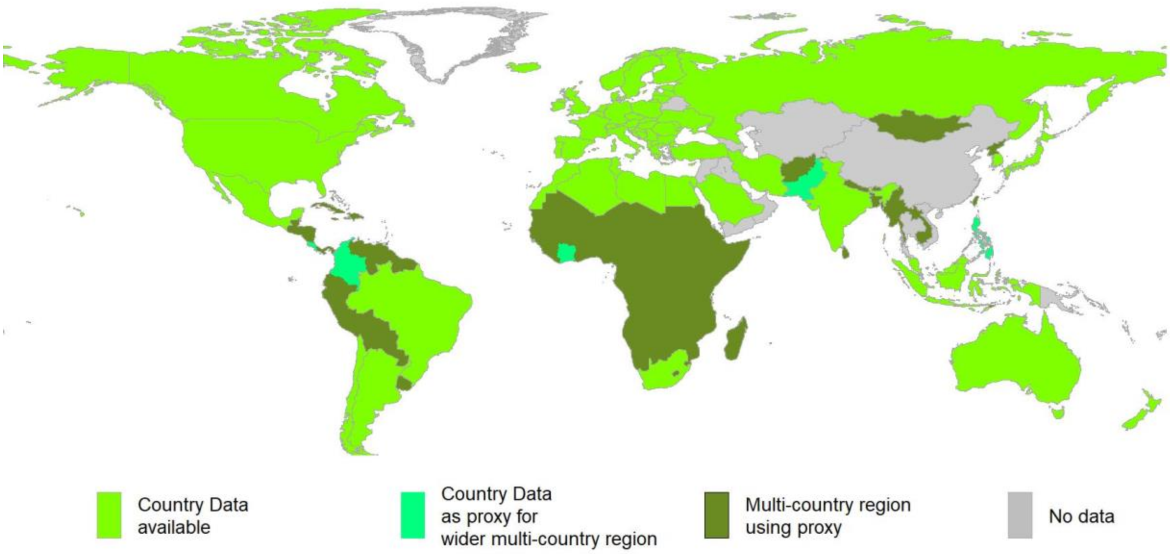
This chapter addresses hourly time series for electricity load and power generation from wind and solar. The origin of the data including its data sources are described. Moreover, the calculation procedures applied to the time series are explained. Finally, an interactive visualization tool allowing to depict the time series for load, wind & solar is presented in section 2.3.

2.1 Electricity load

2.1.1 Global collection

Hourly electricity load data for at least a period of one year has been collected for 63 countries around the world (see map in Figure 1 and Table 1).

Figure 1. Data availability for electricity load time series with hourly resolution.



Source: JRC analysis

For 35 European countries, electricity load time series were downloaded from the ENTSO-E Transparency Platform [5]. The quality and consistency of these load times series made available by ENTSO-E is very high.
Hourly load data for the remaining 28 countries was collected for each country in a different way. For most countries the raw data was retrieved from dedicated websites by manual download or using automatized web data scraping techniques. For some countries hourly load was received after requesting national organisations (e.g. Mexico, Saudi Arabia). Depending on the country, the raw data was either available at country level or for sub-regions of the country. Sources for each country are provided in Table 1.

In order to obtain a consistent data quality across all countries the following data processing steps were applied - if applicable. The first step refers to data refining at the lowest geographical granularity. The data refining applied procedures for the detection and correction of outliers and subsequent interpolation of missing data. Finally, in the case of multi-annual load data an annual trend correction was applied.

If sub-regions of a country referred to different time zones (e.g. Canada, USA), a reference time zone was defined and the time series of the sub-regions were converted to the time in the reference time zone. The reference time zone is provided in Table 1 in the column 'Time zone, relative to UTZ in h'.
In case of sub-regions, the hourly time series by sub-regions was summed-up to the countries' total and the procedures of the refining step were applied in order to obtain the final time series of the electricity load for the respective country.
Table 1 reveals country specific details regarding the geographic scope the times series refer to (e.g. sub-regions) and the data preparation procedure (see column 'Comment' and footnotes).

Some of the regions listed at the very end of Table 1 refer to multi-country regions[1]. These multi-country regions refer to the classification of regions in the POLES model. In the case of NOAN and NOAP these refer to aggregates of the countries Tunisia & Morocco and Algeria & Libya, respectively. RCEU represents an aggregate for the Western Balkan countries (Bosnia and Herzegovina, Republic of Serbia, Montenegro, Republic of North Macedonia).
A proxy country representing the entire multi-country region is used in the remainder of cases (proxy country: i.e. Costa Rica, Colombia, Côte d'Ivoire, Pakistan, Philippines). In the map above (Figure 1) the proxy country (cyan colour) are depicted within their respective multi-country regions (brownish-green colour).

This collection of 63 countries cover the most important countries with the notable exception of China. Data for the missing countries was either not published or upon request to institutions of the respective country not made available.
To sum up, this collection covers hourly load data of at least one year and up to 10 years, for 63 countries. These countries represent about 75% of global GDP. Therefore, the collection can be regarded sufficiently representative for the diversity of the global power systems.

[1] NOAN, NOAP, RCEU, RCAM, RSAM, RSAF. RSAS, RSEA.

Table 1. Overview of hourly electricity load time series by region and the data availability by year.

Region Acronym	Name of Region	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	10 Years Period	Time zone, relative to UTZ in h	Comment	Source
ARG	Argentina											X						-3	Preparation[2]	[6]
AUS	Australia	X	X	X	X	X	X	X	X	X	X	X					yes	10	Scope[3]	[7]
AUT	Austria			X	X	X	X	X	X	X	X		X	X	X	X	yes	1		[5]
BEL	Belgium			X	X	X	X	X	X	X	X		X	X	X	X	yes	1		[5]
BGR	Bulgaria			X	X	X	X	X	X	X	X		X	X	X	X	yes	2		[5]
BRA	Brazil							X	X	X	X	X	X	X	X			-3	Scope[4]	[8]
CAN	Canada								X	X	X	X	X	X				-5	Scope[5]	[9–12]
CHE	Switzerland				X	X	X	X	X	X	X							1		[5]
CHL	Chile			X	X	X	X	X	X	X	X	X	X				yes	-4	Scope[6]	[13]
CYP	Cyprus										X				X	X		2		[5]
CZE	Czech					X	X	X	X	X	X		X	X	X	X	yes	1		[5]

[2] Preparation: Assembled from typical daily profiles (weekday, Saturday, Sunday) per month of total grid.
[3] Scope: Sum of 4 subzones: New South Wales, Queensland, South Australia, Victoria and Tasmania.
[4] Scope: Sum of 4 subzones: Sul, Sudeste, Centro-Oeste/Nordeste and Norte.
[5] Scope: Load for Canada refers to the sum of the load for the grid zones of BC Hydro, AESO, IESO and NB Power; shifting load data by zone to Eastern Standard Time (-5 h) applies.
[6] Scope: The Sistema Interconectado Central (SIC) covers about 70% of electricity production in Chile. The hourly data refers to generation.

Region Acronym	Name of Region	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	10 Years Period	Time zone, relative to UTZ in h	Comment	Source
	Republic																			
DEU	Germany					X	X	X	X	X	X		X	X	X	X	yes	1		[5]
DNK	Denmark					X	X	X	X	X	X		X	X	X	X	yes	1		[5]
EGY	Egypt							X										2		
ESP	Spain					X	X	X	X	X	X		X	X	X	X	yes	1		[5]
EST	Estonia						X	X	X	X	X	X	X	X	X	X	yes	2		[5]
FIN	Finland							X	X	X	X	X	X	X	X	X		2		[5]
FRA	France					X	X	X	X	X	X		X	X	X	X	yes	1		[5]
GBR	Great Britain						X		X	X	X	X	X	X				0		[5]
GRC	Greece					X	X	X	X	X	X		X	X	X	X	yes	2		[5]
HRV	Croatia					X	X	X	X	X	X		X	X	X	X	yes	1		[5]
HUN	Hungary							X	X	X	X		X	X	X	X		1		[5]
IDN	Indonesia					X	X	X	X	X	X	X	X	X				8		[14]

Region Acronym	Name of Region	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	10 Years Period	Time zone, relative to UTZ in h	Comment	Source
IND	India								X	X	X	X	X	X				5.5	Scope[7]	[15]
IRL	Ireland					X	X	X	X	X	X		X	X	X	X	yes	0		[5]
IRN	Iran									p[8]	X	X	X	p8				+3.5	Period[9]	[16]
ISL	Iceland							X	X	X	X							0		[5]
ITA	Italy			X	X	X	X	X	X	X	X	X	X	X	X	X	yes	+1		[5]
JPN	Japan					X	X	X	X	X	X	X	X		X	X	yes	+9		[17]
KOR	South Korea													X				+9		[18]
LTU	Lithuania							X	X	X	X			X	X	X		+2		[5]
LUX	Luxembourg			X	X	X	X	X	X	X	X		X	X	X	X	yes	+1		[5]
LVA	Latvia							X	X	X	X		X	X	X	X		+2		[5]
MEX	Mexico												X					-6	Period[10]	[19]
MYS	Malaysia										X	X	X					+8	Preparation[11]	[20]

[7] Scope: Only data of the Northern Regional Load Dispatch Centre was used. Data for the Western, Eastern and Southern was also available, but not used as the data quality seemed not appropriate.
[8] p: partial.
[9] Period from March 2012 to March 2016.
[10] Period from May 2015 to April 2016
[11] Preparation: The hourly data refers to generation and interconnection flow.

Region Acronym	Name of Region	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	10 Years Period	Time zone, relative to UTZ in h	Comment	Source
NLD	The Netherlands			X	X	X	X	X	X	X	X		X	X	X	X	yes	+1		[5]
NOR	Norway							X	X	X	X	X	X	X	X	X		+1		[5]
NZL	New Zealand	X	X	X	X	X	X	X	X	X	X	X					yes	+12	Preparation[12]	[21]
POL	Poland			X	X	X	X	X	X	X	X	X	X	X	X	X	yes	+1		[5]
PRT	Portugal			X	X	X	X	X	X	X	X		X	X	X	X	yes	0		[5]
ROU	Romania			X	X	X	X	X	X	X	X			X	X	X	yes	+2		[5]
RUS	Russia										X	X	X					+3	Scope[13]	[22]
SAU	Saudi Arabia										X							+3	Scope[14]	[23]
SVK	Slovakia			X	X	X	X	X	X	X	X	X	X	X	X	X	yes	+1		[5]
SVN	Slovenia			X	X	X	X	X	X	X	X	X	X	X	X	X	yes	+1		[5]
SWE	Sweden							X	X	X	X	X	X	X	X	X		+1		[5]
TUR	Turkey											X	X					+2		[24]

[12] Preparation: The hourly data refers to the sum of unit-level generation.
[13] Scope: Sum of 2 subzones: Europe & Urals and Siberia
[14] Scope: Sum of eastern region, central region, western region and southern region.

Region Acronym	Name of Region	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	10 Years Period	Time zone, relative to UTZ in h	Comment	Source
UKR	Ukraine			X	X	X	X	X	X	X	X							+2	Scope[15]	[5]
USA	USA			X	X	X	X	X	X	X	X	X	X	X			yes	-5	Preparation[16]	[25]
ZAF	South Africa							X										+2		
NOAN	Tunisia & Morocco							X										0	Scope[17]	
NOAP	Algeria & Libya							X										+1	Scope[18]	
RCAM	Multi-country region of Central America and Caribbean[19]											X						-6	Scope[20]	

[15] Scope: Western grid zone of Ukraine.
[16] Preparation: Load data time series for the balancing areas (about 240) were shifted to coincide with Eastern Standard Time and subsequently summed at US level.
[17] Scope: Hourly load for Republic of Tunisia and Kingdom of Morocco for 2010.
[18] Scope: Hourly load for Democratic Republic of Algeria and State of Libya for 2010.
[19] Multi-country region of Central America and Caribbean: Bahamas, Barbados, Belize, Bermuda, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Grenada, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, NL Antilles and Aruba, Panama, São Tomé and Príncipe, St Lucia, St Vincent and Grenadines, Trinidad and Tobago.
[20] Scope: Hourly load for Republic of Costa Rica as proxy country for the multi-country region Rest of Central America and Caribbean.

Region Acronym	Name of Region	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	10 Years Period	Time zone, relative to UTZ in h	Comment	Source
RCEU	Multi-country region Balkans[21]			X	X	X	X	X	X	X	X	X		X	X		yes	+1	Scope[22]	
RSAF	Multi-country region of Sub-Saharan Africa[23]					X												0	Scope[24]	
RSAM	Multi-country region of South America[25]											X						-5	Scope	[26]
RSAS	Multi-country region of South Asia[26]					X	X	X										+5	Scope[27]	[27]

[21] Multi-country region Balkans: Albania, Bosnia and Herzegovina, Republic of North Macedonia, Kosovo, Moldova, Montenegro, Serbia.

[22] Scope: Aggregate of Bosnia and Herzegovina, Republic of Serbia, Montenegro, Republic of North Macedonia.

[23] Multi-country region of Sub-Saharan Africa (RSAF): Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Democratic Republic of the Congo, Côte d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia. Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe.

[24] Scope: Hourly load for Republic of Côte d'Ivoire (2008) as proxy country for the multi-country region of Sub-Saharan Africa (RSAF).

[25] Multi-country region South America: Bolivia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay.

[26] Multi-country region of South Asia: Afghanistan, Bangladesh, Bhutan, Maldives, Nepal, Pakistan, Seychelles, Sri Lanka.

[27] Scope: Hourly load for Republic of Pakistan as proxy country for the multi-country region Rest South Asia (RSAS).

Region Acronym	Name of Region	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	10 Years Period	Time zone, relative to UTZ in h	Comment	Source
RSEA	Multi-country region of South-East Asia[28]													X				+8	Scope[29]	[28]

Source: JRC analysis

[28] Multi-country region of South-East Asia: Brunei, Cambodia, Laos, Myanmar/Burma, North Korea, Philippines, Singapore, Taiwan
[29] Scope: Hourly load for Republic of the Philippines as proxy country for the multi-country region Rest South East Asia (RSEA).

2.1.2 USA – eGrid sub-regions

This report also provides electricity load time series for US eGRID sub-regions. The US Environmental Protection Agency uses eGRID sub-regions (Emissions & Generation Resource Integrated Database) for monitoring and analysis of the electricity sector [29,30]. The area covered by an eGRID sub-region corresponds to about the size of one large or several smaller US States.
Hourly load data for the USA is available by balancing areas (BA) [25,31]. Most of the BA's extension is much smaller than the eGRID sub-regions. Load data by eGRID sub-regions was aggregated based on the BAs within their perimeter as defined by their shapefiles [31,32]. The aggregation process applied the processing steps applied in the previous section including a conversion of the time zones of the BAs to Eastern Standard Time.
This report makes available electricity load for 21 eGRID sub-region for at least 3 years and up to 10 years (see Table 2) [33].

Table 2. Overview of hourly electricity load time series by US eGRID sub-regions[30].

Sub-region	**Name of sub-region**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
AZNM	Western Electricity CC[31] - Southwest	X	X	X	X	X	X	X	X	X	X	X
CAMX	Western Electricity CC[31] (WECC) California	X	X	X	X	X	X	X	X	X	X	X
ERCT	Electric Reliability Council of Texas	X	X	X	X	X	X	X	X	X	X	X
FRCC	Florida Reliability CC[31]	X	X	X	X	X	X	X	X	X	X	X
HIOA	Hawaii Power Grid	X	X	X	X	X	X	X	X	X	X	X
MROE	Midwest Reliability Organization - East	X	X	X								
MROW	Midwest Reliability Organization - West	X	X	X	X	X	X	X	X	X	X	X
NEWE	Northeast Power CC - New England	X	X	X	X	X	X	X	X	X	X	X
NWPP	Western Electricity CC[31] - Northwest	X	X	X	X	X	X	X	X	X	X	X
NYCW	Northeast Power CC[31] - NYC/Westchester	X	X	X	X	X						
NYUP	Northeast Power CC[31] - Upstate NY	X	X	X	X	X	X	X	X	X	X	X
RFCM	Reliability First Corporation - Michigan	X	X	X	X	X	X	X	X	X	X	X
RFCW	Reliability First Corporation - West	X	X	X	X	X	X	X	X	X	X	X
RMPA	Western Electricity CC[31] - Rockies	X	X	X	X	X	X	X	X	X	X	X
SPNO	Southwest Power Pool - North	X	X	X	X	X	X	X	X			
SPSO	Southwest Power Pool - South	X	X	X	X	X	X	X	X	X	X	X
SRMV	SERC[32] - Mississippi Valley	X	X	X	X	X	X	X	X			
SRMW	SERC[32] - Midwest	X	X	X	X	X	X	X	X	X	X	X
SRSO	SERC[32] - South	X	X	X	X	X	X	X	X	X	X	X
SRTV	SERC[32] - Tennessee Valley	X	X	X	X	X	X	X	X	X	X	X
SRVC	SERC[32] - Virginia/Carolina	X	X	X	X	X	X	X	X	X	X	X

Source: JRC analysis

[30] Available years of the time series marked by crosses.
[31] CC: Coordinating Council
[32] SERC: State Electricity Regulatory Commission

2.2 Wind and solar power generation

Hourly time series for power generation from wind and solar were calculated based on satellite data. The calculations are based on global wind speed and solar irradiation data from the reanalysis project MERRA-2 of satellite data [34–36]. MERRA-2 provides global gridded data with a spatial resolution of 0.5° x 0.625° and hourly time resolution. The hourly time series for solar and onshore wind generation were derived by applying calculations at grid cell level as described in the following. As a result time series for wind and solar power with a global coverage comprising 50 countries and 10 multi-country regions for period 2004 to 2018 are obtained.

2.2.1 Spatial distribution of generators

Locations have an immense effect on the hourly profile of the renewable generation as profiles for solar and wind generation can vary tremendously within a region. With increasing renewable share this effect will have a high impact on the electricity system. Some models simulate the optimal placement of generators by taking into account a range of criteria for the decision making [33,37]. Optimizing locations of generators at local or regional scale is still a challenging modelling task, as these publications point out. Simulating the appropriate placement of generators at global level and for the next decades is an even more complex and challenging task. Challenges arise due to a range of factors and uncertainties such as (i) availability of locations and competition with other uses, (ii) changes of energy policy and regulations, (iii) future grid extension and (iv) development of technology characteristics.

This work does not attempt to simulate locations for wind and solar generators. Instead this work uses five different stylised cases for global geospatial distributions of capacities:

- Current capacity distribution ('solCap' and 'winCap');
- Distribution by population density ('solPop' and 'winPop');
- Distribution by renewable potential ('solPot' and 'winPot');
- Even distribution by area ('solArea' and 'winArea')
- A so-called base-case spatial distribution ('solBC' and 'winBC') aims to take into account (i) existing capacities, (ii) renewable potentials and (iii) a proxy for grid availability.

The base-case distribution is supposed to describe a plausible future distribution of future renewable capacities based on the continuing development of the *current capacity distribution*. The distribution by renewable potential and the even distribution refer to extreme cases. These extreme distributions have been set up in order to test sensitivities. All spatial distributions are normalised from 0 to 1 in order to compare them. The spatial resolution for the capacity distributions was the same as for the MERRA-2 data.

Figure 2. World maps of spatial distributions of wind and solar capacities.

Figure 2.winBC. Base-case distribution of wind capacities.

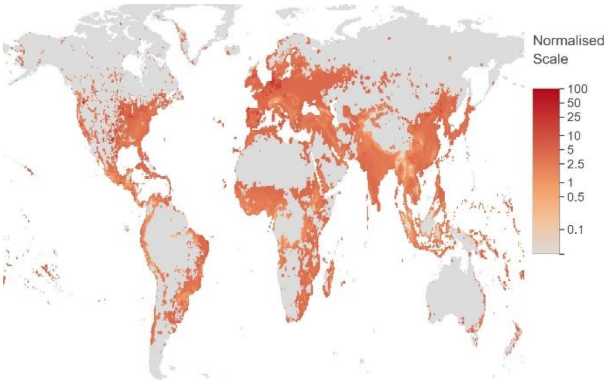


Figure 2.solBC. Base-case distribution of solar capacities.

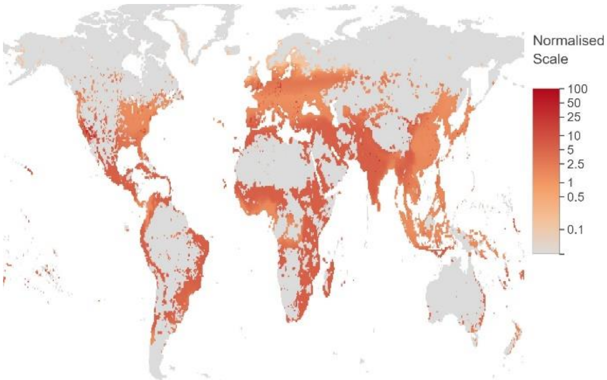


Figure 2.winCap. Current wind capacities.

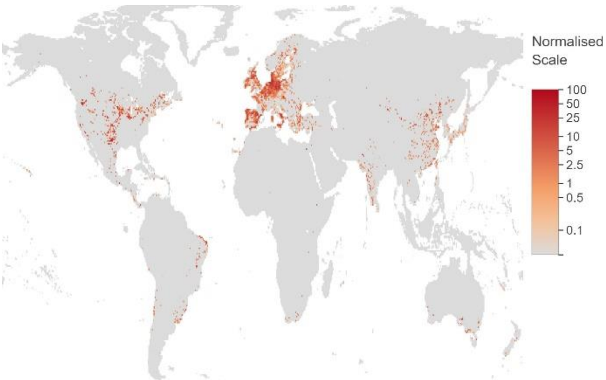


Figure 2.solCap. Current solar capacities.

Figure 2.winPot. Wind power potential based on 10years mean of the cube of wind speed.

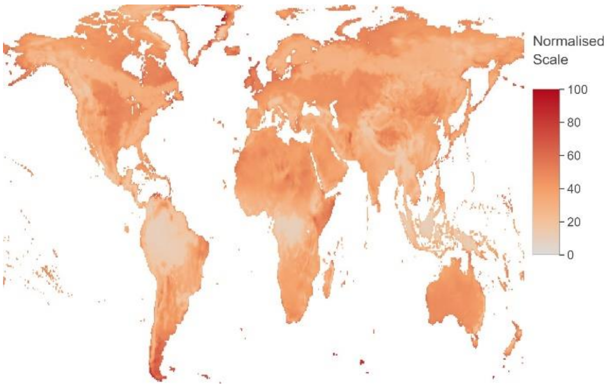


Figure 2.solPot. Solar power potential based on 10 years mean of irradiance.

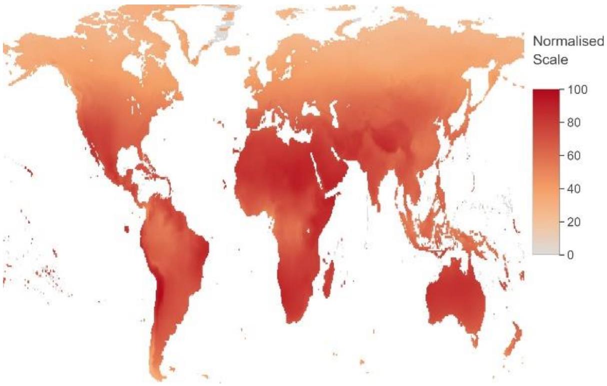


Figure 2.Pop. Population density.

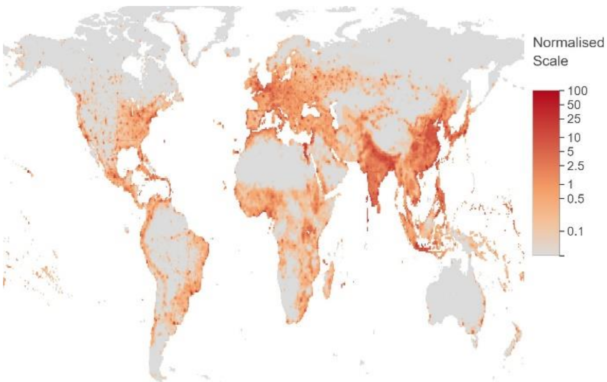
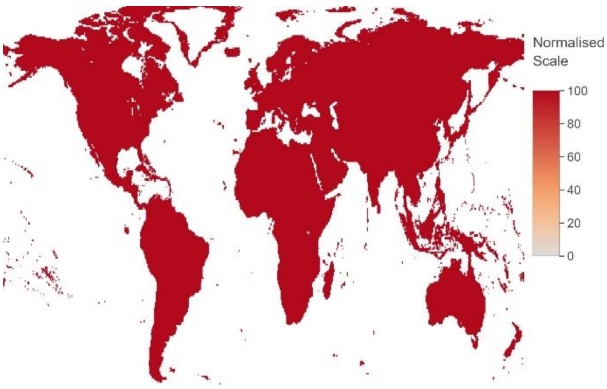


Figure 2.Area. Even distribution by area.



Source: JRC analysis

2.2.2 Wind power time series

Hourly wind power time series were calculated from wind speed data obtained from the global satellite data of MERRA-2. At grid cell level wind speed at 50 m altitude v_{50} was calculated from MERRA-2 data from wind speeds in eastward and northward direction (variables *U50M* and *V50M* in MERRA-2) [35]. For the following calculations a hub height of 100 m for the wind generator is assumed. The wind speed v_{50} was converted to the wind speed at 100 m altitude v_{100} according to the Hellman correction $v_{100} = v_{50}\left(\frac{100}{50}\right)^{0.27}$ [38]. A sensitivity analysis on the generator characteristics indicated that the reproduction of historical time series is not significantly impacted by the coefficients used. According to the generator characteristics chosen, the power generated (i) increases by the cube of wind speed in the range from a cut-in speed of 3.5 m/s and a rated wind speed of 14 m/s; (ii) is constant with rated power in the range from the rated wind speed and the cut-out speed of 25 m/s; and (iii) is zero for wind speeds smaller than the cut-in speed or higher than the cut-out speed. In order to obtain hourly time series by region, the hourly wind power at grid-cell level is weighted with normalised wind capacities at grid cell level. The obtained time series by region are proportional to wind power generated.

This study calculates wind power time series for five different spatial distributions of wind capacities (Figure 2): The first variation refers to the current distribution of wind capacities (see Figure 1.winCap) obtained by aggregating installed wind power at grid cell level according to 'The Wind Power' database [69]. The second variation refers to the potential of wind power (see Figure 2.winPot) calculated from the cube wind speed at 50 m, $(v_{50})^3$, averaged over a period of 10 years (2008-2017). The third variation refers to population density (see Figure 2.Pop). The fourth variation refers to wind capacities equally distributed by area (see Figure 2.Area).

The base-case spatial distribution for wind capacities (5th variation, Figure 2.winBC) aims to take into account (i) existing capacities, (ii) wind potentials and (iii) a proxy for grid availability. It was constructed as follows: first, a relation between mean wind speed and existing capacities at grid cell level was established in order to reproduce past installations and mimic future expansion according to potential. This also accounts for wind capacities where no historical capacities existed yet (e.g. large parts of Africa). In a second step, these wind capacities were only taken into account for grid cells with a population density higher than 10 persons/km2, as a proxy for grid availability.

2.2.3 Solar power time series

Hourly solar power time series were calculated from global irradiance MERRA-2. Irradiance (W/m2) at grid cell level was obtained from global horizontal irradiance at the surface (variable SWGDN data in MERRA-2) [34]. In order to obtain hourly time series by region, it is weighted at grid-cell level with solar capacities. The obtained solar time series by region are proportional to solar power generated.

Analogously to above, solar power time series are calculated for five different spatial distributions of solar capacities (Figure 2).

The first variation takes into account the current distribution of solar capacities (Figure 2.solCap). The current distribution was obtained by aggregating installed solar power at grid-cell level according to the 'World Electric Power Plant' database of Platts [39]. The second variation refers to the potential of solar power (see Figure 2.solPot) calculated from mean solar irradiance over a period of 10 years (2008-2017). The third variation and fourth variation refer to population density (see Figure 2.Pop) and even distribution by area (see Figure 2.Area). Finally, the base-case spatial distribution for solar capacities (Figure 2.solBC.) was obtained with the analogous method to the case of wind.

2.2.4 Time zone conversion

The original hourly MERRA-2 data refers to the Universal Time Zone (UTZ). However, the electricity load time series refer to local time in the respective country or multi-country region.

In order to coincide with the load data, the wind and solar power time series were shifted by the time difference between UTZ and local time as given in Table 1 (see column 'Time zone, relative to UTZ in h'). As a result, the presented time series for electricity load as well as wind and solar power refer to the reference time zone of the respective country or multi-country region as provided in Table 1.

2.3 Interactive data viewer for time series

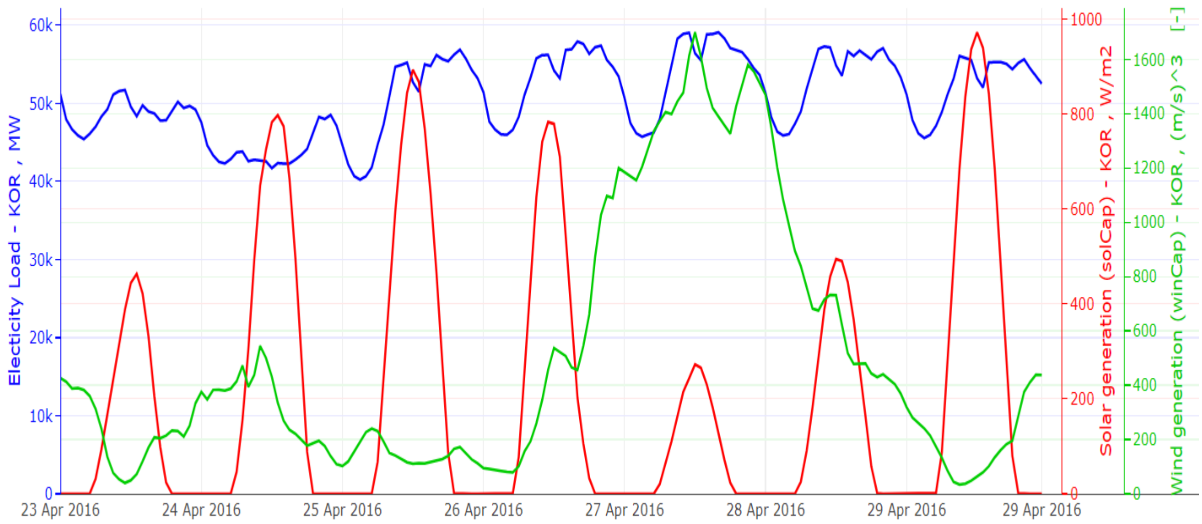
An interactive website makes available the above described hourly times series for electricity load as well as for wind and solar power. Time series for 50 countries, 10 multi-country regions and 21 US eGrid zones are made available with this data viewer (see Table 1 and Table 2):

- Electricity load for these regions is available for at least one year and up to 10 years (for concrete periods see the Table 1 and Table 2 or compare within the Annex of the interactive viewer).
- Wind and solar time series for these regions are available for 2004 to 2018. For each region wind and solar time series are available for the five spatial distributions of wind and solar capacities, respectively. The presented wind and solar time series are proportional to wind and solar power generated, though they are provided in terms of cubic wind speed and irradiance, respectively.

The data viewer can be accessed at https://web.jrc.ec.europa.eu/rapps/pub/TimeSeries_LoadWindSolar. The data viewer allows to depict (see Figure 3) up to 6 time series for an adjustable period of time. Multiple selections and combinations of time series across type (load, wind and solar) and regions can be viewed. The underlying data of the time series is available upon request.

Electricity load for ENTSO-E countries [5] is not shown in the interactive viewer due to intellectual property and copyright considerations; though wind and solar time series can be visualised for these countries.

Figure 3. Interactive tool showing time series of load, wind and solar for Korea for a week in April 2016.



Source: JRC analysis

2.4 Data quality and caveats

An outstanding characteristics of this work is that it provides time coherent data sets of time series for electricity load and the generation from wind and solar at global scale. For wind and solar for each region all years in the period 2004 to 2018 are available, whereas for electricity load the time periods covered is for many regions merely one year. As a consequence, the availability of time coherent data sets (load, wind and solar) is determined by the availability of electricity load time series. For each region at least one year and up to 12 years of time coherent data sets is available as can be seen from Table 1.

The wind and solar power time series are based on gridded data (based on satellites and reanalysis models), which differs from actual measured data in meteorological stations [40,41]. However, these physical stations are unevenly distributed across the globe and are too scarce in some regions like Africa. Therefore, in order to obtain global time series based on homogenous spatial resolution, the gridded data from NASA satellites and model reanalysis was the preferred choice.

Regarding solar power, a drawback is that the irradiance data provided the MERRA-2 reanalysis data overestimates in cloudy conditions the actual irradiance at the location of the solar power plant [40–42]. As a result the solar time series tend to underestimate the solar power variability.

For solar and wind power in Europe the EMHIRES datasets [43,44] provide substantially more refined time series compared to this work. The EMHIRES dataset are substantially more refined as they were calculated based on a higher geographic resolution by applying a sophisticated downscaling methodology. Additionally, for each location specific power curves were used to calculate the generation time series.
In comparison, this work applies merely one standard generator characteristics for all the grid cells (see sections 2.2.2 and 2.2.3). In other aspects this work goes well beyond the scope of EMHIRES. Above all, this work provides regional time series at global scale. Moreover, this work provides time series for 5 variants of spatial distribution in order to analyse the sensitivity of different spatial distributions, with the perspective of long-term energy modeling. On the other hand, the EMHIRES datasets merely refer to current capacity distributions for Europe similar to global variant of the current distributions used in this work (Figure 2.winCap and Figure 2.solCap).

The calculated solar & wind time series are based on meteorological observations (2004 to 2018) and do not consider future changes due to climate changes. These changes might impact the representative daily profiles for more distant scenario years with very high shares of wind and solar generation (see AN-Table 1).
Moreover, the used load time series merely refer to historical data and do not consider changes of the load curves due to transformations of load patterns (e.g. electric vehicles).

Regarding electricity load, the underlying raw data was in some cases incomplete, especially for multi-country regions. Consequently, the raw data quality is in some cases not sufficient and some assumptions were necessary to reconstruct the missing voids. Moreover, countries were assumed to have a copper-plate electric grid, thus allowing a simple sum of their sub-regions and grid zones, even when the country is composed of several time-zones.

3 Representative daily profiles

3.1 Representative daily profiles for energy system models

Coping with temporal variability of electricity load and generation is crucial for modelling power systems adequately. Load varies throughout the day and season due to changing demand patterns. The power generation from wind and solar varies dependent on meteorological conditions, resulting in spatial and temporal variability on time scales from seasonal to hourly. Moreover, the relevance of variability for wind and solar power will substantially increase as their capacities are expected to strongly develop throughout the world, especially in decarbonisation scenarios [45,46].

Particularly, for long-term energy model with global scope, the complexity of temporal variability is challenging for modelling power systems adequately. Taking into account all 8760 h within a year over several decades requires huge computation resources, which are limited.

Therefore, there is a need for reducing the complexity of temporal variability which can be achieved by Time-Series Aggregation (TSA) methods. TSA methods were systematically categorized in a recent review by Hoffmann et al. [47] analysing more than 100 different publications. This analysis concludes that the state-of-the art TSA methods are aggregation based on the time steps' and periods' values making use of information inherent to the time series. These feature-based TSAs include clustering and other machine learning techniques.

This work applies clustering methods in order to obtain a number of representative daily profiles. Because energy or power sector models have to combine electricity load with non-dispatchable production (i.e. zero marginal cost), mainly from wind and solar generation, the choice here is to jointly cluster electricity load, wind and solar. This method retains the simultaneity between load, wind and solar conditions. It also allows computing the *net load* (i.e. electricity load minus generation from wind and solar) based on the constantly evolving share of wind and solar in the system (along hours as well as years). Based on the net load, other power generating technologies, with above-zero marginal costs, are dispatched. Therefore, net load is a crucial quantity for power system models.

The evident daily patterns of load and solar justify the choice of days instead of individual hours or whole weeks. The within-cluster similarity is higher when using days, while achieving a good model performance [48].

The obtained representative daily profiles allow reducing the complexity of the variable time series, but preserving their main characteristics. This allows modeling power systems for a long-term energy scenario model such as POLES-JRC with acceptable computation effort.

3.2 Data preparation

In a first step, some data treatment is applied to the times series before the clustering calculations are carried out. The electricity load time series of a region were normalised to the annual electricity generation from the year 2010 according to the Global Energy and Climate Outlook 2018 [3,4].

In the case of wind and solar, the times series presented in chapter 2 are proportional to the generation from wind and power, but expressed in cube wind speed and solar irradiance, respectively.

In order to obtain power generation from wind and solar, these time series were normalised to their annual generation expressed by the share of wind and solar power in the total annual electricity[33]. Wind and solar shares refer to the 2°C scenario of Global Energy and Climate Outlook 2018 [3,4] for each of the POLES regions (see AN-Table 1). As a result, power generation time series for wind and solar are obtained for the years 2010 to 2050 in 10 years time steps and for 2100.

3.3 Clustering methods

This work studies five different methods (C1 to C5) of clustering for obtaining representative daily profiles. These methods are variants of two common clustering algorithms: (i) agglomerative hierarchical clustering using the Ward algorithm and (ii) K-means clustering.

- **Method C1**
  The first method refers to the clustering approach introduced by Nahmmacher et al. [49]. This method applies hierarchical clustering to normalised time series.

[33] Total annual electricity generation refers to the year 2010 according to the Global Energy and Climate Outlook 2018 [3,4]

In a first step, simultaneous hourly time series of load, solar and wind (comprising at least a period of one year) are selected (see Table 1). In a second step, each of the time series is normalised by their highest value. Subsequently, a dataset consisting of days and its 72 daily components (24 h of load, 24 h of wind and 24 h of solar) is formed by merging and reshaping of the hourly times series. Finally, hierarchical clustering is applied to this dataset in order to obtain a number of representative daily profiles.

- **Method C2**
  The second method also uses hierarchical clustering, although applied to time series weighted by the shares of wind and solar generation relative to annual total electricity demand. This allows to study how the increasing expansion of wind and solar affects the representative daily profiles.

- **Method C3**
  The third method applies K-means clustering on normalised time series. The normalised time series are obtained following the procedure described for Method C1.

- **Method C4**
  The fourth method is a K-means clustering with time series weighted according to the wind and solar shares of the electricity load. The clustering is applied to the same time series used for Method C2.

- **Method C5**
  The fifth method refers to a K-means clustering with weighted time series in two steps: A first algorithm (C4) with a high number of clusters (for example up to 100) identifies the cluster representative of the peak net load (a *priori* method). In a second step, all the data not contained in this 'extreme' cluster is treated again with the weighted K-means clustering (C4). The objective is to combine clustering with some heuristics choosing a day of high net load. Indeed, pure clustering techniques do not capture well the outliers, despite being crucial for dimensioning power systems. This technique is aimed at giving a better indicator of the capacity adequacy.
  This technique does not aim to select the day with highest net load because it is very dependent on the duration of the available time series and their inter-annual variability. The advantage of computing a 'cluster of peak days' is that its representative element is more robust regarding the input data.

<u>Discussion:</u>
The presented clustering methods for obtaining representative daily profiles are inspired by the work of by Nahmmacher et al. [49]. While Nahmmacher (Method C1) uses a normalization of all datasets to their maximal value, arguing that it makes them comparable, we think that this imposes a fixed penetration of wind and solar with respect to the load. The clustering will not perform as well in a system with 20% of the load covered by wind and 80% by solar, than in a 1% wind and 1% solar system. In the first case, the adequate choice of representative days will be focused on wind and solar variability since their role is major, while in the latter case, the load is the primary driver of the net load variability, so its variability will prevail and lead to a very different choice of days. To adapt to the evolving situation in a long-term energy model, we compute the clustering algorithm with different weightings of load, wind and solar, corresponding to different penetrations of wind and solar in the electricity load (Method C2 and C4).

Hierarchical clustering seeks to build a hierarchy of clusters, i.e. tree-type structure based on the hierarchy. Using a specified number of representative days per region is a custom choice for an electricity model for multiple regions. Consequently, this custom requires flattening the actual hierarchical clusters to obtain the specified number of representative days. Method C1 and C2 apply such a flattening algorithm to obtain a specified number of representative days. The very purpose of K-means clustering is to partition data into a pre-specified number k of clusters. Thus, one could argue that determining a specified number of representative days K-means clustering might be more appropriate compared to Nahmmacher's hierarchical clustering benchmark (Method C1).

Method C5 aims to capture a snapshot of the peak net load. It captures an extreme situation with high electricity demand combined with low wind & solar generation. In such a situation, sufficient dispatchable capacities have to be available.
The dispatchable capacities required - potentially increased by a security factor - is crucial for modelling the capacity planning of the electricity system to match supply and demand at any time of the year.

Moreover, the snapshot provides information about the duration of this extreme situation. Based on the duration, the capacity planning might be better decide between investments in power generating capacities or storage capacities.

3.4 Interactive data viewer for representative daily profiles

The five above-described clustering methods were applied to

- 47 countries and 8 multi-country regions;
- wind and solar time series according to the shares of the years 2010, 2020, 2030, 2040, 2050 and 2100;
- The spatial distributions of wind and solar generators are used as described in section 2.2.1. As a result, for each of the wind and solar shares five different combinations of spatial distributions are available;
- Up to a number of 20 representative daily profiles.

The resulting representative daily profiles for this wealth of combinations can be visualised using an interactive data viewer at https://web.jrc.ec.europa.eu/rapps/pub/DailyProfiles_LDC.

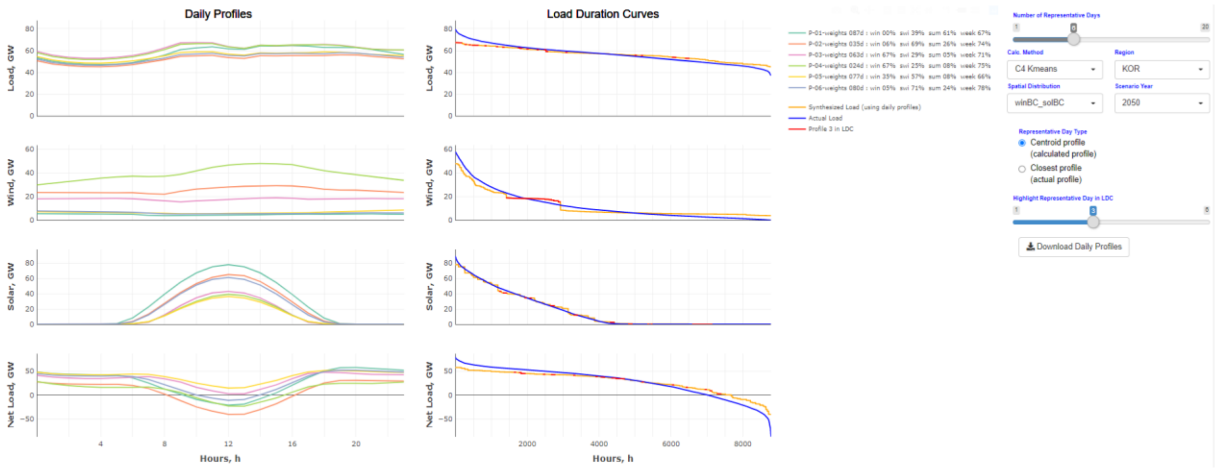
An illustrative example of interactive tool is depicted in Figure 4 for Korea. In the viewer, the right section allows to select the number of representative daily profiles, region, calculation method, combination of spatial distribution and scenario year. The depicted example in Figure 4 shows for the case of Korea 6 representative profiles for the (i) wind and solar shares for the scenario year 2050, (ii) the base case spatial capacity distribution ('winBC_solBC') and the (ii) Kmeans clustering calculations ('C4 Kmeans'). The red sections in the LDC highlight the daily profile number 3.

The left column of the graphs shows the representative daily profiles for the electricity load, power generation from wind and solar as well as the net load. The legend shows the seasonal representation in percentage of each daily profile for winter ('win'), summer ('sum') and the swing season ('swi')[34]. The legend also shows the percentage of workdays ('week') represented by daily profile. According to the selection the daily profile shown could refer to the centroid of the cluster or the closest actual day to that centroid. Moreover, the tool offers the option to download the selected representative daily profiles.

The central column shows graphs for load duration curves (LDC). The LDC results from the data of power related time series ordered from highest to lowest value. The LDC graphs show the actual LDC (from actual time series) and the synthesized LDC made up from the representative daily profiles. The difference between both curves can be interpreted as measure of how well the representative daily profiles correspond to the actual data. With increasing number of representative daily profiles the correspondence to the actual LDC improves.
The Annex of the interactive viewer provides a table listing, by regions, the periods used for the clustering calculations. The time periods covered by the time series used for the clustering calculations, depend on the simultaneous availability of data for electricity load, solar and wind. Therefore, the periods covered vary by region. In general, this work aimed to use the longest possible time period.

[34] The term *swing season* refers to the transition seasons between summer and winter. For countries in the Northern and Southern Hemisphere, we refer to swing season as the months March to May *and* September to November. Differing from this specification, for countries close to the equator, we qualify each month as swing season. The latter applies to Brazil, Egypt, South Africa, India, Indonesia, Malaysia, Saudi Arabia and the multi-country regions NOAN (Tunisia & Morocco), NOAP (Algeria & Libya), RCAM (Costa Rica), RGLF, RPAC, RSAM (Colombia), RSAF and RSEA.

Figure 4. Illustrative view of the interactive tool for Korea.



Source: JRC

4 Conclusions

This work presents a global collection of temporal data with hourly resolution for electricity load and power generation from wind and solar. The global collection covers about 60 countries and multi-country regions. The temporal data consists of time series with a period of at least one year and representative daily profiles.

This data is very valuable for analysing dynamic aspects of power systems due to its hourly resolution. In particular, this global collection of temporal data is useful for power systems modelling. The interactive data viewers allow exploring the wealth of temporal data by visualising time series, representative daily profiles and load duration curves. The collected time series can be made available upon request to the authors. Representative daily profiles are directly downloadable.

This work was carried out in the wider objective of enhancing the power system modelling of the global energy system model POLES-JRC. These enhancements referred mainly to dynamic modelling aspects of the power system such as the operation and expansion of wind and solar capacities, long-term development of sectoral load profiles and storage aspects. Representative daily profiles are used to take into account these dynamic aspects. The approach of using representative daily profiles reduced the computation requirements considerably. As a result, POLES-JRC is able to simulate the power system model for 66 countries and multi-country regions over a time horizon until 2100 in a reasonable computation time.

Results of the global energy scenario POLES-JRC model were used to provide representative daily profiles according to the 2°C scenario of Global Energy and Climate Outlook 2018 [3,4]. The scenario data took into account the shares of wind and solar power in the electricity generation of 47 countries and 8 multi-country regions for scenarios years 2010 to 2100.
Representative daily profiles for electricity load, power generation from wind and solar as well as net load for scenarios years up to 2100 allow studying how the envisaged huge expansion of non-dispatchable renewable energy affects the hourly profiles in the power system. Therefore, further analysis based on the provided representative daily profiles could bring important insights on the future power system for energy system modellers and policy makers.

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List of abbreviations and definitions

DSM	Demand Side Management
ENTSO-E	European Network of Transmission System Operators for Electricity
GECO	Global Energy and Climate Outlook
GHG	Greenhouse Gas
LDC	Load Duration Curve
UTZ	Universal Time Zone

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Annexes

Annex 1. Shares of wind and solar generation

The shares of wind and solar generation in the electricity system of 58 countries and multi-country regions from 2010 to 2050 used in this work refer to the 2°C scenario of the Global Energy and Climate Outlook 2018 [3,4].

AN-Table 1. Shares of wind and solar generation.

	2010		2020		2030		2040		2050		2100	
POLES region	Wind	Solar	Wind	Solar	Wind	Solar	Wind	Solar	Wind	Solar	Wind	Solar
CAN	1.5%	0.0%	7.4%	0.4%	17.6%	0.4%	27.4%	0.5%	32.5%	0.8%	35.4%	2.7%
USA	2.2%	0.1%	8.4%	2.3%	25.3%	3.8%	33.9%	7.8%	32.0%	17.1%	31.0%	20.7%
MEX	0.4%	0.0%	13.2%	0.3%	27.5%	3.0%	34.5%	11.0%	34.1%	21.8%	34.8%	20.6%
RCAM	0.7%	0.1%	5.8%	2.9%	14.4%	22.2%	18.7%	28.7%	16.8%	33.5%	28.4%	32.6%
ARG	0.0%	0.0%	10.4%	0.3%	21.1%	5.2%	32.2%	13.7%	29.4%	24.7%	35.4%	19.5%
BRA	0.4%	0.0%	12.4%	0.4%	16.6%	3.3%	25.3%	11.4%	29.6%	17.8%	28.8%	22.7%
CHL	0.5%	0.0%	4.2%	5.3%	9.9%	17.6%	12.6%	26.0%	12.4%	29.9%	16.0%	23.0%
RSAM	0.0%	0.0%	0.9%	0.5%	4.7%	5.9%	8.8%	28.5%	10.0%	33.8%	23.5%	25.6%
GBR	2.7%	0.0%	13.1%	5.1%	23.4%	10.4%	24.2%	18.5%	30.4%	23.5%	29.9%	18.9%
FRA	1.7%	0.1%	8.8%	4.3%	6.7%	8.9%	10.2%	11.4%	17.3%	17.2%	28.3%	11.6%
ITA	3.0%	0.7%	13.2%	13.5%	23.8%	18.2%	24.2%	24.8%	15.6%	29.2%	21.2%	30.9%
DEU	6.0%	2.0%	18.3%	7.1%	29.7%	14.4%	35.1%	26.1%	29.5%	32.6%	31.7%	29.0%
ESP	14.5%	2.6%	19.6%	14.0%	18.3%	24.1%	15.4%	26.8%	21.8%	24.7%	24.6%	21.2%
GRC	4.6%	0.3%	15.4%	10.8%	33.8%	15.8%	32.7%	31.7%	19.1%	43.2%	43.3%	35.2%
PRT	16.7%	0.4%	24.8%	3.3%	39.7%	7.0%	42.8%	10.0%	44.7%	15.3%	31.1%	26.9%
AUT	3.0%	0.1%	11.2%	2.5%	15.9%	10.8%	15.1%	17.0%	15.6%	22.9%	34.4%	24.8%
BEL	1.3%	0.7%	15.5%	5.5%	31.0%	15.3%	39.9%	28.2%	42.1%	32.2%	49.3%	29.2%
LUX	1.7%	0.8%	7.6%	7.0%	9.8%	46.3%	36.2%	34.8%	48.3%	28.8%	58.8%	25.6%
DNK	20.1%	0.0%	46.8%	3.2%	52.5%	4.8%	55.3%	10.1%	50.6%	16.2%	39.8%	22.3%
FIN	0.4%	0.0%	6.5%	0.0%	21.9%	0.0%	28.7%	0.4%	32.6%	3.1%	32.9%	4.5%
IRL	9.7%	0.0%	29.6%	0.7%	51.4%	1.0%	57.4%	1.4%	56.7%	3.8%	52.6%	3.3%

	2010		2020		2030		2040		2050		2100	
NLD	3.4%	0.1%	10.3%	3.3%	22.6%	12.1%	29.5%	25.4%	30.4%	29.9%	38.6%	24.2%
SWE	2.4%	0.0%	9.5%	0.1%	13.0%	0.2%	14.9%	0.8%	25.9%	2.5%	34.8%	3.2%
HUN	1.4%	0.0%	5.5%	1.3%	27.6%	10.4%	26.4%	27.5%	24.4%	37.3%	35.3%	24.6%
POL	1.0%	0.0%	11.3%	0.2%	29.4%	1.0%	46.8%	2.2%	50.1%	7.7%	43.8%	4.7%
CZE	0.4%	0.9%	4.1%	8.9%	9.4%	34.1%	12.8%	37.1%	21.6%	18.4%	37.4%	22.1%
SVK	0.0%	0.1%	0.8%	4.1%	10.2%	14.4%	12.8%	19.7%	16.0%	23.5%	29.0%	19.9%
EST	2.2%	0.0%	7.7%	0.1%	27.2%	0.5%	47.5%	0.9%	60.7%	2.2%	66.3%	3.1%
LTU	4.7%	0.0%	11.3%	3.1%	32.1%	2.6%	51.7%	2.3%	54.4%	3.3%	47.6%	3.8%
LVA	0.7%	0.0%	4.3%	1.1%	10.1%	3.0%	42.7%	1.7%	51.0%	1.4%	68.5%	1.0%
SVN	0.0%	0.1%	10.7%	1.8%	32.9%	3.4%	25.3%	13.7%	25.6%	18.6%	83.1%	10.1%
MLT	0.0%	0.1%	1.1%	8.6%	10.8%	13.8%	26.0%	12.4%	35.5%	12.0%	49.7%	11.6%
CYP	0.6%	0.1%	8.0%	13.5%	12.3%	41.1%	8.2%	47.8%	17.7%	30.5%	37.7%	39.5%
BGR	1.5%	0.0%	9.2%	3.0%	27.4%	6.0%	31.2%	19.1%	28.6%	24.7%	29.1%	26.2%
ROU	0.5%	0.0%	21.8%	3.9%	47.1%	4.7%	55.9%	6.3%	54.0%	9.4%	37.2%	17.0%
RCEU	0.0%	0.0%	0.6%	0.4%	8.3%	9.4%	12.7%	20.4%	16.6%	29.2%	15.5%	26.2%
HRV	0.9%	0.0%	11.7%	1.4%	20.0%	10.3%	35.5%	23.8%	37.3%	26.4%	25.6%	27.1%
TUR	1.4%	0.0%	14.2%	0.4%	19.3%	3.9%	28.0%	13.9%	29.4%	20.1%	33.5%	18.0%
NOR	0.7%	0.0%	3.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.1%	0.0%	25.3%	2.5%
ISL	0.0%	0.0%	0.1%	0.0%	1.2%	0.1%	4.1%	0.1%	9.6%	0.3%	20.9%	0.7%
CHE	0.1%	0.1%	11.1%	2.6%	20.3%	3.3%	32.5%	4.2%	32.3%	5.1%	50.8%	8.0%
RUS	0.0%	0.0%	1.4%	0.2%	3.9%	4.9%	7.8%	16.1%	8.5%	24.0%	23.6%	28.3%
UKR	0.0%	0.0%	1.4%	0.5%	8.8%	6.0%	16.9%	9.8%	15.6%	7.1%	37.6%	13.0%
RCIS	0.0%	0.0%	0.1%	0.0%	4.3%	4.3%	15.4%	20.1%	22.4%	27.9%	27.9%	21.9%
KOR	0.2%	0.2%	1.9%	0.7%	6.0%	5.6%	16.1%	23.4%	21.3%	29.6%	34.6%	22.8%
CHN	1.0%	0.0%	4.2%	1.2%	16.0%	2.4%	25.3%	11.8%	28.8%	20.0%	32.4%	18.8%
IDN	0.0%	0.0%	0.1%	0.2%	3.1%	6.6%	8.3%	22.3%	11.9%	27.9%	37.2%	19.8%
MYS	0.0%	0.0%	0.1%	0.7%	5.8%	8.6%	15.6%	20.7%	20.1%	25.7%	34.3%	6.5%

	2010		2020		2030		2040		2050		2100	
THA	0.0%	0.0%	9.1%	2.6%	21.3%	8.2%	29.4%	22.6%	19.5%	30.9%	29.2%	20.5%
VNM	0.1%	0.0%	0.5%	0.1%	4.3%	5.3%	16.9%	24.2%	20.8%	29.3%	34.2%	26.5%
RSEA	0.3%	0.0%	1.2%	0.3%	6.5%	6.3%	9.7%	21.8%	9.5%	30.2%	31.0%	23.5%
IND	2.0%	0.0%	4.2%	3.3%	18.2%	11.4%	28.5%	23.5%	28.7%	28.8%	41.4%	20.1%
RSAS	0.0%	0.0%	1.1%	0.3%	8.2%	4.7%	16.8%	25.3%	20.7%	34.4%	38.3%	27.4%
JPN	0.3%	0.3%	2.3%	6.6%	13.1%	10.0%	22.4%	15.8%	25.8%	21.1%	46.2%	16.1%
AUS	2.0%	0.2%	9.7%	3.8%	30.4%	5.8%	45.9%	10.6%	46.7%	15.1%	38.9%	26.6%
NZL	3.6%	0.0%	15.2%	0.4%	21.4%	1.1%	28.1%	2.6%	29.7%	5.4%	32.5%	9.6%
RPAC	0.1%	0.0%	0.9%	0.1%	9.2%	1.0%	20.9%	4.4%	43.9%	10.6%	41.2%	16.0%
NOAN	2.0%	0.0%	10.8%	0.3%	28.4%	2.8%	41.4%	14.5%	41.4%	26.6%	55.5%	28.1%
NOAP	0.0%	0.0%	0.1%	0.0%	4.4%	4.2%	16.1%	21.4%	23.6%	36.5%	45.7%	34.9%
EGY	1.0%	0.1%	14.0%	0.4%	22.1%	6.6%	37.3%	24.8%	36.8%	33.1%	33.2%	32.6%
RSAF	0.0%	0.0%	1.0%	0.3%	9.2%	5.6%	14.9%	22.8%	15.5%	32.2%	31.1%	37.5%
ZAF	0.0%	0.0%	2.1%	2.1%	12.2%	7.9%	27.3%	17.7%	33.2%	22.3%	42.0%	19.3%
MEME	0.0%	0.1%	0.7%	2.9%	7.8%	13.1%	16.8%	30.4%	21.6%	36.8%	36.6%	25.0%
IRN	0.1%	0.0%	0.2%	0.1%	4.5%	6.1%	12.8%	23.5%	20.1%	31.5%	40.4%	24.4%
SAU	0.0%	0.0%	0.5%	0.1%	2.5%	6.0%	14.5%	23.3%	27.3%	28.4%	53.3%	23.6%
RGLF	0.0%	0.0%	0.0%	0.5%	1.0%	9.2%	7.8%	28.4%	18.1%	38.6%	45.2%	32.2%

Source: JRC analysis

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