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Variability and correlation of renewable energy sources in the Portuguese electrical system

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ABSTRACT

The lack of predictability in the output of solar, wind, and small hydroelectric power plants aggravates the problem of consistently matching supply with demand on electric grids. In this paper, a database of renewable power injection, at 15-minute intervals during 2010–2014, into the Portuguese electric transmission system is analysed to characterize the variability and other patterns of renewable energy injection into the system. The system, operated by REN (Redes Energéticas Nacionais), received 20–28% of its electricity from the three renewable energy sources (RES) mentioned, with wind contributing about 90% of that amount. A strong complementarity (smoothing effect) between wind and PV was found, with correlation factors of −0.92 and −0.83 for typical summer and winter days, respectively. The correlation factors for different time scales decrease from annual totals (−0.88) to hourly totals (−0.24), as expected. The results suggest that lower wind power years correspond to sunnier ones. Moreover, the reserve regulation costs appear to decrease when the installed capacity of the three considered RES increase.

Introduction

Over the past five years, Portugal has seen an increase in Renewable Energy Sources (RES) generation capacity of over 25%, with the case of solar to have increased over threefold (though still only accounting for <2% of the load). As these shares grow further to respond to the social and economic trends, the variability of these sources, if not matched by an active energy system management, could pose an increasing challenge to the grid's stability.

Up to now the RES production has been successfully incorporated in the mainland Portuguese power system. RES curtailment is an exceptionally rare event that only occurs in extreme off-peak situations. The strong interconnection between Spain and Portugal and the common electricity market (MIBEL) has facilitated the RES integration success in both countries. The picture is completely different in the Portuguese Atlantic Islands of Madeira and Azores. As these are isolated systems, RES curtailment is relatively frequent, due to the necessity of keeping the reliable diesel generators running, in order to ensure the power system's stability.

RES typically have production at zero marginal cost and benefit from legal precedence of output (dispatch priority), according to EU directive 2009/28/EC, which is in turn reflected on the displacement of non-RES generation along the merit order. Together with the variable electricity generation profile due to meteorological conditions, the system operator may face challenges in keeping up with demand without a relatively significant power reserve (Delarue and Morris, 2015; Mount et al., 2010).

Geographical positioning of electrical systems is relevant when considering high penetration of RES (Solomon et al., 2010). In smaller, more remote and less interconnected systems, when RES are added to the mix, and depending on the demand cycle, the proportion between this and conventional generation (synchronous generators) may increase, leading to a decrease in the inertia of the system and increased "nervousness" of the grid frequency when dealing with the inherent variability (Tielens and van Hertem, 2012).

With the ability to increase the energy system's inertia, though dependent on the correlation of the generation factors between countries, interconnections can facilitate RES integration, though limitations exist when proximity implies large positive correlation of consumption and generation patterns (Göransson and Johnsson, 2011). Electricity is a heterogeneous good across space, with the primary resource constrained by location (Hirth, 2013; Schaber et al., 2012), thus constraining solutions through interconnections. Furthermore, photovoltaic (PV) energy's high potential correlation in the energy production across the border may limit the impact of this otherwise simple balancing source (Delarue and Morris, 2015).

When this occurs, balancing the fluctuations in the output may require additional cycling by the non-RES generation, thus leading to a

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less efficient operation and a reduction in the asset's life span (balancing impact) (Clancy et al., 2015; Fusco et al., 2010).

Yet other options exist for handling local variations of output power. Several papers have identified dispersion in generation to result in a smoother combined profile, increasing the accuracy of forecasts and decreasing the need for reserves or lowering the need for conventional power station's readiness (Widén, 2011; Solomon et al., 2010; Marcos et al., 2012).

The possibility of a more dynamic energy system, able to disrupt the notion of cascading network elements is also being explored, with the emergence of the Smart Grid - a network that can cost-efficiently integrate the behaviour and actions of all users connected to it, including generators, consumers and those that do both, in order to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety (ERGEG, 2010). Several approaches to the regional Smart Grid roll-out have been studied in other papers, namely evidencing how different regulatory options are determined by the respective market structures and the degree of competition among market players (Crispim et al., 2014). Though certainly an enabler of RES penetration, the stage of deployment does not yet offer relevant flexibility to the system operator.

As a country with roughly 30% of RES installed capacity, excluding large hydro, and taking on about 28% of the load, the Portuguese energy system's variability poses a system threat and should thus be studied.

The complementarity of wind and solar resources has been previously studied, namely through the calculation of the correlation between the availability of these energy sources. These studies date back at least to 1981 (Aspliden, 1981), with several posterior corroborations (Markvart, 1996; Gerlach et al., 2011).

The complementarity of sources in a solar-wind system specifically in the Iberian Peninsula has been studied by (Jerez et al., 2013). They found that an optimum configuration enhances the stability of the output throughout the year, relative to a single-source approach.

(Monforti et al., 2014) study the implications of common meteorological issues of wind and solar on electricity generation with a Monte Carlo approach for the whole Italian territory. The findings for both national and regional sets show the negative correlation to increase from hourly to seasonal time spans.

(Solomon et al., 2016) verify the possibility of harnessing the negative correlation of wind and solar systems to decrease the need for storage in meeting the load requirements in California, while finding that the optimal wind-solar mix varies with the level of penetration of RES.

To better understand the Portuguese system's RES electricity generation and the inherent variability, the current paper carries out an assessment of the installed capacity and its variable contribution to the power system. This assessment is based on records concerning the renewables' injected power in the grid, in 15 min time periods, from 2010 to 2014. Three renewable technologies have been investigated: PV, wind and Small-Hydro Plants (SHP). Moreover, a fourth situation, composed of the aggregation of these three technologies, has been considered. It should be noted that the analysis excluded large hydro plants (installed capacity higher than 10 MW).

This local study is intended to not only be used for local decision making, but also as a follow up of similar discussions in other countries. Through this study, the authors hope to contribute to a more complete picture of the resource utilization, while confirming the complementarity of renewable energy sources.

The aforementioned database was kindly provided by REN, the Portuguese Transmission System Operator (TSO).

In this paper, Injected power profile analysis section provides a detailed analysis of the installed capacity of the Portuguese renewable energy sources - their evolution in the years for which the analysis is conducted (2010–2014), power output in 15 minute intervals and typical day analysis. Injected power variations analysis section discusses the variations in the injected power on average and typical days. Correlation between power sources section goes on to validate and discuss the potential correlation between power sources, with Impact on the regulation services market section discussing the costs of regulation reserve required to balance the variations from the maintenance of the previous time period's available power. Conclusions section draws conclusions on the analysis of the paper.

Injected power profile analysis

Considering the analysis of utilization and variability performed in this paper and the recent increases in RES technology in the power system, the first step was to normalise the installed capacity by technology. This normalisation is achieved through the division of the available by an appropriate base power, usually, the installed capacity of the concerned renewable technology. To clarify the concept of installed capacity, this was considered as the rated capacity for all RES but PV. For the latter, the peak-power, i.e., the output power at Standard Test Conditions (irradiance = 1000 W/m^2 and cell temperature = 25 °C) was considered as the installed capacity. Due to limitations of the data, it is not possible to know the exact installed capacity of the technology at the particular time instant of each record. To overcome this challenge, an approximation has been taken: to consider as base power the average between the installed capacity in the previous year and the installed capacity in the current year.

Table 1 shows the considered base power for each technology, alongside with some abridged statistics of each renewable technology, in Portugal, during 2010–14 period. Additionally, the figures for the altogether renewable generation are also shown.

The favourable conditions for PV are immediately visible through the high values of the respective capacity factors. Values of 2000 kWh/kW (a 23% capacity factor) are generally considered for “very high irradiation” locations (IEA, 2010). With such factors above 20%, Portugal's favourable solar radiation is apparent. This stability of favourable climatic conditions is regrettably not available for the SHP generation, with a highly variable capacity factor reflecting the changing raining conditions, throughout the years. With the decrease in overall electricity consumption and the increase in renewable generation (excluding

Table 1
Total installed capacity, considered base power, supplied energy, utilization factor and capacity factor (2010–14).

		Installed capacity (MW)	Base power (MW)	Energy supplied (GWh)	Energy supplied (% load)	Utilization factor (h)	Capacity factor
PV	2009	95					
	2010	123	109	204	0,4%	1870	21%
	2011	155	139	262	0,5%	1886	22%
	2012	220	188	357	0,7%	1904	22%
	2013	283	252	440	0,9%	1751	20%
	2014	396	340	592	1,2%	1745	20%
WIND	2009	3357					
	2010	3706	3532	9024	17%	2555	29%
	2011	4080	3893	9003	18%	2313	26%
	2012	4194	4137	9981	20%	2413	28%
	2013	4364	4279	11,751	24%	2746	31%
	2014	4541	4453	11,813	24%	2653	30%
SHP	2009	395					
	2010	410	403	1377	2,6%	3420	39%
	2011	412	411	1019	2,0%	2478	28%
	2012	417	415	619	1,3%	1494	17%
	2013	415	416	1335	2,7%	3210	37%
	2014	415	415	1509	3,1%	3635	41%
RENEW. (PV + WIND + SHP)	2009	3847					
	2010	4239	4043	10,605	20%	2623	30%
	2011	4647	4443	10,283	20%	2315	26%
	2012	4831	4739	10,958	22%	2312	26%
	2013	5062	4947	13,527	28%	2735	31%
	2014	5352	5207	13,914	28%	2672	31%