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

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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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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.

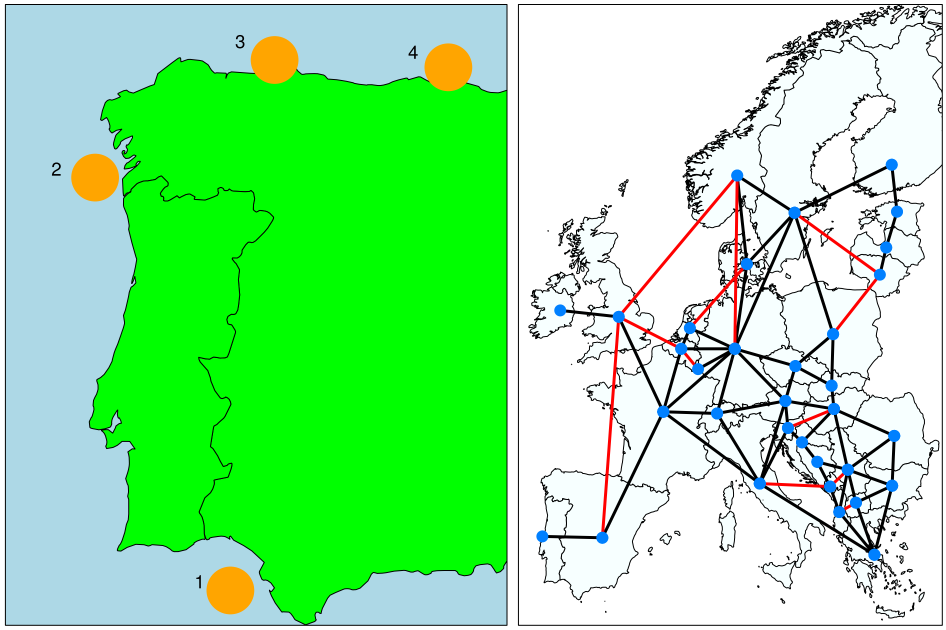

Fig. 1. Left: Locations of the buoys whose data was used for wave power calculations. Right: The topology of the investigated simplified European power system. Countries are treated as nodes, which are interconnected by links. Blue links indicate existing inter-country connections, red lines planned. Portugal and Spain are treated in the simulations as a single node. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

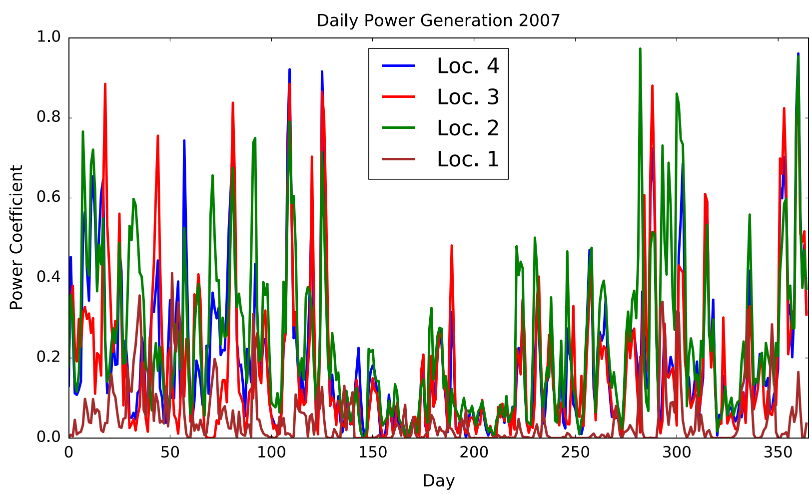

Fig. 2. Daily generation from wave power for different bouy locations computed using the power matrix of a Pelamis power converter (Silva et al., 2013; Drew et al., 2009). The locations of the buoys are illustrated in Fig. 1.

backup (if $\Delta_n < 0$). The backup energy need in the given period of time T is computed via

$$B_n^E = \int_T B_n(t)dt. \quad (8)$$

The share of renewable generation of a node is denoted as α_n and is defined via

$$\alpha_n = \frac{\langle G_n(t)\rangle}{\langle L_n(t)\rangle}. \quad (9)$$

The share of renewable generation of the whole system consisting of multiple nodes is given by

$$\alpha = \sum_n \alpha_n \frac{\langle L_n\rangle}{\langle L\rangle}. \quad (10)$$

By convention of terminology, $\alpha \geq 1.0$ refers to a fully renewable scenario.

2.3. Conventional generation dispatch strategy

For $\alpha < 1.0$ the difference between average load and average renewable generation is assumed to be covered by perfectly flexible conventional generation G^C. Technologically this might be similar to the backup power that is investigated (e.g. highly flexible gas turbines). However, it is treated in a different way and independently. This conventional generation is assumed to have neither power nor ramping constraints. The generation from conventional sources in node n is given by

$$G_n^C(t) = -c^C \min\left(\{0, \Delta_n(t)\}\right), \quad c^C \in (0, 1], \quad (11)$$

where the constant of conventional generation c^C is determined by the share of renewables,

$$c^C = (\alpha - 1)\frac{\langle L\rangle}{\langle \min\left(\{0, \Delta\}\right)\rangle}. \quad (12)$$

Δ_n is the residual mismatch after transmission and the use of dispatchable renewable sources (hydro). This can be understood as: If there is a residual load after renewable generation and transmission, a fixed share of this residual load is covered by these dispatchable sources.

2.4. Hydro usage strategy

Hydro power on the Iberian Peninsula is modelled as a storage (reservoir capacity κ_H^S: 21 TWh, generation capacity G_+^H: 20.5 GW) with a natural inflow of ca. 23 TWh per year. These numbers were derived within the RESTORE 2050 project (BMBF, Fkz. 03SFF0439A). It is assumed that the use of hydro is free of losses. Generation from hydro $\tilde{G}^H(t)$ is then calculated as

$$\hat{G}^H(t) = \max\left(\{0, -\Delta_n(t)\}\right), \tag{13}$$

$$\tilde{G}^H(t) = \min\left(\{\hat{G}^H(t), G_+^H, S^H(t)\}\right), \tag{14}$$

where $S^H(t)$ is the hydro energy storage filling level. $\Delta_n(t)$ is the mismatch after transmission. This means that hydro is used whenever possible with respect to the constraints.

2.5. Transmission

The nodes of the model are connected via links. Hence, nodes can exchange excess energy and partially balance their mismatches. For transmission the equations of a full electric power-flow in an alternating current (AC) electricity network are used in a common linear approximation (Oeding and Oswald, 2004). The transmission is formulated as an optimization problem that consists of two steps and reads in the first step:

$$\underset{P(t)}{\text{minimize}} \quad \sum_n B_n(t) =: B^{\min}(t) \tag{15}$$

$$\text{subject to} \quad \sum_n P_n(t) = 0 \tag{16}$$

$$\mathrm{F}_l^- \le \left[K^T L^+ P(t)\right]_l \le \mathrm{F}_l^+. \tag{17}$$

This first step minimizes the required backup energy at every single time step and fixes it for the second step. However, the solution P is generally not unique. Therefore the program consists of two steps. The second step ensures the uniquety of the solution by minimizing the dissipation $\sum_l F_l^2 = \sum_l \left[K^T L^+ P(t)\right]_l^2$:

$$\underset{P(t)}{\text{minimize}} \quad \sum_l \left[K^T L^+ P(t)\right]_l^2 \tag{18}$$

$$\text{subject to} \quad \sum_n P_n(t) = 0 \tag{19}$$

$$\mathrm{F}_l^- \le \left[K^T L^+ P(t)\right]_l \le \mathrm{F}_l^+ \tag{20}$$

$$\sum_n B_n(t) = B^{\min}(t). \tag{21}$$

The result is the injection pattern $P(t)$ as the unique solution of the optimization problem. The incidence matrix K is defined as

$$K_{nl} = \begin{cases} 1 & \text{if link } l \text{ begins at node } n, \\ -1 & \text{if link } l \text{ ends at node } n, \\ 0 & \text{otherwise,} \end{cases} \tag{22}$$

and the Laplace Matrix L is given by

$$L_{nm} = \begin{cases} -1 & \text{if node } m \text{ and } n \text{ are connected by a link,} \\ \deg(v_n) & \text{if } n = m, \\ 0 & \text{otherwise.} \end{cases} \tag{23}$$

L^+ refers to the Moore–Penrose pseudoinverse of the Laplacian. This transmission model is described in more detail in Heide (2010). An equivalent transmission model is used in Becker et al. (2014), Heide et al. (2011) and Kies et al. (2016). If the transmission links have no limits $F_l^\pm$ imposed, the transmission capacity of a link in one direction connecting two nodes is defined by the 99th percentile,

$$0.99 = \int_0^{\kappa_l^T} p(|F_l|)dp, \tag{24}$$

where $p(|F_l|)$ is the time sampled distribution of the absolute flows over the link. A transmission capacity computed this way is thus sufficient in 99% of the time.

3. Results

This section is split into two parts. First, the case of an isolated Iberian Peninsula is investigated and the optimal mix of generation determined. This scenario is justified if the inter-country transmission grid of today is not strongly reinforced by the time high shares of renewables in the power mix are reached. Second, the Iberian Peninsula is connected to the European power system. For this scenario again the optimal mix is determined. To find the optimum the backup energy need is computed for different mixes of generation from different sources of renewables (β_n^j), $j \in (W, S, O)$ and n being the Iberian Peninsula:

$$B_n(t) = B_n(\beta, t), \tag{25}$$

$$\beta_n^j = \frac{\left\langle G_n^j \right\rangle}{\sum_j \left\langle G_n^j \right\rangle}. \tag{26}$$

The corresponding optimization problem reads

$$\underset{\beta}{\text{minimize}} \quad \int_T B_n(\beta, t)dt \tag{27}$$

$$\text{subject to} \quad \sum_j \frac{\left\langle G_n^j \right\rangle}{\langle L_n \rangle} = \alpha - \frac{\langle G_n^H \rangle}{\langle L_n \rangle}. \tag{28}$$

This minimum defines the optimal mix. $\langle G^H \rangle$ is the average generation from hydro power.

For a renewable share of 100% ($\alpha = 1$) the backup energy need for the isolated Iberian Peninsula in dependency of the renewable mix with and without hydro power can be seen in Fig. 3. If no hydro is included and thus only generation from wind, PV and wave is considered, the minimum is found to be 20.8% of the consumption. This corresponds for a single year to approximately 75 TWh of backup energy. This minimum occurs at a mix of 52% wind, 23% PV and 25% wave. Without wave the minimum of the backup energy need is 22.1%. This minimum is reached at a mix composed of 77% wind and 23% PV, i.e. the share of wave power is fully replaced by wind power (!). Expressed in terms of energy, this relative reduction of approximately 6% (wave vs. no wave) or 1.3% of the total consumptions equals approximately 6 TWh annually. This is the possible benefit from the complementary adding of wave power to the optimal mix.

If hydro is included in addition to the three other sources and used in the simple way described in Section 2.4, the optimal mix of wind/PV/wave is virtually unchanged (51% wind, 23% PV and 26% wave). At the optimal mix the need for backup energy equals 14.8% of the consumption. It can be seen that the backup energy is reduced by the controllable nature of hydro power, but the dependency on the mix remains very similar. If hydro is considered but wave is not, the minimum is at 16.1% of the consumption for a wind share of 74% and a PV share of 26%. Hence, adding wave power leads to a relative reduction of the backup energy need at the optimal mix of 8% which is equal to approximately 6 TWh/a.

Thus, the benefit of adding wave power to the optimal mix is very similar, whether hydro power is included or not.

If the renewable share α differs from one, results for the backup energy need can be seen in Fig. 4 (top). The optimal mix was calculated for every discrete value of α (and the four setups shown) and the backup energy need calculated. For a renewable share of 70%, the need for backup energy is reduced by approximately 0.6% of the consumption, if wave power is added. This equals an relative reduction in the range of 10%–15% (with and without hydro). For $\alpha > 1$ (overinstallation) the relative benefit from wave keeps growing. At $\alpha = 1.1$, when average generation from renewable sources is 10% higher than average load, the reduction of the backup need due to complimentary wave power equals 1.4% of the consumption. This is a relative reduction of ca. 10% with or without hydro.

What happens, if the Iberian Peninsula is no longer isolated? Instead, it is assumed to be connected to a fully renewable European power system (i.e. $\alpha_n = 1$ for every country) with unlimited transmission capacities. Wind/PV mixes and relative loads are given in the Appendix. This is the opposite end of the possible spectrum of realizable transmission scenarios. Fig. 4 (bottom) shows the need for backup energy in dependency of the mix. Hydro power is not considered here. The minimum of backup energy need achievable on the Iberian Peninsula is 13.5%. This minimum is reached at a mix of wind 75%, PV 4% and wave 21%. Without wave, the optimal mix is 93% wind and 7% PV resulting in a need for backup energy of 14%. The relative reduction of 4% is slightly smaller than in the isolated case (6%). Major results of all setups are briefly summarized in Table 1.

4. Discussion

The two discussed cases (isolated vs. unlimited transmission) are the two possible extremes for the transmission system. To judge which is more realistic, the required transmission capacities of unlimited transmission are computed and compared with values realized today (Net Transfer Capacities 2010/2011, published by ENTSO-E) and planned extensions (Ten Year Network Development Plan 2016). Transmission is modelled as described in Section 2.5. Transmission capacities of each link are computed according to Eq. (24). The resulting transmission capacities around the Iberian Peninsula are shown in Fig. 5. Three values of transmission capacities of links topologically close to Spain are shown: The first value is the NTC reported for 2010/2011. The second value is the expected one for 2030 by the 2016-TYNDP (2030 visions, ENTSO-E, 2016). The values from the 2016-TYNDP correspond to an expected share of renewables in the power mix in Europe of 60%. The third value is the calculated transmission capacity (Eq. (24)) required for unlimited transmission in the fully renewable scenario ($\alpha = 1$). The most striking aspect is: Even if the planned reinforcement of the transmission capacities described in the TYNDP between the Iberian Peninsula and the remaining Europe is realized, these 8 GW are merely 15% of the transmission capacity (63.2 GW) necessary to realize a transmission grid that is able to transport all surpluses. This apparent discrepancy is not caused by wave but also found in other studies. In Rodriguez et al. (2014) the required transmission capacity for the link from Spain to France able to transport all surpluses in a fully renewable (wind/PV) Europe is calculated to be 75 GW. For the other links shown in the figure the discrepancy between expected values and need for unlimited transmission is considerably less.

The optimal mix of the isolated Iberian Peninsula is roughly 1/2 wind, 1/4 of PV and 1/4 of wave no matter whether hydro power is included or not. This is very close to findings for the optimal mix of the Danish power system. In Lund (2006) the optimal generation mix of the Danish power system is described to be 20% PV, 30% wave and 50% wind, if the renewable share exceeds 80%. This mix is optimal with respect to the produced excess energy (note: in the methodology of this paper, the optimum with respect to the produced excess energy is equivalent to the optimum with respect to the need for backup energy).

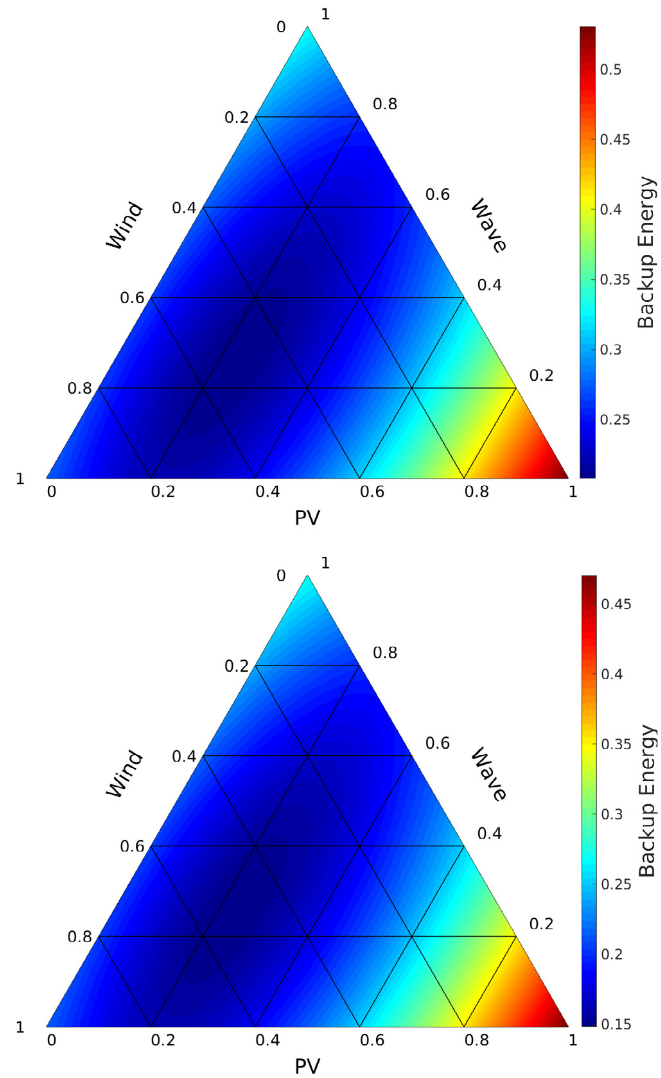

Fig. 3. Backup energy need of the isolated Iberian Peninsula in units of the consumption in dependency of the wind/PV/wave generation mix. Top: Without hydro. Bottom: With hydro.

If wave power is not included in the Iberian power mix, the optimum is ca. 3/4 wind and 1/4 PV, so the share of wave power is entirely moved to wind power. This finding is similar to findings for the entire European power system; For a fully renewable wind/PV power system in Europe, the optimal mix between wind and PV was found to be 20% with respect to backup energy (Kies et al., 2015) or 40%, if the standard deviation of the monthly mismatch is minimized (Heide et al., 2010). If the Iberian Peninsula is connected to a fully renewable European power system, the optimum is identified to be 75% wind, 4% PV and 21% wave and changes to 93% wind and 7% of PV without wave. This very low share of PV is most likely due to the fact that wind speeds over distances of hundreds of kilometres have little correlation (Hasche, 2010). Thus, the Spanish wind share can be well fed into the European power system and vice versa.

It should be noted that considerations of the wave energy potential of the Iberian Peninsula are not within the scope of this work. Anyhow, if the wave energy flux is estimated to be

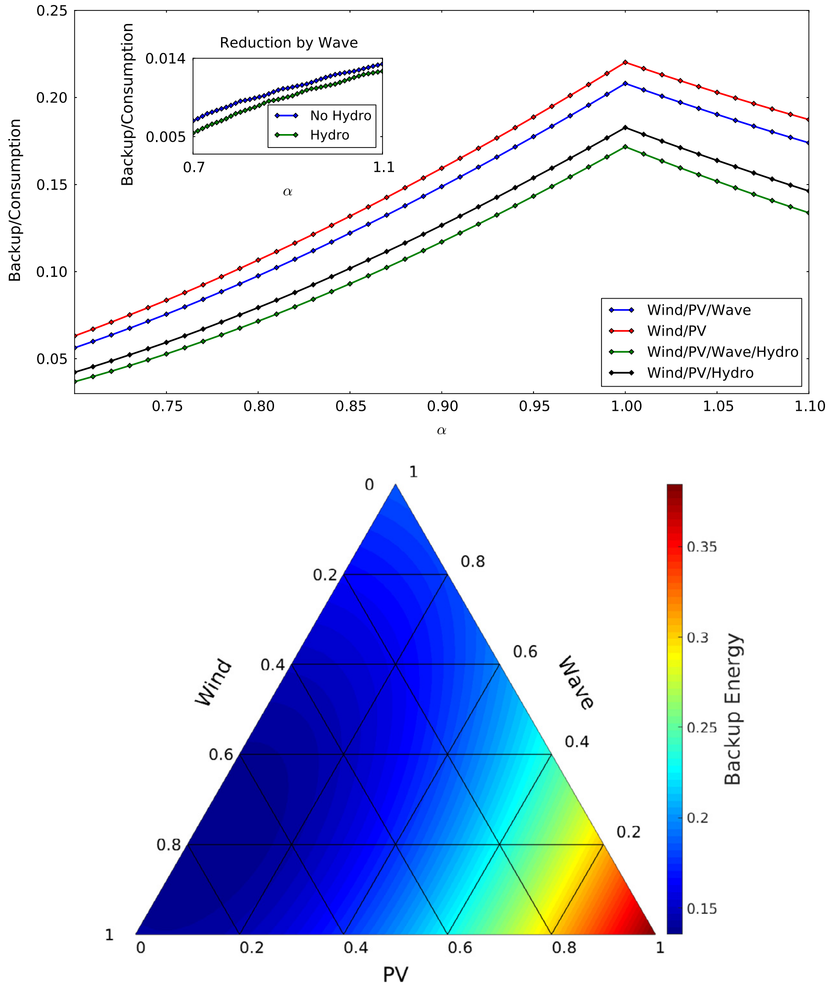

Fig. 4. Top: Backup energy need in the power system of the isolated Iberian Peninsula in dependency of the share of renewables (α) for the optimal mix in units of the consumption. For $\alpha < 1$, conventional generation was used as described in Section 2.3. The enclosed Fig. shows the difference of backup energy need for the optimal mix with and without wave. Bottom: Backup energy need of the Iberian Peninsula in units of the consumption in dependency of the renewable generation mix from wind, PV and wave for $\alpha = 1$. Unlimited transmission capacities for all European links are assumed.

Table 1
Backup energy need and the optimal share of wave for the three setups on the Iberian Peninsula. A renewable share of 1 is assumed for all cases. Backup energy is given in units of the consumption.

	No hydro/isol.	Hydro/isol.	No hydro/conn.
Backup energy/wave	0.208	0.148	0.135
Backup energy/no wave	0.221	0.161	0.14
Optimal share wave	0.25	0.26	0.21

around 30 kW/m – as at the northwestern Iberian nearshore environment (Rusu, 2014) – and if all 700 km of the Spanish coastline were to be populated with wave power plants, this would equal a constant power inflow (at 100% efficiency) of ca. 20 GW, which is only ca. 50% of the Spanish energy demand. Thus, 20% of wave power in the mix on the Iberian Peninsula do not seem to be technologically realizable. All the results in this paper were aiming at optimality with respect to the need for backup energy and can be seen as a complimentary solution to the general problem of renewable power feed-in: The generation–load-mismatch problem. Considered at an early stage, the optimal mix of power generation can contribute to the solution of the generation–load-mismatch problem in a cost-efficient way. If storage capacities were to be considered instead of backup, the optimal mix might be shifted, because storages are more sensitive towards extreme weather conditions (similar to backup, if ramping constraints are considered).

5. Summary and conclusions

Besides wind, PV, and hydro, waves are a potential future source of renewable generation. While the idea of the conversion of wave energy to useable electricity is not new, existing wave power facilities are still rare today. However, recent investigations suggest that wave power might complement the future European power systems in a beneficial way. This paper has analysed the impact of the generation mix from the sources wind, PV, wave, and hydro on a highly renewable power system on the Iberian peninsula. The applied methodology allows to investigate the impact of the generation mix on the interplay of different renewable sources with focus on wave power. The impact was quantified via the need for dispatchable backup energy. For the isolated Iberian Peninsula the optimal mix is roughly 1/2 wind, 1/4 wave and 1/4 PV or ca. 3/4 wind and 1/4 PV without wave, so the share of wave power is entirely moved to wind power. The picture changes, if the Iberian Peninsula is connected to

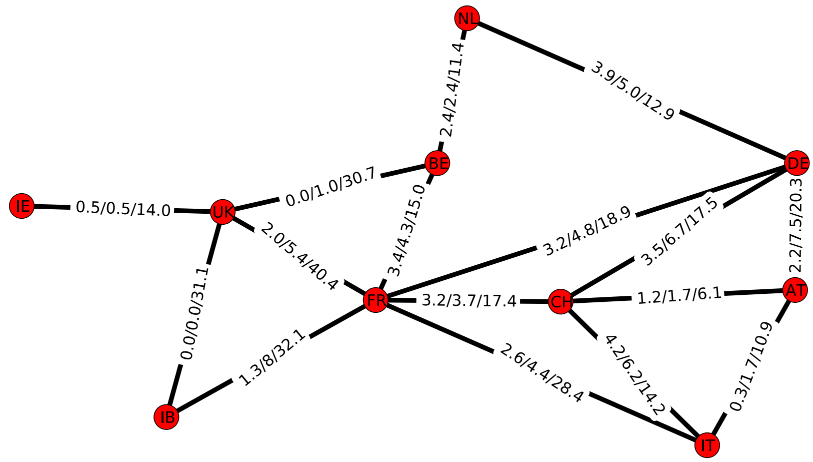

Fig. 5. Selected transmission capacities close to the Iberian Peninsula. Left values: net transfer capacities (NTC) [GW] reported by ENTSO-E for winter 2010/2011. If NTC are asymmetric, higher value is shown. Middle values: planned capacities [GW] (2030 Visions) according to the 2016-TYNDP (Ten Year Network Development Plan). Right values: required transmission capacity [GW] for a fully renewable transmission system as defined by Eq. (24).

Table 2
Share of different renewable generation types in the renewable power mix of the single nodes. IB denotes the Iberian Peninsula (Spain and Portugal) and loads are given as multiples of the load on the Iberian Peninsula L_{IB}.

Node	β_n^W	β_n^S	$\frac{\langle L_n \rangle}{\langle L_{IB} \rangle}$
AT	0.45	0.55	0.19
BA	0.26	0.74	0.05
BE	0.96	0.04	0.28
BG	0.34	0.66	0.11
CH	0.04	0.96	0.18
CZ	0.64	0.36	0.20
DE	0.81	0.19	1.61
DK	1.00	0.00	0.12
FI	1.00	0.00	0.25
FR	0.85	0.15	1.69
UK	0.99	0.01	1.18
EL	0.38	0.62	0.18
HR	0.30	0.70	0.06
HU	0.20	0.80	0.13
KO	0.19	0.81	0.02
LU	0.32	0.68	0.02
ME	0.23	0.77	0.01
MK	0.16	0.84	0.03
IE	0.99	0.01	0.09
IT	0.28	0.72	1.06
LT	0.90	0.10	0.03
LV	0.91	0.09	0.03
NL	0.92	0.08	0.35
NO	1.00	0.00	0.38
PL	0.95	0.05	0.45
RO	0.16	0.84	0.16
RS	0.28	0.72	0.12
SE	1.00	0.00	0.43
SI	0.19	0.81	0.04
SK	0.17	0.83	0.08

a fully renewable European power system: In that case the optimal mix is 75% wind, 4% PV and 21% wave. It changes to 93% wind and 7% of PV, if no wave power is included. However, it was shown that the transmission capacities required for unlimited transmission are one order of magnitude larger than the planned reinforced capacities according to the latest Ten Year Network Development Plan (TYNDP). This renders the realization of this scenario questionable. The difficulty with the Spain–France transmission capacity is also recognized by ENTSO-E as it is the only one described in the 2014-TYNDP as "adequate in no visions" (ENTSO-E, 2014). Hence, it can be concluded that once high shares of renewables close to 100% are reached, the transmission grid between the Iberian Peninsula and the remaining Europe will likely not be reinforced sufficiently strong to realize the described case of unlimited transmission.

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Appendix

A.1. Generation mix nodes

The renewable generation mix of the single nodes can be seen in Table 2. It is adopted from the installed capacities in Pfluger et al. (2011).

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