



Space-time variability of climate variables and intermittent renewable electricity production – A review



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ABSTRACT

A major part of renewable electricity production is characterized by a large degree of intermittency driven by the natural variability of climate factors such as air temperature, wind velocity, solar radiation, precipitation, evaporation, and river runoff. The main strategies to handle this intermittency include energy-storage, -transport, -diversity and -information. The three first strategies smooth out the variability of production in time and space, whereas the last one aims a better balance between production and demand. This study presents a literature review on the space-time variability of climate variables driving the intermittency of wind-, solar- and hydropower productions and their joint management in electricity systems.

A vast body of studies pertains to this question bringing results covering the full spectrum of resolutions and extents, using a variety of data sources, but mostly dealing with a single source. Our synthesis highlights the consistency of these works, and, besides astronomic forcing, we identify three broad climatic regimes governing the variability of renewable production and load. At sub-daily time scales, the three considered renewables have drastically different pattern sizes in response to small scale atmospheric processes. At regional scales, large perturbation weather patterns consistently control wind and solar production, hydropower having a clearly distinct type of pattern. At continental scales, all renewable sources and load seem to display patterns of constant space characteristics and no indication of marked temporal trends.

1. Introduction

Weather and climate conditions have a significant influence on both the production and the demand of electricity. With increasing renewable energy (RE) potentials and prospects at the global scale, this influence will grow [1]. Understanding the sensitivity of electricity systems to climate and weather variability is a step to better assess its potential and added-value to society [2]. The growing interest for modeling the link between energy and climate has various interconnected motivations. Firstly, feasibility studies show that generating electricity, heat or bio-fuels from RE sources may cover current and future global energy demand in 2050 using less than 1% of the world's land for footprint and spacing (e.g. [3]). Some countries, like Denmark, are already prepared for this scenario [4]. Secondly, the peak fossil fuel

risk (i.e. the risk of fossil fuel production being unable to keep pace with demand) can be prevented if the growth rate of RE production follows the one of the world mobile phone system [5]. Thirdly, RE deployment has become a high priority in policy strategies for energy and climate mitigation at national and international levels – see for instance [6], the European Renewable Energy Directive adopted in 2009 [7] or the IPCC report on RE sources and climate [8].

The intermittent “climate related energy” (called CRE hereafter) considered in this paper are represented by wind- and solar-power as well as small-scale and run-of-the-river hydropower. They are distinguished from non-intermittent RE sources like biomass, large hydropower systems with reservoir and geothermal power [9]. The CRE availability depends on several climatic variables, including solar radiation, wind velocity, air temperature, precipitation and river runoff.

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The word climate encompasses here meteorological and hydrological processes and their short and long term behaviors. These variables fluctuate in space and time, exhibit correlations and, in turn, control the intermittency of CRE sources, which, *stricto sensu*, means the sporadic interruption of a source. The combined variability of CRE production and demand leads to periods of so-called positive “residual load”, when CRE production does not meet the demand, and other periods of negative residual load with CRE surplus generation [10]. Therefore, the space-time variability of CRE production challenges one of the primary goals of electric utilities, which is to balance supply and demand. The terms stability (or sometimes regulation), balancing (or sometimes load following) and adequacy designate the supply-demand balance over, respectively, high (less than seconds), medium (minutes to days) and low (month to years) frequency. They characterize the “flexibility” of electricity systems (IEA [11]), which also evolves with consumption patterns under the influence of market mechanisms and smart grids (e.g. [12]).

Stability and adequacy issues are beyond our present scope of interest. The grid stability is sensitive to high frequency voltage perturbations that are reduced by power-electronic technology – for instance, local wind turbulence is absorbed by “fault ride-through” devices satisfying grid rules set by system operators [13]. The adequacy of CRE production depends on long term climate variations and hence on climate change. An expected fall of CRE potential may force a decrease of consumption [14]. Systems may be more sensitive to climate extremes [15], but further investigations are needed [16]. Social acceptance of CRE deployment [17] and environmental impacts [18] are also important constraining factors in achieving long term targets of adequacy policy. They need further attention for wind- and solar-power [14] as well as for hydropower [19]. In the following, we briefly exemplify typical balancing issues in a system with a high CRE share.

Balancing at time scales from minutes to days responds to meteorological processes ranging from meso- to synoptic-scale, including diurnal and orographic local circulations as well as larger scale perturbations as described by Orlanski [20]. Connecting CRE production utilities to transport grids smooths such medium frequency variations, as long as their space-time co-variability is weak enough over the connected domain (e.g. [21]). Wind and solar energy production may experience large and sudden variations called “ramps” linked, respectively, to wind turbulence and cloud circulation [22,23]. Demand response programs, schedulable power production and energy storage are used to level out the residual load that is not smoothed by grid transport [24]. Among the schedulable power means for balancing residual load, reservoir-type hydropower is the most commonly used RE type [25], whereas gas fired power plants are the most promising non-RE type. Energy storage technologies for balancing scales include batteries, compressed air, hydrogen fuel cells, pumped hydropower, compressed air, and earth heat (thermal energy storage) [26–28], where compressed air and pumped hydropower are mature and commercialized technologies that cover the 24 h variations [27]. Hydrogen fuel cells and earth heat are the only technologies that cover the seasonal time scale [26,27].

Storage is expected to be a “game changer” in CRE balancing [29,30]. Balancing needs high enough prices during peak demand periods to compensate economic losses during curtailment periods [26,31]. In a similar way, the cost-effectiveness of storage technologies is a major limitation for introducing new storage technologies [27]. The need of balancing power and/or energy storage and their profitability are closely related to the variability of CRE sources [24].

Based on the background given above, this paper summarizes the current scientific understanding about the space-time variability of atmospheric and hydrologic variables driving hydro-, solar- and wind-power productions (Sections 2–6) and their joint management in electricity systems (Sections 7–9). To the best of our knowledge, this is the first work presenting a comprehensive review of this vast body of

literature. The next section summarizes the elements featuring the variability that we traced in the reviewed paper, such as the resolution and extent of the study areas and the various statistical tools used to characterize space-time patterns. Sections 3–5, respectively, deal with solar-, wind- and hydropower production, examining the governing natural processes, their transformation and aggregation by electricity systems and their variability in time and space (e.g. statistical distribution at a point or correlation at a distance). Section 6 summarizes the main features collected along the previous three sections by providing two synthetic figures, one comparing a set of illustrative power spectrum densities and another displaying a set of characteristic sizes in time and space. Section 7 briefly introduces demand dependence on climate variability, while the following sections deal with the solar- and wind-power complementarity (Section 8) and the role of hydropower (Section 9) with respect to electricity management. Section 10 brings concluding comments.

2. Literature analysis and organization

Our focus is on weather and climate variability and its connection to RE production-consumption systems. Overall, we have found in the literature and have analyzed 279 papers and published works in the last 25 years, of which over 60% were published in the last 5 years. This sample of references represents around 1.5% of the published articles referred by the Web of Science under the key-words solar/wind/hydro-power/-energy (18,318 references) and 16% of those selected by adding the key word variability (1735 references, among which only 49 come from journals dealing with weather, climate or hydrology). Fig. 1 shows the cumulative number of references by year of publication for each energy source (and selected combinations) and for electricity demand. The majority of the references were published after 2000, with wind, hydropower and the combination of solar- and wind power are the topics that have the largest number of references. As illustrated by Fig. 2, the majority of the case studies covers Europe and North America (ranging from local to continental). Fig. 3 shows a histogram of the 40 most frequently used authors’ key-words. We see that the meaning of different key-words overlap (e.g. “Storage” and “Energy storage”), and that key-words that include “Wind” are the most frequent in papers included in this review paper.

We approached the literature review with two questions in mind: (1) What are the type of data and their basic characteristics with respect to variability, i.e. resolution and extent? (2) What are the basic characteristics of co-variability in space and time for the three considered CRE sources?

Answers to the first question were easily extracted from the reviewed works that explicitly mention the resolution and extent used in both space and time (151 studies), and are summarized in Fig. 4 (for resolution) and Fig. 5 (for extent). In Table 1, the references used for

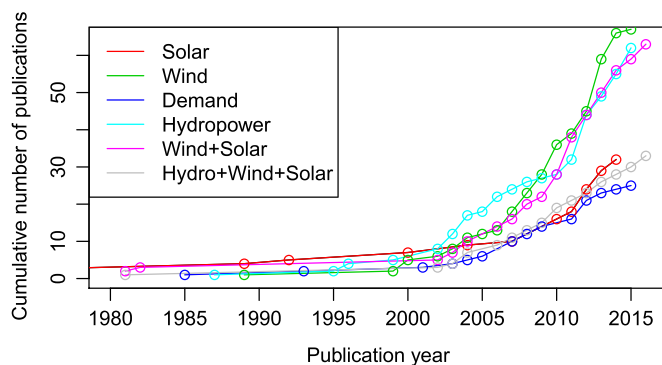


Fig. 1. The accumulated number of references as a function of publication year is reported for each of the sections addressing solar-, wind- and hydropower (Sections 3–5 respectively), demand (Section 7), the combination of solar- and wind power (Section 8), and the combination of solar-wind and hydro power (Section 9).

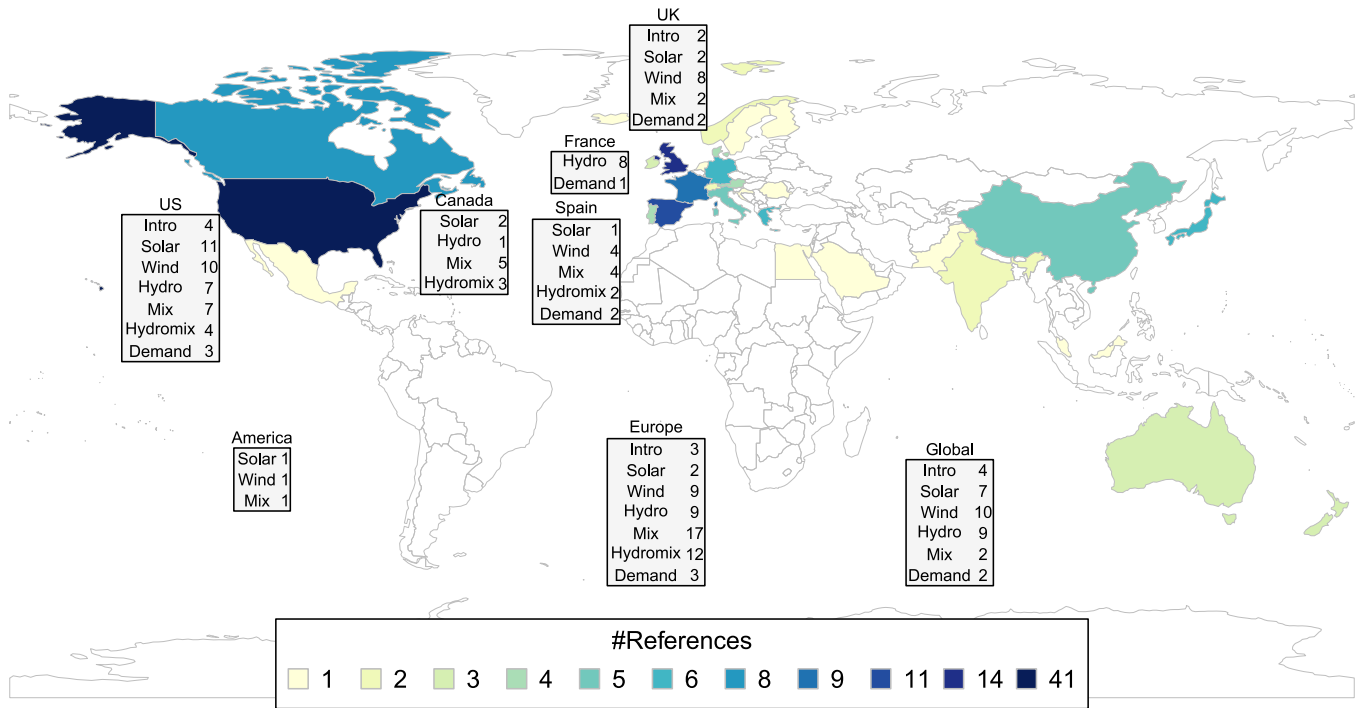


Fig. 2. The geographical distribution of the number of case studies located within each county is shown, and small tables are added for the five countries with the largest number of case studies (United States, United Kingdom, Canada, France, and Spain). In addition, there are several regional and global case studies, and tables summarizing American, European and Global case studies are added to Fig. 2.

creating Fig. 4 are specified and grouped according to temporal and spatial resolutions.

Fig. 4 shows that the dispersion of the resolutions is quite vast, ranging from the second and the meter to the year and the continent and includes unexpected areas of resolution such as the combination of high time resolution at very coarse space resolution. The time resolutions of one hour to one day and the space resolutions of 1–100 km cover 60% of the works. Except for some weak tendencies, neither the considered theme (Fig. 4-a) nor the type of data used (Fig. 4-b) appear to be specific of a choice of resolution except light tendencies. The variability of each individual CRE source is studied with resolutions covering all possibilities, while the mix of sources is seldom looked at scales below the km and the hour (Fig. 4-a). The link between space and time resolutions looks narrower when using data coming from grids such as atmospheric model outputs (30% of references), re-analyses (9%) or remote sensing images (6%) than when using meteorological (44%) or production (11%) data measured at ground

(Fig. 4-b). We must bear in mind that space resolution needs interpretation in the case of networks of measurement stations. We decided to take the network density as resolution. In terms of how to resolve the synoptic meteorological systems related to high winds and cloudiness, a resolution of at least 50 km is recommended [32] and satisfied in over 70% of the reviewed references using model outputs or re-analyses. The remaining studies use the classical GCM (Global Climate Model) resolutions, which are larger than 50 km. In time, the recommended resolution of 1 h or less is only used in 66% of studies.

The dispersion of the study extents met in the reviewed studies is also vast, ranging from the day and the meter to the globe and a thousand years (see Fig. 5). The different themes are equally distributed in extents (not shown), whereas for the types of data, we see that beyond extents of a few decades (maximum 5), only model outputs provide long data series. The space extent is easier to define, whereas the time extent is not straightforward to interpret, especially when only consecutive periods of non-zero values are considered as in the cases of

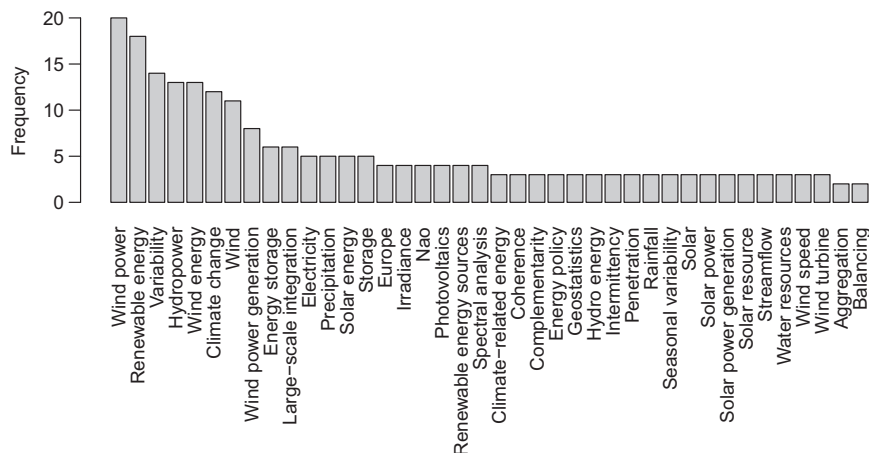


Fig. 3. Histogram of the 40 most frequently used authors' key-words. We see that the meaning of different key-words overlap (e.g. "Storage" and "Energy storage"), and that key-words that include "Wind" are the most frequent in papers referred to in this paper.

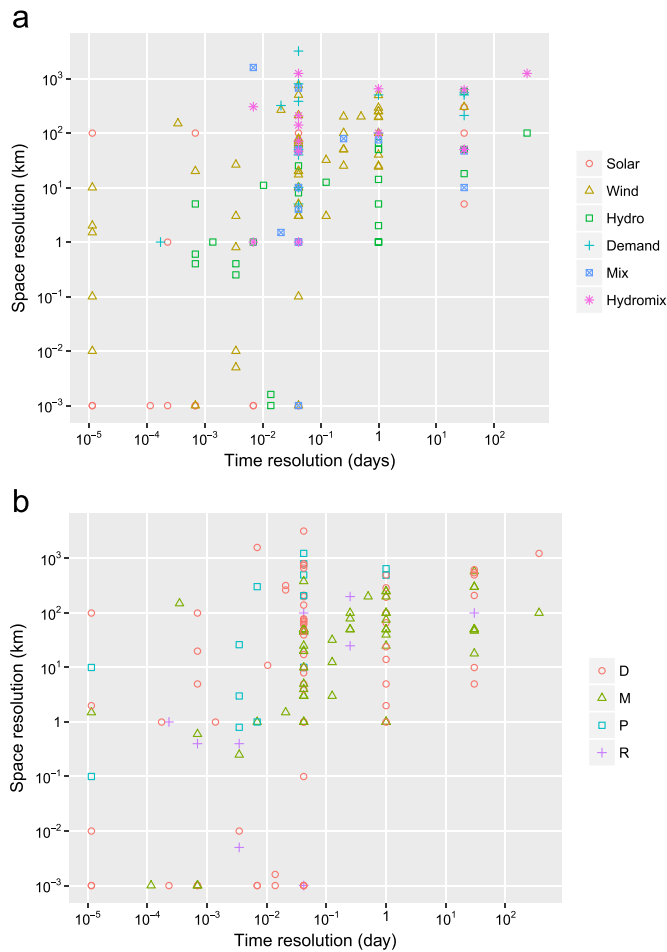


Fig. 4. Space and time resolutions of the 151 cited papers where they are explicitly mentioned. (a) distinguishes the different themes dealt in this paper according to the sections devoted to solar (19 papers), wind (53 papers) and hydro (32 papers), demand (18 papers), merging solar and wind (18 papers) and merging hydro with solar or wind (14 papers). (b) distinguishes the different sources of data: ground meteorological data (circles), model outputs (triangles), energy production data (squares) or remote sensing data (plus signs). The most visible alignments correspond to hourly, daily and monthly time steps.

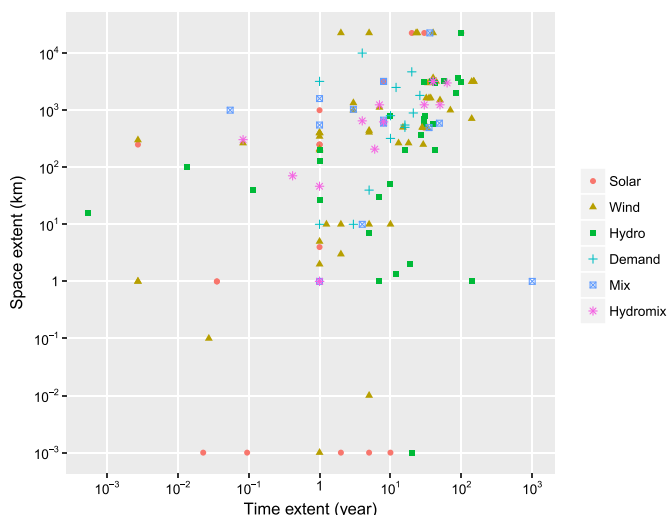


Fig. 5. Time versus space extent for the same set of reviewed papers and making the same distinction according to the types of data as in Fig. 4.

nights for infra-daily solar radiation or in wind episodes or “gusts”. This way of dealing implicitly with the “intermittency” of these variables, in the sense of periods during which there is no production at all, modifies the subsequent analysis of variability.

Answers to the second question were more challenging to extract from the literature. As a first step, we chose some synthetic elements that allowed us to summarize the variability of the three considered CRE sources through works that mix different data types and transformations, and that use varied statistical tools. In the reviewed papers, the data are of various types (see above about Fig. 4-b) and are often either normalized (e.g. expressed as a percentage of the mean or, more classically, reduced by the variance and centered around the mean) or transformed for practical considerations (e.g. first-order time differences for wind and solar, considering the so-called “ramps” as an important component of variability, or the normalization by the potential solar radiation, considering sky clearness as a more pertinent source of variability than astronomy). Most statistical tools in use in geo-mathematics are applied to these data, including statistical moments and frequency distributions, regressions, structure and harmonic analysis (see for instance [33] or [34] as reference textbooks). More fundamental papers such as the ones by Taylor [35,36], who first proposed stochastic characteristics of turbulence, have been widely used for analyzing space-time variability in a number of disciplines. In order to derive some common synthetic elements enabling to compare the variability of the considered sources, we focused our attention on basically two tools – the power spectrum density and the autocorrelation function. These are known to be linked [36,37], and are used in quite specific ways in the reviewed literature to qualify the persistence of CRE, either in time or space.

The power spectrum density (PSD) $S(f)$, with f the frequency, is estimated by Fourier transformation of a series of data. The PSD shows the existence of repetitive structures or correlated patterns in the signal process. In the reviewed works, only time series are considered. Cyclic variations (daily, annual) in a time series appear as peaks. For atmospheric isotropic turbulence, a self similar process over a wide range of scales, Kolmogorov [38] (see [39] for an English translation) shows that a power law $S(f) \approx f^{-b}$ fits the PSD of this process with a slope $b = -5/3$. The slope reveals the degree of auto-correlation. For a white noise, the slope is zero and for correlated time series, the slope is negative, often described as “red noise” since low frequency variations get the highest PSD-values. A white noise is “reddened” by integrating it in time (e.g. Brownian noise), which is manifested as a steeper slope and an increased importance of low frequencies. A change in the slope of a PSD might indicate critical time scales and changes in governing processes. The PSD derived from the reviewed studies are shown in Fig. 6 and will be commented along the following sections.

The autocorrelation functions (ACF) are estimated by computing correlation coefficients at varying distances in time and space. They allow to derive decorrelation distances that can be considered as characteristic sizes of a process in time and space. In the reviewed works, almost no pairs of space and time autocorrelation functions were available. We thus had to compile several pieces of correlation information, including correlation coefficients between time series at points, space correlograms or variograms, and coherence spectra between points. To obtain consistent characteristic sizes, we arbitrarily set a chosen level of correlation (50% of explained variance) and used the distance at which the correlation drops below this threshold to determine the pattern size in space. This distance is sometimes denoted d_{50} (and t_{50} for time correlation) in the literature. Since the corresponding characteristic size in time is, in general, not available from the reviewed studies, we decided to take by default the time step considered as the corresponding characteristic time. This choice is sound when the sampling time step is adapted to the characteristic time variability of the process. We compiled in Fig. 7 the above defined characteristic sizes in a classical log-log plot where atmospheric variability is idealized by the space and time characteristics of a series

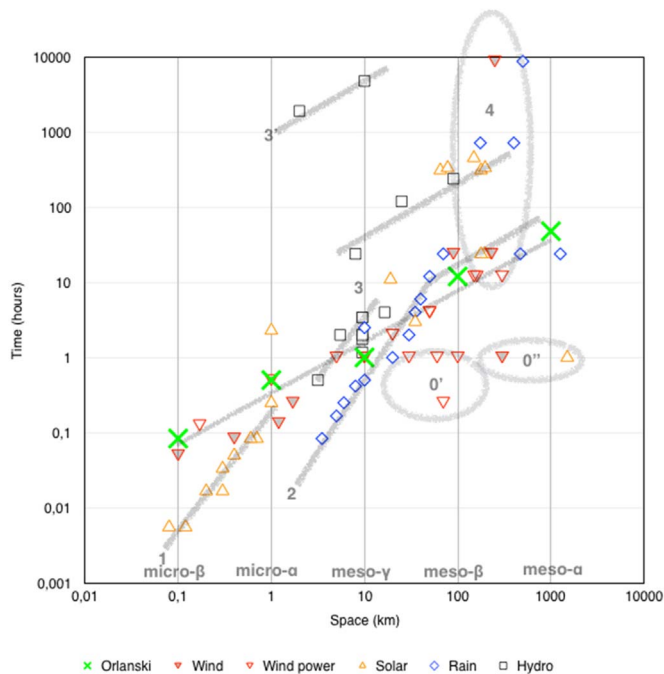


Fig. 7. Characteristic space-time size of patterns of solar radiation (up triangles), wind velocity (down triangles), precipitation accumulation (diamonds) and hydrologic flow (squares) derived from correlation information provided by 25 reviewed articles. The characteristic size of atmospheric thermals, deep convection, thunderstorms, squall lines and fronts are reported after Orlandski, [20] (crosses). Wind velocity is distinguished from wind power (respectively grey and transparent down triangles). Hydrologic flow is separated into surface-, soil- and ground-waters. The alignments and set of points grouped in grey and numbered are commented in the text.

technology converting solar radiation into electricity [43] solar power has gradually become ranked as the most promising RE according to its potential and to a set of socio-technical considerations [44]. The technical potential of solar energy has been estimated at above 420 TW, compared to a total potential between 4.4 and 75.6 TW for the other common renewable technologies [45]. In this section, we mainly focus on PV systems, but most considerations also pertain to CSP.

The solar radiation reaching the Earth's surface is primarily governed by deterministic astronomical considerations with the cycle of day and night, seasonal effects that depend on latitude, as well as exceptional events like eclipses or local screening effects due to topography [46]. The solar radiation is predicted nearly-perfectly under clear sky conditions [47,48]. As a result, the solar power potential depends mainly on the latitude; the annual resource of global radiation is, for instance, more than double in Southern Europe compared to Northern Europe [49]. In addition to these deterministic diurnal and seasonal cycles, atmospheric optical transmissivity modulates the amount of extra-terrestrial radiation reaching the ground, with the attenuation due to clouds and aerosols following atmospheric circulation patterns [50].

The power output from a PV generator depends quasi-linearly on Global Irradiance (GI in W m^{-2}) and on an efficiency conversion coefficient. GI is the sum of three components: i) direct radiation from the sun, ii) diffuse radiation scattered by clouds, atmospheric gases and aerosols, and iii) reflected radiation from the ground [51]. Information on cloudiness can be used to estimate the actual GI [52]. The efficiency conversion coefficient decreases with increasing PV panel operating temperature – ca. 0.5% per $^{\circ}\text{C}$ change in temperature for silicon modules [53,54]. This justifies the notion of “average efficiency” used in some studies, which specifies the bulk production of a PV converter as a percentage of its peak production (e.g. [49]). However, such a simplification needs revising when diffused radiation becomes dominant due to heavy cloud cover [55]. The radiation reaching a PV panel

depends on its orientation since GI is a function of the tilt and azimuth angles of the surface [56]. Beyond temperature and radiation types, other weather factors like wind, hail, lightning and sand transport may also affect the functioning or the integrity of PV sensors (see [57]).

Temporal and spatial variability of solar radiation is mainly controlled by astronomical parameters. In order to filter out the astronomical part of the signal from sunset to sunrise, Liu and Jordan [58] introduced the “clearness index” (CI in %) as the ratio between the measured terrestrial GI and the (extraterrestrial) radiation arriving at the top of the atmosphere (see also the “clear sky index” computed the same way, but dividing the GI by the expected clear sky radiation at ground in [59]). CI and GI are used to analyze the “non astronomical” space-time variability of solar irradiance, and in turn in solar PV output, due to the presence and behavior of clouds. CI moderately depends on the air mass, hence on the season, and on atmospheric turbidity [60,61]. The probability distribution function (pdf) of CI depends primarily on the average clearness of the considered daily or monthly period [62]. It changes from a bimodal behavior due to individual cloud effect at high-frequency (minutes and less) to a unimodal asymmetric behavior due to multiple cloud integration at low-frequency (hours and more) [60,61].

Regarding temporal variability, power spectral density functions (PSD) of GI taken in Colorado show, i) as expected, a marked peak of one order of magnitude at a frequency of 24 h and ii) a quite constant power decay rate down to a few minutes, a priori not confirming the above drastic change in behavior at one hour (see the corresponding PSD in Fig. 6 sketched from [63], Fig. 5). At lower frequencies (from days to month), the GI power spectra become flatter with peaks due to weather patterns (a few days) and the seasonal variability. Many studies deal with the differences between successive GI or CI values in time, called “steps” or “ramps”, with the benefit to filter out longer term trends like astronomical cycles [59,63–66]. Perez et al. [67] differentiates CI and thus filters twice. Lave et al. [59] show that the ramp pdf depends on the aggregation timescale between 1 s and 1 h. The authors show that a 20-min moving average filters out most large ramps, giving a way to define the required storage-time capacity to stabilize production from a single site.

Regarding spatial variability of radiation, Mulder [68] provides analytical derivations showing how astronomy structures the space-time distribution of solar energy over very large grids (continental scale), with compensations coming from daily and yearly cycles. Apart from these large scale deterministic co-fluctuations, analyses of experimental data from distributed meteorological stations or satellite data deal with GI (e.g. [64,66]) or CI (e.g. [59,67]). The correlation between sites decreases with distance and increases with temporal aggregation. For instance, correlation coefficients equal to 0.7 (i.e. 50% of explained variance) for 5 min and 3 h are found at, respectively, 0.5 and 35 km [65,66] and the decrease is linear below 15 min [69]. Assuming that stable cloud patterns move at a constant velocity, Perez et al. [69] convert time- into space-autocorrelation, showing the role of wind velocity in the GI variability. The authors find space correlations that are consistent with those of [66] (0.7 km instead of 0.5 km at 5 min aggregation time). At short time steps (less than 2 min), the correlation depends on cloud motion, with lower values along the motion direction [66]. The correlation is well explained by the so called “dispersion factor”, which is the distance between measuring points divided by the product of the wind velocity and the time step considered, namely the distance covered by clouds during the measurement [64,70]. Mills and Wisser [66] indicate that, at short time steps, a dispersion factor of 30% corresponds to 50% of explained variance. After experimental evidence by Lave and Kleissl [71], Arias-Castro et al. [72] show how advected clouds, described by a Poisson distribution, numerically reproduce an exponential decay of the correlation, which depends on the distance, the time step, and the wind velocity. From the power spectral density derived from GI data at 5 min resolutions, averaged over 4 sites in Colorado, Lave and Kleissl [63] find that the smoothing effect at this ca. 100 km radius scale starts below 5.8 days. From coherence spectra

analyses Lave et al. [59] show that between sites ca. 1 km apart, the sill of 50% of explained variance is reached for an aggregation time of ca. 2 h.

The variability of GI aggregated in time and space is analyzed using different wordings like “diversity filter” [65] or “output variability” when focusing on solar power systems [64]. It is known to be linked to the covariance function (“block variance” in geostatistics – [34]). Such studies show that the variance of the average radiation (or average solar power generation) over an area depends on its size and on the considered time step. Lave et al. [59] indicate that the output variability over a ca. 1 km radius gets below 50% of the point variance below 20 min. As noticed by [64], the lowest limit of the output variability is reached in the absence of correlation among sites and is simply equal to the generation variance divided by the square root of the number of averaged sites. The aggregation in space is also analyzed with PSD functions of the average PV power (see, for instance, the PSD of the European solar power average in Fig. 3 of [49] and reproduced after appropriate transformation in the Fig. 6 of this paper).

4. Wind power

After 3 millenniums of exploitation, a severe decay during the first half of the 20th century (see [73,74] for historical perspectives) and remarkable advances of modern wind turbine technology [75], wind power is today a fast growing CRE source of electricity in many countries [76–79]. Operating at only 20% of their rated capacity, land-based 2.5-MW turbines installed in non-forested, ice-free, non-urban areas could supply 40 times the present worldwide electricity consumption [80].

From global circulation to local wind profiles, the atmospheric phenomena that govern wind variability and, in turn, wind-power generation are well described in [81]. The dynamics of the lowest atmospheric layers over flat and complex terrains deserves special attention, although they are often poorly represented in GCMs with a coarse spatial resolution [82–84]. Sudden changes in wind speed such as gusts or lulls may affect turbine integrity [85] or may sharply change wind power production, causing the “ramps” [86,87]. In addition, land-use effects may evolve with time [88,89].

Power output from a single windmill depends on local wind properties integrated over the vertical slice occupied by turbines. Wind-to-power transfer function is non-linear. The windmill needs a certain amount of wind to start, and having a maximum production for wind speeds between ca. 15 and 25 ms^{-1} and no production for wind speeds higher than 25 ms^{-1} [90,91]. When wind speed is measured at ground, an extrapolation of the wind speed to around 80 m, which is the altitude of the turbine hub, is either performed using a power law equation [92], or can rely on measured wind profiles (from atmospheric soundings as in [93]). At the farm level, the quantification of the role of wind turbine spacing on power losses due to wind turbine wakes is essential. Studies show that the average power output of a down-wind windmill can be reduced by up to 60%, depending on wind direction [94]. Other critical combinations of wind, air temperature and water content can impact operation and maintenance of windmills, as in the case of icing, for instance [95]. Off-shore turbine towers may be damaged by sea ice and sea waves [90]. Wind velocity, and hence wind power, are highly variable across time and space scales [96]. Wind velocity usually fits an asymmetric Weibull statistical distribution, which analytically converts it into average energy production [97,98].

Regarding temporal variability the power spectrum density (PSD) of wind power, like for wind velocity, follows Kolmogorov’s second hypothesis of similarity from several days to minutes (see for instance Fig. 7 to 11 in [99] sketched in Fig. 6 of this paper). At the upper end of the spectrum, the inertia of wind turbines filters out turbulence frequencies below the minute. A diurnal cycle is detected in observations at mid-latitudes [100], under the notable influence of clouds [101], although it is not visible on the published PSD. Annual fluctuations seem to be steadily around 15% of the mean, from the farm to the continental level [102,103]. Persistent weather systems

may lead to consecutive periods of several days and even weeks, with very low wind speed, leading to sustained underproduction [104] as for the well-studied situation of the winter 2010 in the UK [105–107]. Average and extreme wind velocities exhibit seasonal to decadal variations that are described at local [102], regional [98,108–112], and global [113–115] scales. Over the last 140 years, no significant long-term trend has been found, although multi-decadal variability is observed in many regions [116].

Due to the above described wind variability the average production of an individual wind power plant is of the order of 20–30% of the installed capacity. This so-called capacity factor exhibits seasonal and inter-annual fluctuations of 10% and 5%, respectively [117,118] and decreases when the global production increases, i.e. when less productive areas are equipped [119]. Like in solar power, many studies deal with ramps [86,87], making the distinction between ramp rates (MW/h), ramp swings (MW) and ramp durations (h) [87]. The ramp rate is defined as a variation in power output exceeding a minimum amplitude over a limited duration [120], i.e. the most variable part of the power signal. Local application of Wavelet Analysis allows a continuous detection of ramps over a frequency window [121]. The obtained “ramp function” can be used to show, for instance, the daily cycle of ramps or the correlation of ramp occurrences at individual wind turbines (see [121] for an example in North-Western Spain). The meteorological description of wind ramps requires specific field experiments and modeling exercises [122].

Regarding the spatial variability of wind power production, most studies empirically investigate smoothing effects by using distributed wind power data at individual mills or farms and by employing a set of statistics, including power and ramp rate frequency distributions, correlations and power spectra (see [123] for a summary of methodologies). Using the notion of “diversity factor” (see Section 2), Holttinen [117] finds that the hourly variance of wind power integrated over a 100 km diameter area, is 4 times less than the variance at a windmill and that the smoothing effect has a limit around a factor of 16 at 1000 km. The benefit of interconnecting farms is also empirically shown with i) generation duration curves becoming flatter [93,124], ii) coefficients of variation lowering [125] or mean variance portfolio decreasing [126] when adding farm productions and iii) PSD functions of the average wind power over, for instance, Europe (Fig. 3 in [49] reproduced after appropriate transformation in Fig. 3 of this paper). The integration effect of wind power is also addressed using numerical weather model outputs [127–129]. More specific questions such as wind ramps and other local wind-turbine interaction issues also benefit from numerical modeling exercises [81,122,130,131].

When analyzing spatial dependencies between individual wind turbine productions as a function of time aggregation in Germany, Ernst [100] finds correlation coefficients of 0.7 (50% of explained variance) at 200 m for time aggregations of 10 min and at 160 km for 12 h, Haslett and Raftery [132] finds the same correlation level at 250 km for hourly data in Ireland. Converting ERA-40 6-h wind velocities in power, autocorrelation coefficients of 0.7 are found at distances spanning over 70–280 km and time-lags of 1–3 time steps, depending on the regions in Europe (Fig. 15a in [133]). The use of variograms to analyze wind velocities indicates i) decorrelation time and distance of, respectively, 12 h and below 10 km for hourly data in Japan [134] and ii) decorrelation distance of 90 km for daily data in England [135]. The smoothing effect of interconnecting wind farms is therefore more effective on short time scale variations (less than 24 h). Nanahara et al. [136,137] show that the number of turbines in a farm has more influence on short-term regulation (up to 5 min) than the separation of wind farms (up to two hours for less than 200 km), and Wan [138] confirms this short-term intra-farm smoothing of ramp rates.

5. Hydropower

Like sun- and wind-power, power generation from river and channel flows is a multi-century practice [139] that contributed to

the high efficiency and low carbon emission in electricity development over the last century. Its worldwide technical potential is estimated to 14,576 TWh/yr. The 2009 production of 3551 TWh was equivalent to 16.3% of the global electricity production, a share that is declining given the faster development of other CRE sources [140]. Representing 22% of the present electricity production capacity worldwide and with a growth rate over 2% [141], hydropower still has a substantial development capacity, ranging from 47% in Europe to 92% in Africa [142]. Its present and near future trajectories of development are along small hydropower plants [143,144] and hybrid power systems [145]. Hydropower storage capacity, sometimes called “blue battery”, is recognized as a central asset for electricity supply security [146]. Marine hydropower is developing fast (see [40]), but is out of the scope of this paper.

Compared to wind and solar energy, hydropower has at least three different characteristics: i) its drivers are not only related to the atmosphere but also involve earth surface processes, ii) harnessing strategies may involve controlled storage that modulates the variability of atmospheric and hydrologic drivers, and iii) hydropower generation interacts with water management and governance (including water policies and programs for a sustainable use of water resources) as well as other energy sources, such as thermoelectric power plant cooling [147]. These key issues are briefly reviewed in the three following paragraphs before we look in more details to the variability of hydropower in time and space.

The hydrological driver of hydropower is river streamflow, the integrated catchment response to atmospheric water input (precipitation) and loss (evapotranspiration). Many surface processes control the short term component of this response, such as infiltration or snowmelt. The surface processes are well documented and define how atmospheric precipitation and temperature control runoff generation given a number of factors, such as topography, soil properties or land cover (see [148] for a textbook and [149,150] for recent illustrative field studies). Underground processes transferring infiltrated waters from unsaturated soils to riparian aquifers regulate the medium to long term components of river response [151,152]. Depending on catchment characteristics and wet/dry conditions, different processes are dominant at different space and time scales [153,154]. There is a fundamental difference between time and space in how the landscape interacts with the meteorological forcing and modifies their variability, in order to generate streamflow. The temporal variability reduces due to infiltration and runoff processes, whereas the spatial variability increases due to the complex catchment geometry and properties. The watershed morphology, collecting and distributing the streamflow into the branching structure of river networks, is a central geophysical driver of river streamflows, and is controlled at very long term by erosion and sediment transport processes [155,156].

Hydropower generation from a turbine linearly depends on mainly two terms: the water inflow, and the head (i.e. the difference in water altitude between the inlet and the outlet of the installation). These two terms tend to vary in opposite ways when moving in river systems: the slope decreases from upstream to downstream along the longitudinal profile of the river while the size of the watershed, and thus the streamflow, is increasing [157]. The upstream morphology and the local setting of each individual equipped site explain in good part the vast variety of large- to small-scale power plant types in terms of storage and equipment. Hydropower plants can use the natural flow of water with limited or no storage – run-of-the-river, or they can have artificial reservoirs filled by an upstream river and/or with pumped water [158]. The type of turbine and the resulting efficiency (typically 80–85% for small hydropower plants, up to 95% for large systems – in [159]) also depends on the water inflow and head [145].

Although water, as a working fluid, is not consumed by hydropower plants and thus available for other uses, hydropower technology is one the most environmental and social sensitive power generation technologies

[158]. The operation of reservoir-type hydropower leads to artificial fluctuation in streamflow that affects aquatic ecosystems [160], and large reservoirs might necessitate resettlement of people [161]. The topics of “green hydropower” and multi-scale water usage are amply debated, showing the sustainability of well conducted hydropower projects in spite of climatic and socio-economic risks [162–164].

In the following, we examine the variability of precipitation and temperature, and their combined effect on streamflow variability through basin morphology.

Precipitation variability primarily depends, like wind, on atmospheric circulation dynamics and is further complicated by cloud microphysics that controls precipitation formation [165]. The temporal variability of precipitation as described by the slope of the power spectrum density can be interpreted into three regimes of variability (see for instance Fig. 7 in [166] sketched in Fig. 3 of this paper). Convection activity and associated turbulence (PSD slope of -1 to $-5/3$) dominate accumulation times below one hour over typical space scales of 10–100 km. Perturbations and associated baroclinic instability (PSD slope around $-1/2$) rule one hour up to a few days accumulation times at typical scales of 100–1000 km. The succession of weather systems, controlling larger accumulation times (nil PSD slope beyond a few days), i) responds to planetary oscillations like for instance the North-Atlantic Oscillation (NAO, controlling weather circulation in Europe) or the Atlantic Multi-decadal Oscillation (AMO, controlling precipitation in Brazil and Africa as well as North American and European summer climate) and ii) designs continental scale drought and precipitation excess patterns opposing northern to southern Europe for instance [167,168]. The PSD of precipitation intensities varies from one climatic region to the next and the PSD of precipitation intermittency, i.e. the precipitation/no-precipitation process, looks more uniform in slope and less variable in space [169]. A rough description that summarizes well the vast body of works dealing with precipitation variability in space is that characteristic size of precipitating areas increases as a power law from 5 km to 500 km when precipitation accumulations are taken over 10 min to 1 year (see for instance, at increasing scales, [170–174]). As far as hydropower production is involved, a second major driver of precipitation variability is orographic enhancement, i.e. the triggering of precipitation production by topography [175–178]. As a result, these mechanisms lead to disproportionately large precipitation and hence river discharge, in region of steep slopes, i.e. of high water gravity energy. In humid areas, mountains supply up to 20–50% of total discharge while in arid areas, mountains contribute from 50% to 90% of total discharge, with extremes of over 95% [179].

Temperature is a simpler tracer of atmospheric turbulence and, as such, its time variability follows Kolmogorov's theory through a wide range of scales (see Fig. 3 in [169] where PSD of temperature and precipitation are compared). Temperature also presents two strong determinisms, one, is astronomic with diurnal and seasonal cycles, like for sun radiation, the other one is topographic with a typical average vertical gradient of 5°km^{-1} [180].

The combination of scale dependent variations in precipitation and temperature results in river flow variability. The strategies applied to hydropower plant management vary according to this variability, also called hydrologic regime [181]. At the weather time scales (up to daily time step) that are central for run-of-the-river hydropower, the river streamflow fluctuations are well explained by the average precipitation intensity over the catchment. In cold areas (in high altitude and/or latitude), solid precipitations do not instantly contribute to river streamflow. Space heterogeneity of precipitation fields, linked to the movement and shape of raining areas, also contributes to streamflow fluctuations, in particular when the Horton's mechanism of surface runoff formation by infiltration-excess is at work and when the soils are initially dry (see recent typical empirical and modeling studies in [182–185]). At the climate time scales that are central for dam hydropower (monthly and over), the long term memory water storage in soils and snow is as important as the

precipitation input to understand large river flows (see [186,187] for general studies; see [188,189] for soil memory, see [190] for snow storage). Using power spectral density functions of monthly flow anomalies of many large rivers worldwide, Milly and Wetherald [191] show that their “red noise” shape under mid-latitudes can be interpreted as the application of filters with a physical significance to the power spectrum of monthly basin total precipitation. For the Danube River at Orsova (576,000 km²), the conversion of precipitation into surface runoff causes a relatively constant reduction in variability across frequencies while groundwater and surface water storage in the river basin causes a strong reduction in high-frequency variability, hence the “red-noise” shape (see Fig. 6 of this paper based on Fig. 1 in [191]). Gudmundsson et al. [192] investigated the (co-)variability of observed monthly river flows and weather variables (precipitation and temperature) at 358 small catchments in Europe. They give strong evidence that space-time patterns of low-frequency runoff (time-scales larger than one year, including inter-annual and decadal variations as well as trends) follow closely their main atmospheric drivers (precipitation and temperature). They also point that influence of climate may vary largely among rivers, depending on the long-term water budget. In a model-based study of the Colorado River, Vano et al. [193] investigate percent annual variation in runoff with respect to the percent annual variation of precipitation (“elasticity”) and temperature (“sensitivity”). Elasticity is higher in basins where precipitations and/or runoff are lower and sensitivity is positive in small areas, primarily at mid-elevation, while elsewhere most sensitivities are negative (declines of up to 9% per °C increase). In the Iberic Peninsula, the large inter-annual variation of hydropower production (factor 3 between wet and dry years) is modulated by the impact of NAO on December to February (DJF) precipitations and subsequent flows in January to March (JFM). Correlations of up to -0.8 is found between the DJF NAO-index and the JFM streamflows [194].

Mapping streamflows and streamflow regimes, i.e. computing time statistical moments across space, is not a trivial interpolation task since the space organization of streamflows depends on both the branching structure of the river network and the 2D horizontal variability of atmospheric forcing. Two ways are open to derive such maps either using hydrologic models forced by climate variables (see for instance [195]) or interpolating measured streamflows under the constraint of the basins organization (see for instance [196] for instantaneous streamflows and [197] for streamflow statistical moments). Like for wind- and solar-power, the aggregation concept of “filter” or “block-variance” shows how increasing watershed areas from point up to 670 km² smooth the space-time variability of precipitations (reduction of ca. 30%) and resulting local runoff (reduction of ca. 70%) [198]. Statistical scaling unifies spatial streamflow statistics as an emergent property of the above described complex hydrological system [199]. For instance, average or peak river outflow grows i) like the square-root of the basin area over 1 km² and ii) more intuitively like the basin area under 1 km².

6. Three distinguishable regimes of CRE variability

At this point, we have two ways for comparing multiscale variability of the three CRE sources here considered. The first is to analyze the set of illustrative power spectrum densities (PSD) collected from literature and shown in Fig. 6. The second is to analyze the set of characteristic sizes in time and space that we extracted from literature and is shown in Fig. 7. We have discussed the PSD in Fig. 6 in the previous sections. We therefore start this section by general comments on Fig. 7 before deriving some general comments about the scale issues featured by these two figures.

As explained in Section 2, Fig. 7 was derived from correlation information contained in 25 reviewed studies – correlation coefficients between points, space correlograms or variograms, and coherence spectra between points. Each point represents the characteristic size of the space-time patterns of a given CRE at the scale considered in

each study. This presentation allows the compilation of a large number of results in a classical presentation where atmospheric variability is idealized by the space and time characteristics of a series of typical meteorological “objects” proposed by Orlanski [20]. Each type of CRE has its characteristic pattern, as illustrated in Fig. 7 and commented in the following paragraph.

Most points representing wind velocity and wind-power patterns broadly follow the slope defined by the cascade of Orlanski’s objects over a wide range of scales, indicating that classical meteorological circulation patterns are commensurate with wind energy production patterns. The smoothing effect of wind-mills and -farms is clear at scales up to 10 km with wind-power points below wind-velocity points. The atmospheric processes behind solar patterns follow the same tendency at meso-scale but seem to consistently deviate at micro-scales, displaying a steeper slope (Group 1), which is possibly the signature of non-precipitating cloud patterns. This confirms that, at this “plant” scale, solar varies more than wind-power. Rain variability deviates from Orlanski’s objects at scales below a few tens of km, displaying a light break around 10 km (Group 2). Hydrological processes, such as surface runoff and underground storage, are known to be slower than atmospheric processes by, respectively, one (Group 2) and three (Group 3) orders of magnitude as shown at meso- γ to meso- α scales. They show a quite constant multiplicative “delay”, which is obviously interesting in terms of backup capacity for wind- and solar-power. They apparently follow the deviation of precipitation at micro-scales (less than 10 km).

The common slope between rain and hydro becomes steeper and leads to hydrologic variability of the same order of magnitude as wind or solar, which has implications regarding run-of-the-river micro-hydropower. At meso- α scale and over, the spatial size of the patterns linked to precipitation, solar and wind reaches a limit (Group 4). This result could be linked to a practical difficulty to assess correlation ranges given the extent of the investigated areas (see Fig. 5). It might also mean that accumulated patterns are statistically stationary and that perturbations would be the ultimate organizing atmospheric structures that govern CRE patterns in the studied areas. We can notice that wind patterns seem to reach this limit before solar and rain, but these scales are scarcely explored. The points in Groups 0’ and 0’’ describe wind and solar pattern characteristics coming from i) three distinct studies for 0’ [99,118,123] and ii) from the same study covering Scandinavia for 0’’ [200]. Their common hourly time step is seemingly short by almost one order of magnitude compared to the autocorrelation in time of the studied processes, although it is not analyzed in the referred publications. If not linked to a regional specificity, they show that taking by default the sampling time step as a proxy of the decorrelation time may introduce a remarkable bias.

Figs. 6 and 7 consistently invite to define three regimes, or ranges of time and space scales, governing the variability of CRE sources. The first regime is defined by local scales (say up to 1 h and 10 km or micro to meso- γ). In this regime, the three considered CRE sources have drastically different levels of time variability (Fig. 6) and pattern sizes (Fig. 7) in response to small scale atmospheric processes such as cloud and precipitation formation. These scales concern the production technology like the plant design, and also the local stability of grids with the associated question of their “smart” use.

The second regime is defined by regional scales (say up to 300 km and 3 days or meso- γ up to meso- β scales). In this regime, the large perturbation weather patterns consistently control wind and solar production as well as runoff generation, leading to a convergence of their time variability and their pattern sizes. The land surface processes controlling hydropower have nevertheless a clearly distinct type of pattern bringing interesting delays in terms of energy mix. The grid smoothing at the continental scale clearly operates in this regime, considerably diminishing the time variability (Fig. 6). This regime concerns the transport, storage and backup management as well as market issues, and it matches with the best predictability for weather

forecasts.

The third regime is defined by continental scales (meso- β and meso- α) with all CRE sources displaying patterns of comparable space characteristics and no indication of marked temporal trends. These results need to be further strengthened since they concern the long term reliability of these energy sources under changing climate conditions.

7. Electricity demand and residual load

Electricity demand reflects human activity under socio-economical, technological and also climatological drivers, which are, essentially, the sun radiation and the temperature. Considering the distinction between residential and industrial demand, weather seems to have greater impact on the residential sector, and cold weather appears to affect demand more than hot weather [201]. The energy consumed by the industrial sector, including agriculture, is more often studied in terms of management, technologies and policies of energy saving than in terms of sensitivity to climatic factors [202]. Over the last four decades, socio-technical and cultural studies of energy consumption have emphasized the important diversity of human behaviors [203,204]. In California, human activity or life-style proves to largely dominate the other factors and, in particular, climate conditions, which explain less than 10% of the observed individual consumption variability [205]. Nevertheless, taken over an area integrating multiple individual behaviors, and to the exception of a weekly cycle that is purely social, residential electricity demand shows daily and yearly cycles linked to sun radiation and depends on air temperature and cloud cover [206–208].

Temperature dependence patterns (TDP) of energy demand appear as L- to U-shaped curves at monthly [209–211], daily [207,208] and hourly [212] time steps. They mainly reflect “heating, ventilating and air conditioning” consumption (abbreviated HVAC). Their non-linearity is expressed taking the difference between the current temperature and threshold temperatures specific to start heating and cooling in the considered area – the “air temperature turning points” that design the L and U shapes [212]. Turning points evolve in time under the inner logic of social evolution, incorporating climate perception [213] as well as daily and seasonal variations (see [206] for France). In California, based on detailed energy billing, it is shown that the TDP shapes also vary greatly in space [214]. To a lower extent, other weather variables affecting the demand are cloud cover during the winter (see [210] for Italy), humidity in relation with the condensation around air conditioner coils during the summer (see [212] for Japan) and wind velocity (see [215] for Spain).

The power spectrum density (PSD) of the time variability of the load over a control area is i) flat for the base load (frequency over 2–3 days), and ii) follows a $-5/3$ slope for intermediate load (frequencies from 1 day down to 1 h) and peak load (frequencies from 1 h to a few minutes), with peaks of power of one order of magnitude at 24 h and its harmonics (see Fig. 13 in [99], sketched in Fig. 6 of this paper). When interpreting this variability with respect to climate variables, we can see that the base load reflects seasonal variations, whereas the intermediate and peak loads seem to be influenced by turbulent air temperature variations (Kolmogorov's $-5/3$ slope of temperatures associated to turbulent wind [216] except for the 24 h radiation cycle). Beyond climatic considerations, load variations can merely be analyzed and forecast at regional scales along with the main seasonal, weekly and daily cycles that rhythm human activity (see [217] for Australia and [218] for a review).

The notion of residual load (or net load in some studies), i.e. the difference between production and demand at the considered time step, is central. For a given base load generation from conventional power plants, the residual load cannot go below a minimum level, corresponding to the “must-go” for the conventional generation (this level features the system flexibility). The spilled CRE production is

non-linearly linked to this level and to the installed CRE capacity, as shown by studies of PV penetration in Texas [219] and wind penetration in Europe [220]. High penetration of CRE sources will likely increase the hourly residual load variance in the absence of correlation between CRE production and load, as demonstrated for wind power production in Iowa [221] and Scandinavia (Denmark, Finland, Norway, and Sweden) [222]. In the UK, although hourly wind power is weakly correlated to load (ca. 10% of explained variance), the hourly wind power output averaged over hourly peak demand periods is 30% higher than its annual average [118]. In India, negative correlation between wind-power supply and cooling demand during active monsoon phases (low demand, high supply) and breaks (high demand, low supply) exacerbates fluctuations of the residual load [223].

8. Solar- and wind-power complementarity

As seen in previous sections, solar radiation is primarily governed by astronomical considerations. It drives atmospheric temperature, which controls wind dynamics and, in turn, cloud formation. This physics structures the co-variability of solar radiation, wind velocity and temperature, which are the atmospheric variables ruling the balance between solar-, wind-power and energy demand [68]. Weather and climate models represent this physics with varied levels of details. For instance, the link between temperature, pressure and wind is explicitly modeled while the cloud formation is parameterized and thus affected by added uncertainty [224]. The soundness of the way this is modeled is reflected on the quality of short-term predictions of solar and wind fields [225,226] as well as on long-term reanalyses that complement scarce measurements of direct radiation and wind velocity at ground stations [227].

Mixing solar- and wind-power production starts with quasi punctual installations using hybrid renewable energy systems [228]. One set of examples includes emerging concepts of equipment for building roofs [229], vineyard [230] or road [231] monitoring. Another example set is the concept of Virtual Renewable Power Plant (VRPP), which merely consists in showing the local complementarity of CRE. In Portugal, a VRPP of solar and wind-power has shown improvements of the capacity factor of the order of 5% [232].

At the point scale, statistical analyses show the importance of daily and seasonal cycles. Solar radiation has more pronounced cycles than wind [68,233] and a weaker persistence [2]. Beyond this astronomic effect, solar radiation, wind velocity and temperature are weakly correlated. Windy periods are somewhat cloudier: daily correlations between radiance and wind speed are, on average, between -0.4 and -0.2 in Great Britain [233]. Cloudy days are somewhat colder: a daily correlation between temperature and cloud cover of -0.5 , but only of 0.2 between temperature and radiation was observed at US stations [234] and a correlation of 0.23 between demand and radiation, in the UK [2]. In both cases, there is no evidence of lagged correlation, i.e. between one day and the next. At the hourly time step, correlation coefficients between wind speed and temperature, humidity and radiation are lower than 0.35 , i.e. less than 10% of explained variance in selected stations in the US ([235] cited by [236]).

Correlation between solar- and wind-power varies in space and depends on the time scale considered, as illustrated in the two following examples. In Italy, in 2005, the monthly correlation was positive in the north (up to 0.8 over the 12 months) and negative in the south (around -0.6), while the hourly correlation was spottier and showed a clear disparity between negative correlation in mountain areas (where the wind energy is almost twice larger on average) and plain and coastal areas [237]. In Great Britain, for the period 1979–2013 and at the daily time step, Bett and Thornton [233] shows stronger anti-correlation in Atlantic-facing regions than along the east coast (-0.5 to -0.1 from coast to coast in Scotland). This polarity is quite stable through seasons despite the strong seasonality of the weather situations giving clear and calm days (5 times more in

summer) and cloudy and windy days (5 times more in winter).

The important question of the space-time co-variability between solar- and wind-power is, to our best knowledge, tackled in very few published studies. Some examples are given below. The correlation is organized in space at the hourly time step, i.e. at the weather variability scale. For instance, over the Iberic Peninsula, in 2008–2010, consistent meso-scale spatial patterns, called “balancing patterns”, paved the region into areas of concomitant high (or low) wind and solar energy [226]. Identified from a canonical analysis of weather model outputs, these areas display a marked seasonality. Sometimes, like in the winter, distinct patterns show possible balance by integrating solar and wind patterns over a region. Sometimes the patterns are overlapping indicating no possible balance at all scales of space integration. The balancing patterns are related to synoptic scale circulation and to regional topography (the Strait of Gibraltar, for instance, in [226]). This correlation is also organized in space at longer time scales under NAO influence over the Mediterranean Basin, with north-south dipolar patterns that change the winter solar-wind energy availability by 20% [238].

Several studies investigate the “smoothing effect” of the integration of a mix of solar- and wind-power over large territories such as countries or large electricity grids. Most studies concern actual or potential wind- and solar-power sources. Sparse meteorological stations over Central US, considered as a portfolio of solar and wind energy plants (8 and 26 respectively), show that i) the statistical distribution of the portfolio production is much smoother than the distribution of individual plants, reducing notably the probability of no production, ii) both the total production and its standard-deviation vary by a factor of three depending on the fraction of equipment put on each individual plant, and, iii) at a given level of production, the standard deviation of the portfolio production is half the standard deviation of individual plants, where the standard-deviation of the portfolio depends on the covariance between plants [21]. These conclusions are confirmed in similar studies. In Ontario, smoothing increases by adding space integration to the mix [239]. In Sweden, a variation by a factor of 4 of the average national production variance depends on the solar-wind equipment mix ratio with a minimum at 3/7 [200]. In Spain, annealing algorithms allowed to find an optimum setting, defined as the one maximizing the production and minimizing its monthly variance, for a portfolio of solar- and wind-plants [240]. These studies on the smoothing effect of integration are similar to those mentioned for solar- and wind-power separately, under the wording “diversity factor” (Sections 3 and 4). [241] makes the distinction between the smoothing benefit from the space integration of each energy source and from the mix itself. At the hourly scale, over selected areas in China, the smoothing in space is greater for wind- than for solar-power and it equals the smoothing effect of the mix.

The fact of considering the residual load of a mix of solar- and wind-power leads to introduce in the analyses the variability of, at least, a third weather variable governing the demand, i.e. the temperature. Since climatic variables driving CRE production and energy demand are weakly correlated, the space integration and the combination of different CRE sources are expected to first contribute to the base load. They can be adapted to intermediate and peak loads by adding more dynamic control of the demand [21]. Using a weather model over Europe for the 2000–2007 period (ca. 50 km resolution considered as needed to resolve synoptic systems), Heide et al. [32,242] define the optimal mix of wind- and solar-power by applying four criterions to hourly residual load: i) the load variance, ii) the energy storage capacity, i.e. the min-max difference over the time series of cumulated load, iii) the amount of balancing energy, i.e. the time series of the cumulated negative load, and iv) the needed balancing power, i.e. a chosen high quantile in the load distribution. All four criterions depend on the statistical distribution of residual loads, and the third one also depends on the autocorrelation in time. They vary significantly with the mix ratio [242]. On average over Europe, the seasonal optimal mix, i.e.

the one minimizing the monthly variance and the storage need, is of 55% wind and 45% solar, which is a stable figure when the CRE contribution to the demand is over 50% [32]. The optimum varies non-uniformly with the time resolution. The highest shares of solar are around 55% and 60% at weekly and daily scales and the lowest, around 20% at hourly scale [49]. Both require storage capacity. Energy and power balancing decrease significantly when the average CRE contribution is larger than the average demand. An excess generation of 50% allows balancing capacities in agreement with the current “blue batteries” of hydropower from the Alps and Scandinavia [242]. As opposed to no energy flow across national borders, the above hypothesis of a common European control zone decreases the variance of residual load by 50% [49]. Applying a dispatch strategy that minimizes the balancing needs, an upper limit of the synergy between balancing and storage may be defined, showing that a relatively small storage capacity is enough to reduce intra-day balance mismatches [243]. The complementary concept of penetration, i.e. the percentage of actual production that is used considering a given time step, shows that i) a mix with 20–40% solar provides the best penetration in Denmark [244] and ii) an optimum mix of solar- and wind-power can cover up to 50% of the German demand without curtailment and storage [245]. The relationship between CRE penetration rate and the storage needed to avoid spilled production is a powerful analysis tool to economically review projects as the Pan-American solar Grand Plan, when storage and production costs evolve at different paces [246]. The above optimizations are sensitive to storage efficiency, which, for instance varies from 0.9 to 0.6 between pumped-hydro and hydrogen [32]. In a context closer to operational conditions, i) production data over the Pacific Northwest region in the US and forecasting simulations show that a mix can reduce the reserve requirement, i.e. the generation reserve hold by operators [247] and, ii) the geographical choice of solar- and wind-plant settings in southern Australia influences the economic cost of reserve requirement [248].

9. The role of hydropower in a CRE system

In an electric system, hydropower is a useful complement to wind- and solar power since it can be used both for balancing (reservoir type hydropower) and storage (pump type hydropower). Although hydropower is obviously a CRE, very little scientific literature deals with its use in complementarity with solar- and wind-power, despite the fact that they share common driving meteorological and climatological phenomena, and they are supposed to be the three master pieces of a 100% renewable scenario. The difficulty to find appropriate data or models [249], the multiple forms of hydropower harnessing (size, storage, scale of operation), and the potential interactions with other water usages might explain why some authors consider it to be “ill-suited as a third component” in CRE studies [250].

Regarding atmospheric and hydrologic variables controlling the global CRE production, on the atmospheric side, the statistical analysis and modeling of cloud cover, air temperature, precipitation, radiation and wind show very low correlation coefficients between variables at the sub-daily time scale [236]. On the hydrologic side, we saw in Section 5 how the relationship between river streamflow and atmospheric variability simplifies when moving from weather to climate time-scales, i.e. when integrating hydrological processes over time. To our best knowledge, there are more studies that look at the co-fluctuation between atmospheric and hydrologic variables at synoptic time scales [251]. For instance, in Europe, large scale circulation modes or teleconnections as the NAO, the Eastern Atlantic and the Scandinavian Patterns seem to consistently control monthly patterns of wind velocity, temperature and precipitation at continental scale (as well as sea wave heights), which dominate the global CRE production and load balance (see [194,252,253] for Europe and the Iberic peninsula or [254] for Scandinavia). Feedback effects might cause connections between weather variables across scales as, for instance, in

the Mediterranean region, where low winter precipitation and high summer temperatures are connected and where spatial temperature variability is shown to depend on precipitation as well as latitude and altitude [255].

The space-time variability of the energy quantities that make the global CRE production is seldom analyzed as such. For instance, in New-Zealand most of the correlation between daily wind production and hydropower storage levels comes from the seasonal components of both signals and the residuals to these trends are independent [256]. This analysis underlines the need to account for seasonal trends in correlation analyses and brings useful insights for installing wind farms at places where the seasonal variation helps satisfying better the demand. Nevertheless, the storage level in dams is an indicator of hydropower variability that already integrates complex management characteristics of the river stream and the electricity demand.

Most studies investigate the effect of integrating wind-power production on the management of large dams, i.e. dams designed for seasonal balance over medium to large basins (ca. over 1000 km²). They usually do not describe the underlying space or time scales of atmospheric and hydrologic variability. In New-Zealand, hydropower storage has considerable advantages over the installation of new peaking plants [257]. In Quebec, where the wind regime varies dramatically from the coast to the interior [258], time patterns of electricity demand, wind speeds and hydraulic flows show that wind-power requires deterring backup capacity to compensate for wind fluctuations [259]. However, any proportion of wind up to 30% integrated to an all-hydro system improves the risk profile of annual production deficit [249]. At a larger space scale, in Canada, creating better transmission between the wind-power of Alberta and the hydropower of British Columbia modifies emission reduction costs by a factor of 3 [260]. In Europe, the connection between wind power in the North Sea (Denmark, UK) and large Scandinavian hydropower facilities (Norway) was already envisaged three decades ago in a pioneering simulation combining Norwegian hydropower data and converted wind measurements in Denmark [261]. This study concluded that the monthly amounts of transferred energy are massively more important than the amounts stored. This connection is ruled by the NAO and exposed to unfavorable cold and calm situations (NAO-) occurring in March, when the Norwegian reservoirs are at their lowest levels. Under a 2020 wind-power capacity scenario, the UK residual load might be nearly 25% of the present-day average rate of March Norwegian hydropower usage [262].

For intermediate catchment sizes (ca. 200 km²), François et al. [251,263] show different degrees of complementarity between solar and hydro-energy coming from either snow-melt dominated or rain-fed catchments. For much smaller basins (say under 10 km²), the complementarity between solar and hydro-energy looks technically promising under quite contrasted climates in Croatia, whether the seasonality of precipitation and radiation are in phase or not [264].

On a more economical ground, the complementary use of hydro-electricity dams and wind-farms is competitive with the production cost of conventional technologies at regional scales in Mexico [265]. A more complete system modeling shows that i) increasing wind penetration in a dam system of North Carolina yields less profit and more downstream river level fluctuations [266] and ii) properly sized energy storage (not necessarily hydropower), with appropriate forecasting and operation scheduling, allows wind power plants to take advantage of hourly price variations in the spot market [267]. The imbalance created by wind variability has an over-cost compensated by allowing wind farms to submit their bids to the markets together with a hydropower generating unit [268]. Future offshore wind production and grid scenarios in the North Sea lead to less storage activation and hence to cost savings in a balancing-market integration [269], provided that sufficient interconnection and pumping strategies are adopted [270]. More specifically for Norway, wind-power integration leads to increased regional network congestion, lower hydropower production,

higher level of storage, increased spillage of water, and considerably lower price levels [271].

The classical hydropower dams are fed by natural river inflows. Hydropower dams may also be used for storing energy by using pumps fed by wind- or solar-energy to fill either classical dams or specially designed pump storage reservoirs, from a less elevated reservoir [272]. Under the name of “Concept-H”, the use of pump storage hydroelectric power plants is presented as a key element to manage the local variability of CRE, including hydropower [273]. In island settings, pump storage moderately improves penetration. On the Canary Island, a region under the influence of trade winds, adding pumping stations to a conventional hydropower system allows a 2% increase of renewable energy penetration [274], while on Lesbos Island wind energy penetration is limited to 18% when wind energy spillage reaches ca. 50% [275]. The study of local pump storage wind-hydropower plants in Greece indicates variable-speed pump as the most effective solution and a weak sensitivity to wind variability [276]. A decision optimization approach shows a ca. 8% profit gain compared to an only-wind solution in a Portuguese example [277].

Studies dealing with solar-, wind- and hydropower altogether are very rare. Based on a minimum residual load variance, Sousa and Martins [278] show that the actual Portuguese mix of 60% hydro and 40% wind can be improved by developing hydropower, adding 5% of solar power and by dramatically reducing wind power to only 8%, because it is not correlated with the demand. François et al. [279] indicate that introducing a share of run-of-river hydropower modifies the solar- and wind-mix optimizing the CRE penetration over 12 representative European regions.

10. Conclusion

This paper aimed at summarizing the current scientific understanding about the space-time variability of atmospheric and hydrologic variables driving hydro-, solar- and wind-power productions and their joint management in electricity systems. We approached this review with two questions: (1) What are the types of data and their basic characteristics with respect to variability, i.e. resolution and extent? (2) What are the basic characteristics of co-variability in space and time for the three considered CRE sources? A vast body of studies pertains to these questions, and syntheses of these results (this paper and also [40]) highlight the richness of these works and their consistency to build a consolidated vision of the regimes of variability governing CRE production and load.

Concerning the first question, we found that: (i) The types of data used for the analyses of RE sources come from atmospheric model outputs (31% of references), reanalyses (10%), remote sensing images (6%) as well as meteorological (42%) or production (11%) data measured at ground. (ii) The resolution ranges from second and meter to year and continent, and around 60% of the reviewed papers use time resolutions of one hour to one day and space resolutions of 1 km to 100 km. A resolution of at least 50 km and 1 h is recommended. (iii) The time and space extents of the studies range from the day and the meter to the globe and a thousand years.

Concerning the second question, we based our approach on plots of the power spectrum density and plots of characteristic space-time sizes of relevant meteorological variables and renewable energy production. These plots give information about variability, periodicity and typical correlation lengths. We identified three broad climatic regimes governing the variability of renewable production and load. The first regime is defined by local scales (up to 1 h and 10 km), where the three considered CRE sources have drastically different levels of time variability and pattern sizes in response to small scale atmospheric processes and where their correlation is weak. These scales are important for the plant design and the local stability of grids. The second regime is defined by regional scales (up to 300 km and 3 days), which are related to large perturbation weather patterns. The pattern

sizes of wind and solar production as well as runoff generation converge at these scales. The correlation between weather variables, especially in wind and solar power production, is more pronounced at this scale and, in many cases, is negative. This regime concerns the transport, storage and backup management as well as market issues and it matches with the usual best predictability for weather forecasts. Optimal mixes of different CRE sources are commonly studied at this scale. The third regime is defined by continental scales and the long term reliability of these energy sources under changing climate conditions.

Based on our synthesis, we want to highlight some topics that are not sufficiently covered in the literature and should be given more attention in the future. These topics are i) the establishment of a common integrating framework for analyzing CRE variability, ii) the analysis of intermediate and large scales patterns and variability of CRE, iii) the role of the structure of energy transport grids, and iv) the relevance of weather data and/or model outputs used in CRE studies.

We believe there is a lack of a common framework for investigating the integration of CRE in power systems, the different reviewed studies generally tackling sub-problems. The studies focusing on the space integration from grids usually favor dimensionless parameters that avoid choices of technologies or economic elements, while those focusing on cost minimization or technology choices are generally non-grid-connected [239]. The vast majority of studies deals with either a single CRE source or with a combination of two CREs, mostly wind and solar, probably because the most advanced countries in terms of wind equipment have very little hydropower potential (Denmark, Ireland or UK, for instance). Fewer studies examine the large storage capacity and flexibility of hydropower systems that have a large potential for both balancing and storing energy in combination with other RE sources. Several studies look at how to better connect regions with large share of hydropower (e.g. Scandinavia and the Alps) to regions with high shares of wind- and solar-power (e.g. green battery North-Sea net).

The multi-scale nature of the CRE integration challenge invites to explore “blind scales”, in the sense that they are not explored by previous studies in spite of their interest. Various studies consider wind and solar and their co-fluctuation at small time scale. The co-variability of wind- solar and hydropower is, however, linked across a range of scales. On the one hand, they are all directly linked to the 2-D horizontal dynamics of meteorology. On the other hand, the branching structure of hydrological systems transforms this variability and governs the complex combination of natural inflows and reservoir storage. There might therefore be potential adverse or favorable co-fluctuations at intermediate time scales involving water scarcity/abundance that are not yet considered. It could be especially interesting to study how the pronounced large-scale fluctuations in inflow to hydropower (intra-annual) and smaller scale fluctuations in wind- and solar power (daily) interact in an energy system. In the same way, it seems that the debated interest of infra-daily fluctuations for analyzing CRE production varies depending on one's goal, which can be resource assessment or operation reliability. Climate change issues are an additional invitation to develop the integrating framework in question.

The energy transport grid connects CRE and demand variability across scales. There is a need to better represent its intricacy, e.g. how the grid structure and capacity influence the regional- and continental scale variability. This question is further complicated by market issues that appeared during the last two decades. The recent movement towards deregulation in the electricity industry introduces new competitive and market-based mechanisms. Their effect on the reliability of power supply needs to be investigated under current and future climate change conditions.

Last, but not least, the correctness of weather and CRE variability when using either raw or adjusted outputs from numerical weather models for estimating CRE production potential is rarely assessed in the literature. It deserves further investigations since systems that

introduce non-linear transformations and complex interactions might be sensitive to the effective resolution of the numerical weather prediction model, the parameterizations of sub-grid processes, as well as the basic assumptions in the applied downscaling method.

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