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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

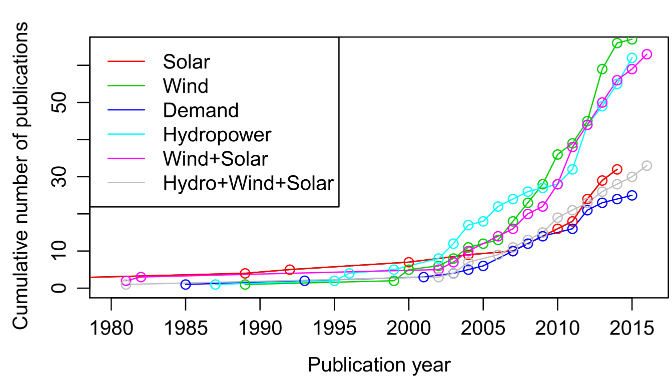

Fig. 1. The accumulated number of references as a function of publication year is reported for each of the sections addressing solar-, wind- and hydropower (Sections 3–5 respectively), demand (Section 7), the combination of solar- and wind power (Section 8), and the combination of solar-wind and hydro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