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Complementarity between solar and hydro power: Sensitivity study to climate characteristics in Northern-Italy

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A B S T R A C T

Climate related energy sources such as wind, solar and runoff sources are variable in time and space, following their driving weather variables. High penetration of such energy sources might be facilitated by using their complementarity in order to increase the balance between energy load and generation. This study presents the analysis of the effect of a 100% renewable energy mix composed by solar and run-of-the-river energy in Northern Italy where these two energy sources are the main alternative energy sources. Along a climate gradient from the Alpine crest (snow melt dominated area) to the Veneto plain (rainfall dominated area), solar power is generated in the flat plain, and run-of-the-river hydropower at two mountainous locations. Covering all possible mixes of these two sources, we analyze their complementarity across different temporal scales using two indicators: the standard deviation of the energy balance and the theoretical storage required for balancing generation and load. Results show that at small temporal scale (hourly), a high share of run-of-the-river power allows minimizing the energy balance variability. The opposite is obtained at larger temporal scales (daily and monthly) essentially because of lower variability of solar power generation, which also implies a lower storage requirement.

1. Introduction

Climate related energy sources (CREs) like solar power, wind power (WP) and hydropower (HP) are important contributors to the transition to a low-carbon economy [35]. At the global scale, the technical potential of CREs covers several times the energy load and thus could be a sustainable way to supply the energy load avoiding, or at least limiting, the use of conventional power plants [19]. Supplying the energy load using only CREs, or at least a high rate of CREs is also likely to be feasible at regional or even local scales as highlighted in recent studies for a number of case studies worldwide (e.g. Ref. [22] with a mix of solar, wind and hydropower for New York (US) state [4]; with a mix of solar and wind for Europe).

One of the limitations for the integration of CREs in the power production system is their high intermittency. The power from CREs and the energy load fluctuate in time and space following their driving climatic variables, mostly precipitation, wind speed, solar radiation and temperature. For instance, spatial variations of hydropower classically originate from the location of major mountain ridges, creating gradients in elevation that enhance precipitations and increase drop heights. This is the case in Scandinavia and the Alps for Europe as highlighted by Lehner et al. [23]. Pronounced spatial patterns may be also observed for wind and solar energies (e.g. Ref. [33] for wind and Ref. [11] for solar). The spatial heterogeneity classically also combines with seasonality. For hydropower, seasonality is expected to be very high in catchments at high latitude or high elevation with snow dominated regimes. Specific space-time organization patterns are also observed for wind and solar energies. At the European scale for instance, the seasonality and spatial heterogeneity of both energies is high, solar according to latitude (highest potential in Mediterranean countries in summer) and wind according to the exposure to Atlantic influence (highest

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potential in Scandinavian countries in winter) [4].

Depending on the space and temporal scales considered, weather variability may synchronize or desynchronize the different CRE sources and the load. This opens the possibility of using a portfolio of CRE production from different regions or different natures, taking advantage of their complementarity to compensate for the intermittency of each individual source (e.g. Refs. [31,32] for wind and solar power respectively; Refs. [36,34] for a wind and solar mix). The complementarity can be derived from the temporal organization of the generation/load signals, from their spatial organization or from their combined spatial-temporal organizations [20]. The latter configuration is the case for the European region, where the potential of wind and solar energies is anti-correlated in space and time (winter vs. summer; North vs South; [4]).

For a given region, the spatial-temporal organization and co-fluctuations of the different CREs and the load pattern determine the optimal mix that should be targeted to minimize the generation-load imbalance. However, the spatial-temporal organization depends on the spatial and temporal aggregation scales and, as a result, the optimal mix may vary. For Europe for instance, the optimal mix between solar photovoltaic (PV) and wind moves from 20% PV at hourly time step to 40% PV at monthly time step, mainly because of the diurnal cycle effect of PV [4].

Whatever the scales and the region under consideration, an important contemporary challenge is therefore to better characterize and understand how power generation from different CREs co-fluctuate among them, and how these co-fluctuations could be used to meet the energy load.

This issue recently motivated a body of works in several regions worldwide. The corresponding analyses are also motivated by the need to better assess storage and transmission facilities required for balancing the generation-load mismatches (e.g. Refs. [14,36]). Application of different storage technologies relates to the spatial-temporal patterns of CREs, ranging from small-scale, distributed (e.g. smart-grid), to large-scale, centralized. For instance, large-scale storage facilities are provided by pumped hydro or hydrogen storage [29]. Pumped hydro consists in transforming excess power, e.g. from intermittent energy sources (wind, solar, runoff), into potential energy by pumping water and storing it at higher elevation. Different concepts have been proposed in the recent years to represent such systems. The "blue battery" concept was introduced for the use of large hydro storage facilities to smooth wind variability. It was extensively applied in a number of regions worldwide, especially in Northern Europe, where wind and hydro potential are high [24]. The Solar Hydro Electric (SHE) concept is used in regions where the solar potential is high [1]. It similarly takes benefit of at least two connected water storage facilities. Water from the lower reservoir is pumped to the upper one using only solar power generation in excess [10]. These two similar concepts could be easily extended to hydro storage systems in a configuration where intermittent energy comes from a mix of wind, solar and run-of-the river hydro power. This actually gives the opportunity to explore the optimal mix for a given region.

This paper raises the question of what the complementarity between "small hydro" and solar energy is under a sensitive climatic gradient. The study region of Northern-Italy, a longitudinal transect linking Alto-Adige to the Po valley, is of interest from three main viewpoints. First, it includes runoff regimes that gradually move from snow-melt dominated to rainfall dominated, with a ratio of solid to liquid precipitation drecreasing from 0.6 to almost 0. François et al. [7] highlighted that this ratio controls the monthly correlation between run-of-the-river and solar power generation within this area, and thus the complementarity between those CREs. This climatic gradient is obviously linked to the elevation above sea level, but it also illustrates expected climate change effects like a temperature rise in the region. Second, this region is characterized by a relatively high level of small run-of-the-river hydropower stations related to the initiatives of private actors or small communities. In Italy, small run-of-the-river hydropower plants (i.e. an installed capacity of less than 3 MW) provide 22% of the annual hydropower energy [12]. Third, like in the rest of Europe, the rate of PV equipment is rather high thanks both to public subsidies and easiness of installation [12].

To assess the complementarity of those different energy sources, we first estimate the variability over time of the energy balance for a given integration time step, defined as the difference between the energy load and the energy production from the mix. Within a storage based management system for instance, if the variability increases, the required storage-to-release cycles would become more frequent calling for more flexible operations. This may be however neither easy to achieve nor feasible due to technical or organization constraints.

As already discussed, storage facility is often used to adjust in time the temporal organization of the production to the temporal organization of the load. The storage required capacity is obviously an increasing function of the balance variability. In this respect, the theoretical storage capacity that would be needed to cover the load and its fluctuation in time for a given mix of the two energy sources is additionally used to estimate their complementarity.

This paper is organized as follows: The description of the study area is given in Section 2. The analysis framework is explained in Section 3. Among other, this section details the models used to estimate energy load and power production from the different energy sources. Section 4 presents the analysis of the generation-load time mismatch for each energy source. Section 5 discusses the corresponding theoretical storage requirements. Finally, Section 6 concludes and presents some outlooks.

2. Study area

The area selected in North-eastern Italy represents a climatic transect crossing part of the Alps and including three main administrative units: Regione Veneto, Provincia Autonoma di Trento, Provincia Autonoma di Bolzano-Southern Tyrol. This transect was selected because it provides a template for the analysis of the water-energy nexus on a climatic gradient from rain fed basins at the Southern edge of this transect to essentially snow-fed catchments at the Northern edge of the transect. The spatial extent of this transect is also relevant for the local stakeholders, since one administrative unit develops its own energy policy, optimizing the joint use of solar and hydropower (see C3-Alps project http//www.c3alps.eu).

We selected four medium size catchments: Aurino at Cadipietra (149.8 km^2), Anterselva at Bagni di Salomone (82.4 km^2), Posina at Stancari (116 km^2) and Leno di Terragolo (173.2 km^2) (Fig. 1). Aurino and Anterselva are mainly snow dominated catchments, whereas Posina and Leno are mainly rain fed catchments. In the following, we exclusively focus on these four catchments because they belong to the two opposite climatic areas along the climate gradient [26] and they are not or hardly influenced by dams and significant diversions (for the Leno, we used a procedure to filter out some slight dam effects based on data from the reservoir managing agencies). The catchments represent typical basin size equipped with run-of-the-river plants (ranging from 5 km^2 to 250 km^2 in this region).

The main renewable energy sources in the area are hydropower and PV. Veneto province is the second largest producer of PV power in the North of Italy. Its PV power capacity reached more than 370 MW in 2011. The surface covered by PV systems is larger than 18 km^2. In addition to private systems located on house roofs, several big PV farms exist. The biggest farm is located in Rovigo