Energy Reports 2 (2016) 221–228

Contents lists available at ScienceDirect

Energy Reports

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

The optimal share of wave power in a highly renewable power system on the Iberian Peninsula

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ARTICLE INFO

Article history:
Received 20 April 2016
Received in revised form
11 August 2016
Accepted 19 September 2016

Keywords:
Renewable energy systems
Wave energy
Iberian power system
Pelamis power converter
Energy modelling
Optimal mix of renewable energies

ABSTRACT

In a highly renewable future pan-European power system, wave power might complement the renewable generation mix in a beneficial way. The potential of wave energy is estimated to be highest at Western European coastlines. Thus, the Iberian Peninsula is characterized by high wind, photovoltaic and wave resources. Five years of data on generation and load were used to identify the optimal share of wave power in a fully renewable power system on the Iberian Peninsula. This optimal share is defined by the minimization of needed backup energy from dispatchable sources in the system. First, the properties of the mix are investigated for the case of an isolated Iberian power system. Second, the mix is investigated when the Iberian Peninsula is connected to a fully renewable pan-European power system. The optimal share of wave power on the isolated Iberian Peninsula with respect to the need for additional backup is found to be 25% (wind 52%, photovoltaics 23%). This optimum does not change significantly, if hydro power is added to the generation mix. If compared to a system without wave power, the benefit from wave power equals an reduction of 6–8% of the backup energy need. For a fully connected European power system, the optimal mix on the Iberian Peninsula is determined to be 21% wave, 4% PV and 75% wind.

1. Introduction

An enormous amount of energy is carried by ocean waves. However, no significant shares of the European power mix are contributed from oceanic energy (wave and tidal) today. This might change in the future. Studies suggest that by 2050 oceanic sources might contribute a few percent to the European generation mix (Pfluger et al., 2011). The background is the European energy transition, which includes an increasing share of energy from renewable sources (Eurostat, 2015). Major reasons behind the worldwide observed shift from conventional controllable generation to renewable intermittent generation from sources like wind or photovoltaics (PV) are decarbonization and sustainability (Roadmap, 2010).

It comes with a major challenge: The fluctuating nature of renewable sources makes their integration into power systems difficult. Renewable generation facilities do not produce when there is need but in dependency of the meteorological conditions. Solutions to this include storage (Rasmussen et al., 2012; Heide et al., 2011; Budischak et al., 2013; Steinke et al., 2013; Weitemeyer et al., 2015), the extension of the transmission grid (Becker et al., 2014; Schaber et al., 2012), overinstallation of generation facilities (Heide et al., 2011) or an optimal mix between different renewable sources (Heide et al., 2010; Kies et al., 2015; François et al., 2016).

Besides wind and PV (and to some extent hydro), which are likely to be the major energy contributors of the future European power system, wave power is another source able to complement the European power mix. Although there is a certain relationship (in a steady state (wave power) $\propto$ (wind speed)^3 Ochi, 2005) between wind and wave power and combined wind/wave power generation units are in development (Kallesøe et al., 2009), wave power has the advantage of being more predictable than wind or PV power.

The idea of using oceanic energy to generate electricity dates back centuries (Salter, 1974; Evans, 1976) and research on the use of wave energy was promoted by several programs in Europe in the 1980's and 1990's (Clément et al., 2002; López et al., 2013). Speaking of Europe, wave power resources are mostly available at the western coasts. The atlantic potential is estimated to be ca. 4–5 times higher than in the North Sea. For Denmark, the optimal share of wave among wind and PV was investigated and found to be 30%,

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http://dx.doi.org/10.1016/j.egyr.2016.09.002

if renewable penetration exceeded 80% of demand (Lund, 2006; Lund and Mathiesen, 2009). It was also shown for Ireland that power generation from wave and wind correlate little and their combination would increase the reliability of power production (Fusco et al., 2010).

For Spain several studies were carried out to identify the potential of wave power for different locations (Iglesias and Carballo, 2010a; Iglesias et al., 2009; Iglesias and Carballo, 2009, 2010b). Other studies investigated the local potential of wave power for example for Brazil (Contestabile et al., 2015) or the Black Sea (Rusu, 2015).

Aside from Europe, wave power might also complement power systems around the globe. Several studies exist on the worldwide potential. Estimates vary in methodology and findings: Ca. 2 TW, of which 5% might be extractable (Gunn and Stock-Williams, 2012) or between 1 and 10 TW (Thorpe, 2010).

This paper has the following objectives: (i) Finding the optimal share of wave power in a highly renewable power system on the Iberian peninsula. (ii) Investigating the possible benefit with respect to the backup energy need from the inclusion of wave power. (iii) Calculating transmission capacity needs around the Iberian Peninsula for a fully renewable (average generation from renewables equals average load) Europe.

2. Methodology and data

The optimal mix of wind, photovoltaics and wave power is determined for the Iberian Peninsula. Spain and Portugal are a suitable choice for this investigation, because they have a high potential for all three technologies. To determine the optimal share, the need for backup energy of an isolated Iberian Peninsula in dependency of the renewable mix is investigated. In a fully renewable scenario without consideration of losses, this need equals the excess energy.

2.1. Generation and load

A large weather database was used to simulate feed-in from the renewable sources wind, photovoltaics (PV) and hydro. Generation from wind and photovoltaics was simulated on a grid with a spatial resolution of 7 × 7 km and an hourly temporal resolution. Inflow into hydro storages is calculated using a potential energy approach with runoff data from a reanalysis dataset (Dee et al., 2011). Detailed information on the weather database is given in Kies et al. (2015) and Kies et al. (2016). To simulate generation from wave, measurement data for significant wave heights and wave energy periods from buoys was used.

In general, energy of waves can be described by the wave energy flux, given by

$$P = kH_{m0}^2 T_e, \tag{1}$$

where H_{m0} is the significant wave height and T_e the wave energy period. k is a constant given by

$$k = \frac{\rho g^2}{64\pi}, \tag{2}$$

where g (≈ 9.8 m/s^2) is the constant of gravitational acceleration and ρ the density of water. This equation is valid under deep water conditions and is assumed to be a good approximation at the buoy locations (McCormick, 2013). To calculate power from the measured values, the power matrix of a Pelamis wave energy converter (Silva et al., 2013; Drew et al., 2009) was used. The buoys, whose data was used, are located around the Spanish coast (Fig. 1). Hourly data was used from 2004 to 2008 and missing hours (less than 10% of all hours) were taken care of in the following way: If up to three hours in a row were missing, data was linearly interpolated. If days were missing, data was taken from the previous month. If months were missing, data was taken from the previous year. The daily generation in 2007 for all four sites is shown in Fig. 2. The three north-western locations (2–4) have very similar feed-in patterns. Location 1 has a much lower generation due to comparably unfavourable wave conditions. Besides, a strong seasonal pattern with low generation in the summer and considerably more generation in the rest of the year can be observed at all four locations.

In addition to generation data, load data is required for the following investigations. For the load of all considered European countries historical data provided by the *European Network of Transmission System Operators for Electricity* (ENTSO-E) was taken. This data was modified within the RESTORE 2050 project.[1] Modifications include modelled load profiles from e-mobility and heat pumps to account for expected changes in the future.

2.2. Model description

The topology of this European power system is shown in Fig. 1. It consists of European countries aggregated to single nodes with the exception that Spain and Portugal are treated as a single node. The nodes are connected via transmission links as shown. Each node has generation time series for wind $G_n^W(t)$ and PV $G_n^S(t)$. In addition, some nodes have dispatchable generation from hydro power $\tilde{G}_n^H(t)$ and the Iberian Peninsula has a generation time series from wave $G_n^O(t)$. Details on the generation mix for each node are given in the Appendix. Together the time series of non-controllable renewable generation (wind, PV, wave) compose the generation of the node,

$$G_n(t) = \sum_j G_n^j(t). \tag{3}$$

The corresponding time series of the mismatch between generation G and load L is

$$\Delta_n(t) = G_n(t) - L_n(t), \tag{4}$$

or, if transmission is included,

$$\Delta_n(t) = G_n(t) - L_n(t) + P_n(t), \tag{5}$$

where $P_n(t)$ is the injection pattern (Imports–Exports). Details on the transmission model are given in Section 2.5. At each node and at all times, the power system must be balanced. This leads to the nodal balancing equation

$$G_n(t) - L_n(t) = C_n(t) - P_n(t) - B_n(t), \tag{6}$$

where $B_n(t)$ is the additional backup (i.e. dispatchable generation like gas power plants) and $C_n(t)$ is the excess energy that is curtailed. The backup time series is calculated as

$$B_n(t) = \max\left(\{0, -\Delta_n(t)\}\right), \tag{7}$$

where $\Delta_n(t)$ is the mismatch after transmission (Eq. (5)). The left part of the balancing equation (Eq. (6)) is the active part that is determined by the given data, while the right side is the reactive part, i.e. the response of the system. More generally, this equation could be extended by additional terms to account for storage, demand side management etc. After generation, load, and transmission the remaining residual mismatch is handled by the

[1] Frank Merten, Wuppertal Institute, Private Communication via E-Mail, 2014.