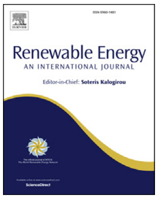
Renewable Energy 87 (2016) 686–696

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene



Increasing climate-related-energy penetration by integrating run-of-the river hydropower to wind/solar mix

B. François [a, b, *], B. Hingray [a, b], D. Raynaud [a, b], M. Borga [c], J.D. Creutin [a, b]

[a] *Université de Grenoble-Alpes, LTHE, 38041, Grenoble, France*
[b] *CNRS, LTHE, 38041, Grenoble, France*
[c] *University of Padova, Dept. Land, Environment, Agriculture and Forestry, Padova, Italy*

ARTICLE INFO

Article history:
Received 26 May 2015
Received in revised form
7 October 2015
Accepted 30 October 2015
Available online xxx

Keywords:
Climate-related energy
Penetration
Energy mix
Complementarity

ABSTRACT

The penetration rate of Climate Related Energy sources like solar-power, wind-power and hydro-power source is potentially low as a result of the large space and time variability of their driving climatic variables. Increased penetration rates can be achieved with mixes of sources. Optimal mixes, i.e. obtained with the optimal share for each source, are being identified for a number of regions worldwide. However, they often consider wind and solar power only.

Based on 33 years of daily data (1980–2012) for a set of 12 European regions, we re-estimate the optimal mix when wild run-of-the-river energy is included in the solar/wind mix. It is found to be highly region dependent but the highest shares are often obtained for run-of-the-river, ranging from 35% to 65% in Belarus and England. High solar shares (>40%) are found in southern countries but solar shares drop to less than 15% in northern countries. Wind shares range from 10 to 35% with the exception of Norway where it reaches 50%. These results put in perspective the optimal 60%–40% wind/solar mix currently used for Europe. For all regions, including run-of-the-river in the mix allows increasing the penetration rate of CREs (from 1 to 8% points).

1. Introduction

Installed capacity of Climate Related Energy (CRE), i.e. solar-power, wind-power and hydro-power, is growing quickly across Europe. A new goal of 27% of renewable share by 2030 has been defined by the EU [5]. For some European countries such as Austria, Spain, Norway or Sweden, this objective is already achieved [21]. On the other hand, the European Climate Foundation states that 100% renewable is an objective to be achieved by 2050 [4]. This scenario is physically realistic even at the global scale since the technical potential of renewable energies covers several times the energy demand [13]. However, it is well-known that this available potential is not equally distributed over space [2]. In Europe, solar power potential is much higher in Southern countries than in the Northern ones. For wind power, it is the opposite with higher potential in the north and along the shores [15]. show that the space distribution of hydropower potential relates with the mountain ranges in Europe: higher is the altitude, the higher the hydropower potential. Ref. [11] illustrated that Europe could take advantage of combining different CREs allowing a limited use of conventional power.

Even though it is not yet clear what will look like such a 100% renewable energy mix, solar and wind energy sources are expected to be important contributors. The main reason is that, contrary to biomass, their weather driving variables (i.e. wind, solar irradiance and temperature) are exploitable everywhere in Europe [20].

For a 100% scenario at the European scale [2]; shows that the mix composed by 60% of wind and 40% of Photo-Voltaic (PV) minimizes the monthly energy balance variance which governs the balancing costs related to energy transport and storage. The hourly energy balance variance is however minimized with a lower share of solar due to its diurnal cycle [11]. show that even if a certain rate of fossil-nuclear still remains in activity (for instance covering lower than 50% of the energy demand on average), the optimal share between wind and solar would not differ significantly [12]. find that oversizing solar and wind power capacities modifies the optimal mix minimizing the storage requirement. Following these studies, Ref. [23] show that the highest penetration rate is obtained in Germany for a wind power share ranging from 60 to 80%.

In some ways, hydropower is never explicitly included in the

---

* Corresponding author. CNRS, LTHE, 38041, Grenoble, France.
E-mail address: baptiste.francois@ujf-grenoble.fr (B. François).

http://dx.doi.org/10.1016/j.renene.2015.10.064

mix computation but considered as a storage facility. Indeed, large hydropower storage is used for balancing production and load mismatches. In this sense, the term of ‘blue battery’ is used when referring to the huge energy storage capacity provided by Scandinavian or Alpine reservoirs [17]. Less attention is paid to small run-of-the-river power (hereafter denoted as RoR power), even if the amount of energy produced is important in several places. In Italy for instance, small run-of-the-river hydropower plants (i.e. with a power capacity lower than 3 MW) provide 22% of the annual hydropower energy which reached 45,823 GWh in 2011, i.e. about 24% of the electricity consumption [25]. In Switzerland, 26% of the generated power is generated by run-of-the river power plants [1]. Even though RoR potential is already significant in Europe, new RoR power plants are under-construction or planned. For instance, an increase of about 33% of small RoR power capacity is under-study in Scotland [18].

In Northern Italy, the challenge of integrating run-of-the river power into the combination with solar energy source starts to be investigated [6]. Different degrees of complementarity are obtained, depending on the hydrological regime of the considered catchments (snow- or rainfall-dominated regimes) and on the time scales (e.g. hourly, monthly).

This study investigates how the use of RoR hydropower coming from uncontrolled river flows may increase the global penetration of climate related energies under the hypothesis that only solar, wind and RoR power are used to meet the demand. We use a benchmark set of 12 regions spread across Europe and covering a wide variety of climates. Neither storage nor transport among regions is considered in this study.

The paper is organized as follows: The description of the study areas and the databases are given in Section 2. The analysis framework is detailed in Section 3. Results are presented in Section 4. Section 5 concludes and gives some outlooks for future research directions.

2. Study areas and dataset used

Fig. 1 locates the different areas selected for this study. In the following, although the areas do not match country border, they will be referred for convenience with country or region names. As the surface area of each domain is roughly 40,000 km^2 (Table 1), we assume that they are large enough for being representative of the in-situ climate, both in terms of weather variable average and time variability. These domains are chosen for two main reasons. First, they represent a variety of climates in Europe moving along two climatic gradients: the north-south gradient mainly explores changes from Scandinavian to Mediterranean hydro-climatic regime. The west-east gradient explores changes from oceanic to continental climate. Second, they correspond to watershed heads. There is therefore no contribution of upstream areas to river flow within the considered domain and the whole hydropower production that can be harvested within the domain does only depend from runoff production within the domain.

Hydro-meteorological data used to assess energy production and demand for the 1980–2012 period are obtained from different observational datasets and models. Daily temperature and precipitation data come from the European Climate Assessment & Dataset (ECAD [10]); with a 0.25° space resolution.

In the present study, wind and solar radiation data are pseudo-observations obtained from climate simulations with the Weather Research and Forecasting Model when forced with large scale atmospheric fields from the ERA-Interim atmospheric reanalyzes (hereafter noted as WRF; [22]). Wind power generation is estimated at a daily time step from mean daily wind speed with a daily production function identified in a preliminary step from 3 hourly wind speed data (see Section 3).

Gathering long time series of runoff observations for unregulated watersheds is also challenging, if not impossible in populated areas. Only seven water discharge time series could actually be obtained for seven out of twelve regions thanks to the Global Runoff Data Center [8]. Unregulated runoff are thus obtained via simulation, for each grid cell of each region with a distributed version of the GSM-Socont hydrological model [19]. This model simulates the snowpack dynamic (snow accumulation and melt), water abstraction from evapotranspiration, slow and rapid components of river flow from infiltrated and effective rainfall respectively. It uses daily precipitation, temperature, and wind speed from above cited databases. A unique set of parameters is used for all regions. It was calibrated from comparisons of simulations and GRDC discharge data.

Observed electricity demand data are obtained from the European Network of Transmission Systems Operators of Electricity (ENTSOE, https://www.entsoe.eu/home/). Data are however only available from 2006. Tunisia and Belarus are not members of the ENTSOE network; and, to our knowledge, there is no auxiliary database available for these two countries. We therefore also reconstructed electricity demand time series for all regions and for the whole analysis period (back to 1980) with a climate-driven demand model developed from regions and periods with observations (Section 3).

3. Study framework

This section describes the computation of the different elements needed in our analysis: i) the power time series obtained from PV solar, wind and RoR, ii) the energy load time series and iii) the penetration rate for a given energy mix. Power generation from solar, wind and RoR are computed for each grid cell *i* and are then summed for each region. For the sake of simplicity, we assume that all grids have the same power capacity, i.e. the same level of equipment for each energy source. We further assume that each region is autonomous: there is no energy import/export with neighboring regions. We consider energy mixes based on solar photovoltaic, wind and RoR hydro only. In other words, we assume that the regional demand can be only satisfied (or not) with the production obtained within the region from these three energy sources. The study framework is applied to the 12 regions presented on Fig. 1.

3.1. Solar power (photovoltaic)

The solar power generation from a photovoltaic generator (P_{PV}) at a given time *t* and from the grid cells indexed by *i* depends on the global solar irradiance I_{eff} (Wm^{-2}) and the air temperature T_a (°C) [9] through the following expression [16]:

$$P_{PV}(t) = \sum_i B\, I_{eff}(t,i)\Big(1 - \mu\,\left(T_a(t,i) - T_{c,STC}\right) - \mu\, C\, I_{eff}(t,i)\Big), \tag{1}$$

with *B* a constant production parameter, defined as the product of the surface area of the PV array (m^2) by the generator and invertor efficiencies (%), and with μ and *C* respectively the temperature and the radiation dependent efficiency reduction factors (%). $T_{c,STC}$ (°C) is the photovoltaic cell temperature corresponding to standard test conditions [26].