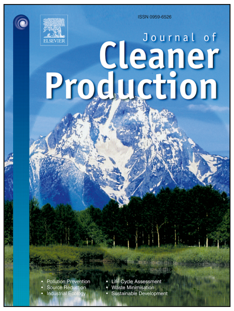

Replacing coal-fired power plants by photovoltaics in the Portuguese electricity system

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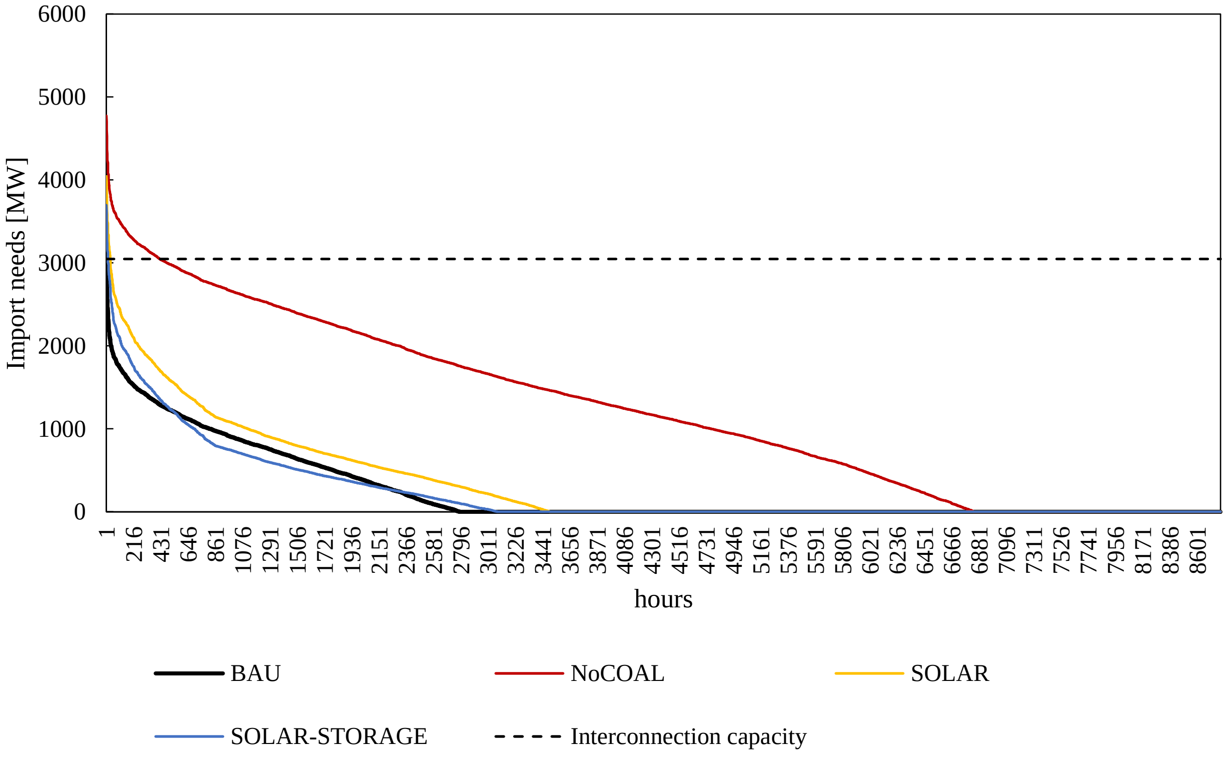
6000
5000
4000
3000
2000
1000
0
Import needs [MW]
1
216
431
646
861
1076
1291
1506
1721
1936
2151
2366
2581
2796
3011
3226
3441
3656
3871
4086
4301
4516
4731
4946
5161
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8601
hours
BAU
NoCOAL
SOLAR
SOLAR-STORAGE
Interconnection capacity

Replacing coal-fired power plants by photovoltaics in the Portuguese electricity system

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Abstract

The decarbonization of the Portuguese electricity system, currently around 50% renewable-based, is undergoing with the commitment to reach 60% of renewable electricity share by 2020. Because of this, the phase-out of the two remaining coal-fired power plants has been receiving close attention, as they currently contribute to about one-fifth of the total electricity generation and two-thirds of the CO_2 emissions in the power sector. This work assesses the impact of eliminating coal-fired generation from the Portuguese electricity system without replacing it, and explores a cleaner supply alternative achievable before 2025. Coal phase-out without substitution results in slightly increased CO_2 emissions for the atmosphere if one assumes that the required additional imports are of carbon-intensive electricity, leading to the need of adding clean power capacity to the system. It is shown that coal plants could be replaced by about 8 GW of photovoltaics if accompanied by a modest increase in the already existing hydro pump capacity. In this case, the renewable electricity share increases to 77%, and carbon footprint decreases by 56%.

Keywords

coal phase-out; photovoltaics; energy storage; electricity systems; renewable energy

Nomenclature

BAU – Business-As-Usual

CF – Capacity factor [%]

CHP – Combined heat and power plants

CO_2 – Carbon dioxide

$CO_2 footprint(total)_i$ – CO_2 emissions correspondent to the electricity generation within the system and to imports scenario i [kgCO_2]

$[CO_2(gen_i)]_{el.mix_i}$ – CO_2 emissions correspondent to the electricity generation within the system for scenario i [kgCO_2]

$[CO_2(imp_i)]_{el.mix_{Spain}}$ – CO_2 emissions correspondent to the electricity imports of scenario i using the Spanish electricity mix [kgCO_2]

$[CO_2(imp_i - imp_{BAU})]_{coal/el.mixSpain}$ – CO_2 emissions correspondent to the difference between electricity imports of scenario i and the imports in the BAU scenario, assuming coal-based electricity or the Spanish electricity mix [kgCO_2]

ETS – Emission Trading System

G_{NG} – Annual electricity generation of natural gas power plants [MWh]

G_s – Annual electricity generation of each s renewable source [MWh]

G_{total} – Total annual electricity generation [MWh]

imp_i – electricity imports in scenario i [MWh]

$LCOE$ – Levelized cost of electricity [€/MWh]

NO_x – Nitrogen oxides

P_{NG} – Installed capacity of natural gas power plants [MW]

PV – Photovoltaics

$RES\ share$ – Renewable electricity sources' share [%]

SO_2 – Sulphur dioxide

1. Introduction

The awareness of climate change has been fomenting carbon-free policies in several places around the world. The power sector is still responsible for about 25% of carbon dioxide (CO_2) emissions (United States Environmental Protection Agency (EPA), 2014), and therefore fossil fuels in power systems must be replaced by renewable energy sources. Coal-fired power plants are among those with higher specific emissions of CO_2 (Moazzem et al., 2012), as well as being one of the great emitters to the atmosphere of sulphur dioxide (SO_2), nitrogen oxides (NO_x) and other pollutants (Wang et al., 2018). Therefore, there is an almost unanimous call for its replacement by cleaner alternatives. Nevertheless, coal-fired power plants are often economically competitive and represent a significant fraction of baseload generation, raising concerns regarding its replacement by non-dispatchable renewable sources (Dolter and Rivers, 2018).

Portugal is an interesting case study of the debate taking place over the phase-out of coal-fired power plants. It had in 2016, a very wet year, 56% of its electricity demand supplied by renewables, the largest of them hydro (28%), followed by wind (22%), biomass (5%) and solar (1%) (National Energy Networks (REN), 2017a). The electricity system is thus dependent on the hydro resource available, which varies significantly: in a dry year, the renewables share may drop to 40%, such as in 2017 (National Energy Networks (REN), 2017a).

The country is still below the national target for 2020 for renewable electricity production, which is 60% (Presidency of the Council of Ministers, 2013); since this share is determined considering the normalized hydro-electricity production of the past 15 years ("Directive 2009/28/EC of the European Parliamentt and of the Council," 2009), it is believed that the target will not be met (Simões, 2017). As far as greenhouse gases emissions, in 2015 Portugal emitted 68.9 Mton of CO_2eq, which is far from the European Union (EU) target of decreasing 20% of the overall CO_2 emissions by 2020, assuming a proportional distribution of the decarbonizing needs among the member states (the target is with reference to 1990, where Portugal emitted 59.1 Mton of CO_2eq) (Pereira et al., 2015; Presidency of the Council of Ministers, 2013).

Policies incentivizing renewable energy have been crucial on the decreasing of CO_2 emissions on the power sector, as confirmed by Delarue and Van den Bergh[1] (Delarue and Van den Bergh, 2016). However, with still 26% of its electricity production coming from coal, the electricity system continues to have room for improvement. Portugal has two coal power plants in operation, Sines – with only 10% of the European coal plants surpassing its absolute CO_2 emissions (Kathrin Gutmann et al., 2014) – and Pego, both accounting for 1.7 GW (National Energy Networks (REN), 2017a).

The Portuguese coal-fired power plants exploration licenses, attributed to operators, are being reviewed: Sines' has already expired in 2017, and Pego's expires in 2021 (National Board of Quercus, 2017). In this context, the closing of those two coal-fired power plants has been receiving attention within the Portuguese media, academia, environmental groups and industry. The discussion was intensified when in November 2017 the Portuguese Government delayed the phase-out of coal-fired power plants to "before 2030" (Gomes, 2017), leveraging a debate on the future of the power system. The electricity utilities are also envisioning their early closure ("before 2025"), mainly due to higher tax burdens – for instance, the 2018 state budget determines the end of the coal exemption of the tax on petroleum products, lowering the competitiveness of the Portuguese coal-fired power plants with respect to those in Spain (Ana Suspiro, 2018). The conversion of these power plants to biomass is one option for them (Bárbara Silva, 2018). The 2050 Roadmap for Carbon Neutrality and the National Energy and Climate Plan, both supported by the Portuguese Government, confirm that the shut-down of coal power plants is on the agenda (GET2C et al., 2018; National Department of Energy and Geology (DGEG) et al., 2019). The roadmaps envision that 80% of the electricity consumption will be supplied by renewable sources in 2030, assuming to be deployed about 9 GW of solar photovoltaics by then (GET2C et al., 2018; National Department of Energy and Geology

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[1] In the same study, Delarue and Van den Bergh (Delarue and Van den Bergh, 2016) concluded that the decreasing emissions on the power sector may not affect the collective CO_2 emissions due to the emissions displacement between sectors that results from cap-and-trade policies, e.g. the EU Emission Trading System (ETS). As the focus of this work is given to the CO_2 emissions on the power sector alone, the emission displacement between sectors will not be addressed.

(DGEG) et al., 2019). The Portuguese Renewable Energy Association (APREN) has also disclosed The Portuguese Market Outlook, where it projects similar figures (Portuguese Renewable Energy Association (APREN);Pöyry, 2018).

Several other EU countries have also been announcing the phase-out of coal power plants during the period 2020-2030: France has made that commitment to no later than 2022, developing the roadmap "The Multiannual Energy Plan" (Ministère de La Transition Écologique et Solidaire (France), 2018). Germany is developing a strategy to phase-out coal, although due dates were yet to reveal at the time of writing this article (Claire Stam, 2018); the United Kingdom expects to phase-out coal by 2025, through the implementation of new emission policies (Adam Vaughan, 2018); in what concerns Spain, the Government believes that the power system will be coal free by 2030, although some coal power plants might be in operation after this date (Morgan, 2018). A summary of the coal phase out in Europe can be followed in Ref. ("Europe Beyond Coal - healthy. prosperous. sustainable.," 2018).

This paper explores a possible path for the removal in the short- to medium-term of coal-powered electricity from the Portuguese electricity system. A solution envisioning the replacement of coal with photovoltaics coupled with hydro pump is assessed, and its impacts for the operation of the system regarding energy balances and CO_2 emissions[2] are determined. The proposed solution must not be seen as an optimum one, but as a possible vision that should prove attainable in the near future. The document is structured as follows: Section 2 briefly contextualizes the Portuguese electricity system; Section 3 summarizes the methods used; Section 4 describes a possible configuration for the coal-free Portuguese electricity system and assesses its impacts; Section 5 discusses the economic implications of the proposed scenario; finally, Section 6 draws policy implications and Section 7 concludes the work.

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[2] The focus in this work is given to CO_2 emissions due to its global impact compared to the local consequences caused by the remaining pollutants (Zhao et al., 2017).

2. Context: the Portuguese electricity system

The Portuguese electricity system is highly sensitive to meteorological and weather conditions due to its high share of renewables. Precipitation is critical: in rainy years the system tends to be much less dependent on fossil fuels than on dry years, as Figure 1 shows. For this reason, the study of the impact of a phasing-out of fossil generation is more useful using a year with low precipitation, when coal is more relevant. The year 2015 was a dry year with an annual precipitation of 599.6 mm (Portuguese Institute of Sea and Atmosphere (IPMA), 2015).

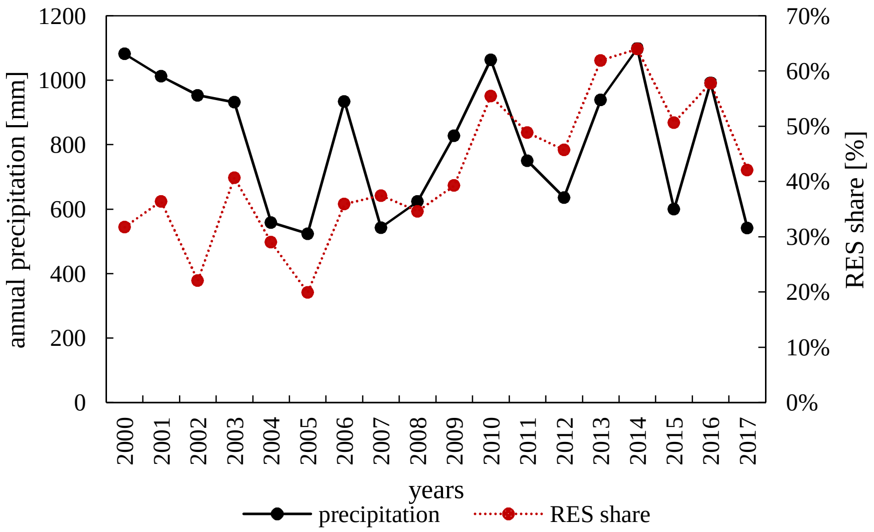

Figure 1 - Annual precipitation and renewable electricity sources (RES) share from 2000 to 2017 ("Production - Evolution of the Electricity Generation in Mainland Portugal (2000-2017)," 2018).

In 2015 the distribution of installed capacities was as it is presented in Figure 2: renewables accounted for 64.8% of the total installed capacity, contributing to 51% of the total electricity generation, as in Figure 3 (National Energy Networks (REN), 2015a, 2015b). About 1.6 GW of hydro pumping was also available for storage in 2015, corresponding to 3,071 GWh of energy storage capacity in dam hydro power plants (National Energy Networks (REN), 2015b)(National Energy Networks (REN), 2015c). It is noteworthy that the value has been increased to 2.4 GW in 2016 (National Energy Networks (REN), 2016) and to 2.7 GW in 2017 (National Energy Networks (REN), 2017a).

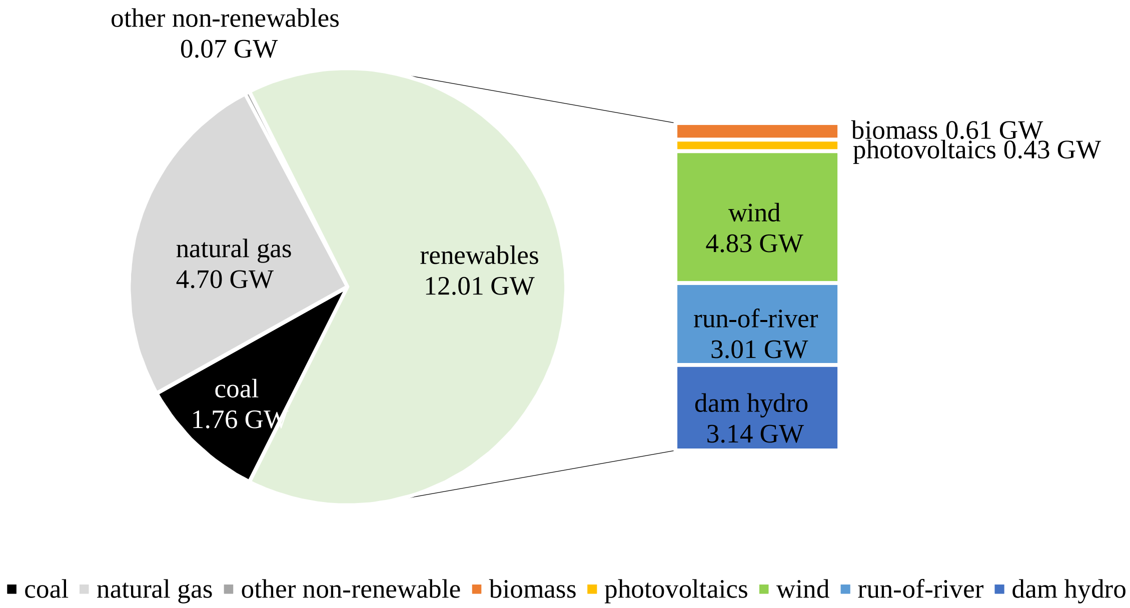

Figure 2 - Installed capacities of supply sources in the Portuguese electricity system in 2015 (National Energy Networks (REN), 2015b).

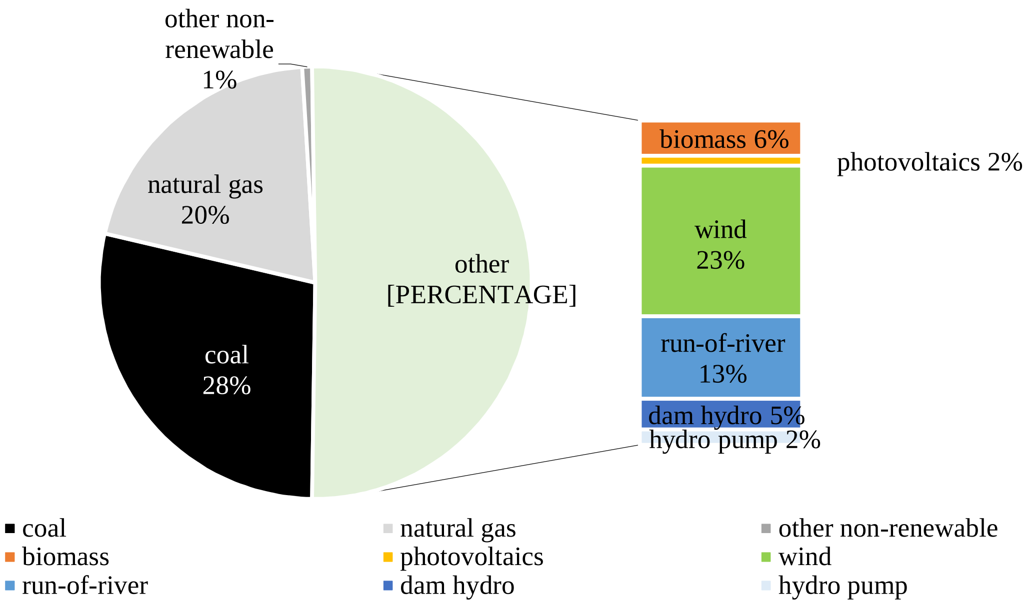

Figure 3 – Electricity generation mix of the Portuguese electricity system in 2015 (National Energy Networks (REN), 2015b).

The Portuguese electricity system includes two types of thermal power plants: (1) condensing power plants (coal, natural gas, biomass and residues); and (2) combined heat and power (CHP) power plants (natural gas, biomass and residues). The operation of the main type of condensing power plants – coal and natural gas – is fundamentally different, as shown in Figure 4. The coal-fired power plants are operating at their nominal power half of the year (with a capacity factor close to 90%), while the natural gas condensing power plants are always operating at power levels much lower than their nominal capacity (with a capacity factor of 15.9%), since part of these plants are mainly used for backup in case of necessity.

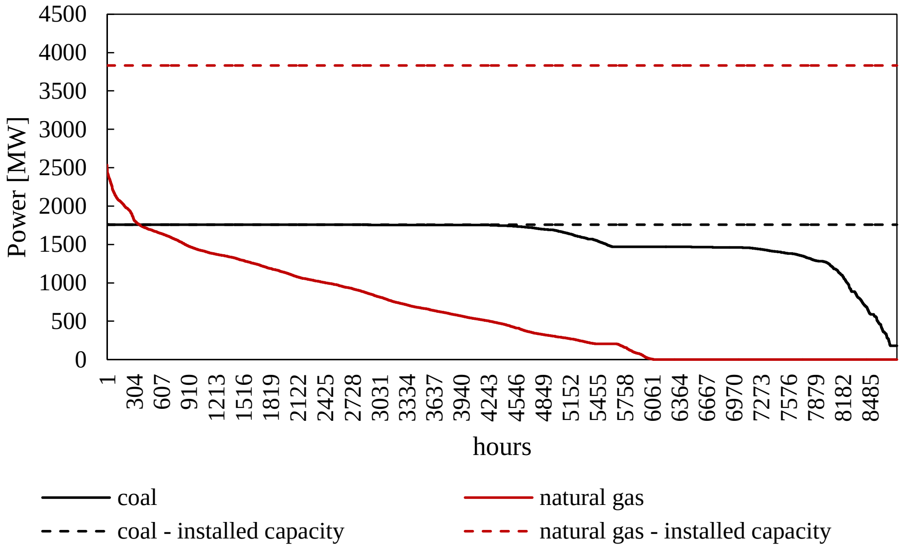

Figure 4 – Load duration curves of the operation of the coal and natural gas-fired condensing power plants (National Energy Networks (REN), 2015a).

The Portuguese electricity system is only interconnected with the neighbouring country, Spain. The peak of interconnection capacity used during 2015 was 3 GW (National Energy Networks (REN), 2015a). The energy trades are defined by the electricity prices of MIBEL market, the regulated electricity market operating in Iberia. The imports accounted for 9% (about 4.5 TWh) of the total electricity demand (about 49 TWh), while about 5% of the total electricity generation (2.2 TWh) was exported.

3. Methods

This section describes the model and presents the indicators used to quantify the impact of modifying the electricity system.

3.1. Electricity system simulation

The Portuguese electricity system was modeled with the EnergyPLAN tool (version 13.0) (Aalborg University, 2017), using as reference the year 2015 – this is the Business-as-Usual (BAU) scenario. At the time of performing this analysis, the most recent year with the required available data was 2016; since this was a wet year, the year 2015, a dry year was the chosen one for the analysis (c.f. Section 2).

The EnergyPLAN is an established energy planning software that enables the simulation of energy scenarios using a technical or economical optimization. It is widely spread in the field to study the impact of policy implementations on the power and energy systems, namely the introduction of carbon taxes, energy efficiency measures and investment on cleaner/alternative technologies (Assefa Hagos et al., 2015; Connolly et al., 2014; Hong et al., 2013; Ouellette et al., 2014; Vanegas Cantarero, 2018). It uses a deterministic approach to simulate the load diagram of an electricity system on an hourly-basis for one leap year. It considers the electricity system as one single point in space, ruling out the spatial distribution of supply and demand. The system is characterized by inputting elements including installed capacities, hourly time-series of supply and demand for one-year, annual fuel consumption and interconnection capacity. Having the model built, EnergyPLAN optimizes electricity balances between supply and demand, calculating hourly time-series for each supply source and for imports/exports, the annual fuel consumption, CO_2 emissions, among others.

The two types of thermal power plants of the Portuguese electricity system are managed differently in EnergyPLAN:

- Condensing power plants are modelled as a single power plant to satisfy the demand when all other power sources are not able to. Before validation, its efficiency is obtained by the ratio between net production from condensing power plants and their total primary fuel consumption;
- Combined heat and power plants (CHP) are modelled as a single constant supply, since it is mostly associated with heavy industry.

Wind, photovoltaics and run-of-river are modelled as non-dispatchable sources, to which priority is given entering the grid. Biomass is modelled using the appropriate distribution of the fuel consumption in each type of thermal power plants (condensing plants and CHP) and its annual consumption, considered to be always the constant for the present discussion.

Large hydro power plants, a part of it having pumped-storage capability, are simulated as dispatchable and the resource is characterized by the annual water supply and its hourly distribution throughout the year. The model operates such that hydro pumping is just possible if the upper reservoir is not full. Conversely, hydro electricity production from large dams occurs only if the reservoir is not empty. For each hour the model performs a balance between hydro pumping, hydro power production and water supply (surface and ground water flows, modelled from historical data ("Monitoring - Database," 2017)(National Energy Networks (REN), 2015c)) to the reservoirs, accounting for energy losses related to the efficiency of the processes (80% for pumped hydro (Hadjipaschalis et al., 2009)), to calculate the amount of storage available. A double penstock system is assumed (Figure 5), meaning that the turbine and pump can operate together – this way the excess of energy production can be stored using the pump, while at the same time the turbine can contribute to stabilize the grid producing power, allowing to achieve higher variable renewable energy penetration than single penstock systems.

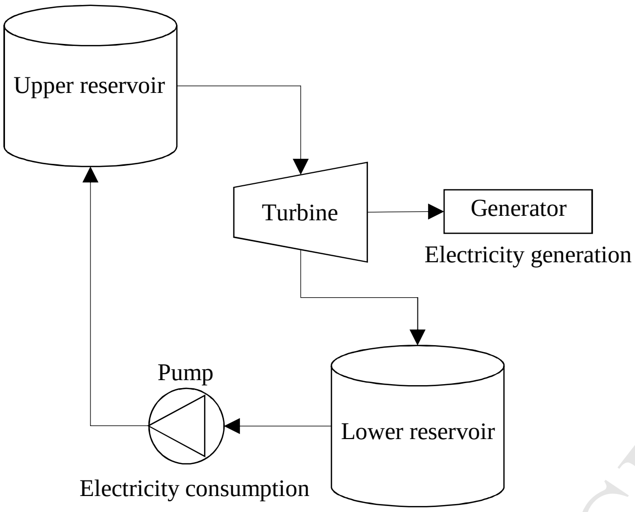

Figure 5 - Double penstock system of a hydro pumping storage system (adapted from (Rehman et al., 2015)).

Dealing with high shares of non-dispatchable supply sources can easily lead to technical challenges in the electricity system. For security reasons, it is crucial to assure the grid stabilization by assuring a solid base generation and backup capable of load following (Paul Denholm et al., 2018); this was modelled by constraining the minimum hourly operation power for condensing power plants and the minimum share of dispatchable generation. For the former it was considered the minimum power at which the condensing power plants operated during the reference year, which was of 580 MW, and for the latter it was assumed that the minimum hourly observed ratio between the dispatchable generation (thermal and dam hydro power plants) and the total generation (Nunes and Brito, 2017), which was 18.1%.

Model validation is crucial to trust the results of a simulation. Following Ref. (Nunes et al., 2014), the validation was performed matching simulation results with historical data (e.g. generation per source, fuel consumption per type of fuel, CO_2 emissions, etc.) by adjusting parameters such as the power plants' efficiency and the water supply. The validation results are presented in Table 1.

Table 1 – Validation of the model in the reference year 2015 (National Department of Energy and Geology (DGEG), 2015; National Energy Networks (REN), 2015b, 2015c).

	2015 historical data	2015 simulation	Difference [%]
Electricity demand [TWh]	49.08	49.08	0.00
Electricity generation [TWh]			
Thermal Power plants[a]	26.61	26.63	+0.08
Reservoir	2.32	2.32	0.00
Run-of-river	6.20	6.20	0.00
Wind	11.35	11.35	0.00
Photovoltaics	0.76	0.76	0.00
RES share [%]	50.5	49.9	-1.19
Hydro pumping [TWh]	1.47	0.78	-46.9
Import/export balance [TWh]	2.27	1.98	-12.7
Primary fuel consumption [TWh]			
Coal	37.74	37.76	+0.05
Natural gas	24.78	24.78	0.00
Biomass	18.52	18.52	0.00
Other non-renewable	5.96	5.96	0.00
Total consumption	87.00	87.03	+0.03
CO_2 emissions [Mton] [b]	19.53	19.53	0.00
Other parameters			
Thermal Power plants efficiency [%]	35.89	36.18	+0.81
Water supply [TWh]	2.47	2.65	+7.29

[a] Including industrial CHP.

[b] Excluding imports resulting emissions.

The differences between the historical data and the simulation observed both on hydro pumping and the import/export balance is due to the type of optimization of the simulation engine, which is technical, whereas the system dispatch is market-driven. Both energy trades with the outside and energy storage through hydro pumping are strongly dependent on market prices, which justifies the observed differences.

3.1.1.Limitations

Models are essential tools in energy analyses, but they are inherently limited, regardless their sophistication, providing accurate results within certain tolerances. In particular, the model used in this work suffers from some caveats that ought to be discussed below.

Regarding hydro pumping, the simulation performed has limitations in three aspects: 1) it assumes only one big reservoir, which neglects the differences that may exist between reservoirs of different regions of the country as well as the geographical distribution of them (they are mainly located in the northern and central regions of Portugal); 2) it does not account for any constraints in the lower reservoir, i.e., it assumes that water is pumped up as long as there is energy in excess, independently of the filling of the lower reservoir; and 3) it is considered that the water stored is totally available for electricity generation, overlooking other possible uses for the water, such as irrigation.

Regarding the transmission/distribution network, as mentioned before, the simulation tool adopted considers the whole country as one single point in space, neglecting possible constraints within the national transmission/distribution network. This is a critical issue, since significant changes on the location of the generation/demand can lead to energy flows the infrastructure is not prepared for and that the model does not identify. Nonetheless, given the significant changes that the electricity system faces (e.g. distributed variable generation, the emergence of prosumers and smart-grids, etc.) and the plans of the TSO to improve its transport capacity (for period 2018-2027 – the first part, until 2022, representing an investment of 474 million euros, is underway (Ana Batalha Oliveira, 2018; National Energy Networks (REN), 2017b)), the authors believe that this issue should not be seen as a major bottleneck for the coal phase-out alternative presented in this work.

3.2. Indicators

To assess the impacts of the different scenarios, three main indicators were chosen: (1) share of renewable energy sources; (2) CO_2 footprint, and (3) the capacity factor of thermal non-coal power plants.

3.2.1.RES share

RES share is the share of the total generation coming exclusively from renewable electricity sources, as Equation 1 shows.

$$RES\ share\ = \left(\frac{\sum_s G_s}{G_{total}}\right) \times 100 \tag{1}$$

Here, G_s corresponds to each of the s renewable sources' annual generation (wind, dam hydropower, run-of-river, biomass and photovoltaics) and G_{total} is the total annual electricity generation within the Portuguese electricity system for each scenario.

3.2.2.CO_2 footprint

CO_2 footprint is determined considering the fuel required to supply the system demand, according to the specified emission factor for each type of fuel, Table 2. In this work, the concept of CO_2 footprint excludes any embodied emissions related to equipment or power plants. Only the emissions of burning fossil fuel are considered.

Table 2 – CO_2 emission factor for each type of fuel (Portuguese Environmental Agency (APA), 2013).

	Emission factor [kgCO_2/GJ]
Coal	94.1
Natural Gas	56.6
Other non-renewable[c]	78.9

[c] The non-renewable fuel was considered to have the same emissions as fuel-oil.

For each scenario i, the estimation of the CO_2 footprint ($CO_2 footprint(total)_i$) considers the emissions corresponding to the energy generation within the system ($[CO_2(gen_i)]_{el.mix_i}$) and to imports. For the latter, two assumptions are made. Imports in the BAU scenario were considered to be of electricity with the same specific emissions of the average Spanish electricity mix ($[CO_2(imp_{BAU})]_{el.mix_{Spain}}$) – about 0.28 Mton/TWh for the period 2015-2017 (*Spanish Power Systems 2017*, 2017)) – while any further imports in other scenarios entail CO_2 emissions ($[CO_2(imp_i - imp_{BAU})]_{coal/el.mix_{Spain}}$) assuming two alternatives for that electricity:

1) to correspond to the average electricity mix of the Spanish electricity system, representing a balanced case;
2) to come from coal-fired power plants with an efficiency of 30%, below the present Portuguese coal-fired power plants' efficiency, which is about 36%. This approach is so to make the analysis conservative and in accordance to the following: as stated by the CEO of EDP, the dominant Portuguese electricity operator, owner of Sines, and also an important player in Spain, "these power plants generation would be replaced by imports from less-efficient coal-fired power plants in Spain" (Milheiro, 2018). Even though

> Spain has openly expressed the will to shut down its coal power plants until 2030 (Morgan, 2018), the authors believe that a realistic scenario in the short-term should consider the current framework under which the electricity system operates, not only in Portugal but also in its neighboring country, Spain. This is a worst-case scenario, aiming to show the impact of a sudden coal phase out in an economic-driven market as MIBEL: without any other changes, the shut-down of the Portuguese coal power plants would pressure Spain to increase its coal generation to help supporting the Portuguese electricity needs. If the Spanish coal power plants also close, it is to expect a strong pressure in the MIBEL electricity prices before the system adapts.

If the imports of scenario i are lower than those of scenario BAU, it is considered that the total CO_2 footprint corresponds to the emissions generated in the country plus the ones from imports, considering, respectively, the electricity mix of scenario i and the Spanish electricity mix. Thus, the CO_2 footprint refers always to the electricity generation within borders and to imports.

Equation 2 defines the above analytically.

$$CO_2 footprint(total)_i = \begin{cases} [CO_2(gen_i)]_{el.mix_i} + [CO_2(imp_{BAU})]_{el.\ mix_{Spain}} + [CO_2(imp_i - imp_{BAU})]_{coal/el.mix_{Spain}}, & if\ \ imp_{BAU} < imp_i \\ [CO_2(gen_i)]_{el.mix_i} + [CO_2(imp_i)]_{el.mix_{Spain}}, & if\ \ imp_{BAU} \geq imp_i \end{cases} \quad (2)$$

3.2.3.Capacity factor of natural gas power plants

The **capacity factor of natural gas power plants** (CF) corresponds to the average level at which the gas-fired condensing power plants are operating during the year in relation to their nominal power, as in Equation 3.

$$CF[\%] = \frac{G_{NG}}{P_{NG} \times 8{,}784} \times 100 \quad (3)$$

Here, G_{NG} [MWh] and P_{NG} [MW] represents the energy generation and installed capacity of natural gas power plants, respectively.

4. Coal-free electricity system

In this section, several sequential scenarios will be presented: (1) the NoCoal scenario – where the coal generation was removed from the BAU scenario; (2) the SOLAR scenario – where a strong photovoltaics penetration in the system was considered to replace part of the coal generation removed; and (3) the SOLAR-STORAGE scenario – where a storage option was added to avoid excessive photovoltaics exports.

The scenario without coal[3] – the NoCOAL scenario – aims to assess the impacts of putting coal power plants offline taking as reference the BAU scenario. It explores whether it is possible to replace the energy generated by those coal-fired power plants with already existing installed capacity, thus without increasing the system dependence from the outside, i.e., increasing imports. It must be noted that this is a *ceteris paribus* type scenario, as all scenarios in this study, i.e., all other conditions, e.g. installed capacities, remain the same.

When coal-powered electricity is eliminated, there is an increase in the capacity factor of natural gas power plants from 15.9 to 30.7%, and a rampant five-fold increase in imports (Figure 9)[4]. These imports exceed the import capacity limit for 422 hours during the year (about 4.8% of the time). Figure 6 shows heatmaps comparing the import needs of the two scenarios along the year, showing a clear increase of the needs during daytime and evening hours in the NoCOAL scenario. This suggests that import needs could be replaced by solar energy coupled with storage.

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[3] It was assumed for the non-coal condensing power plants an efficiency calculated by removing the coal part, i.e., the coal primary energy consumption and the respective energy generated from the calibrated overall condensing power plants' efficiency of the BAU scenario.

[4] If in the NoCOAL scenario instead of considering 1.6 GW of hydro pumping (imports totaling to 10.83 TWh) it had been considered 2.7 GW, imports would amount to 10.76 TWh, and hours above the cross-border capacity to 410 (4.7% of the time).

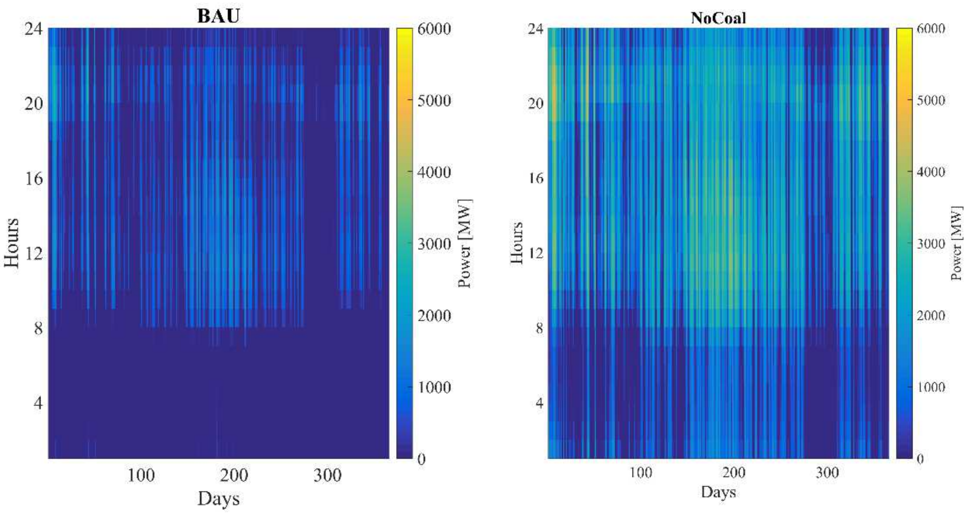

Figure 6 – Heatmaps of import needs during the year for the BAU and NoCOAL scenario.

The appropriate photovoltaic (PV) installed capacity to add may be determined by defining that electricity imports ought to be balanced on an annual basis by the export of excessive generation. This leads to an optimum of 8 GW of installed capacity. Less PV than that does not compensate entirely the generation deficit and the high import needs, while additional PV than that leads to excess generation, to be exported at low value since the most accessible international electricity market (Spain[5]) also has large amounts of solar power at the same time (and is expected to have more (Conor Ryan, 2018)). This PV capacity is the basis for the SOLAR scenario.

Although 8 GW corresponds to eighteen times the current deployed PV capacity in Portugal, this is achievable, and even expected, within a four/five-year period. In fact, after many years of an immature PV market in spite of very favorable insolation levels in Portugal[6], recently over 1 GW of subsidy-free PV power plants has been licensed, while further 2.2 GW (corresponding to

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[5] It should be mentioned that interconnection to the rest of Europe across the Pyrenees is rather limited, only 2.8 GW, even though it is expected to increase to 5 GW (Juan Prieto et al., 2017).

[6] About 5 kWh/m^2/day, corresponding to 1,825 hours of peak production – in Germany, which has the third largest solar installed capacity in the world (*Renewables 2017 Global Status Report*, 2017), it is of 3 kWh/m^2/day, corresponding to 1,025 hours of peak production (Commission and Transp, n.d.).

91 new PV power plants) await licensing ("Economy - Licenses for renewable electricity production will be allocated by lottery," 2018; Prado, 2017), signaling that PV generation is now cost competitive, which paves the way for its fast deployment.

Furthermore, it is worth mentioning that it has been shown that long-term CO_2 emissions targets in Portugal require the deployment of over 13 GW of photovoltaics (Nunes et al., 2014), therefore deploying 8 GW of solar power to replace coal-fired generation only accelerates existing roadmaps. Moreover, as mentioned in Section 1, recent roadmaps point to a strong deployment of photovoltaics, some pointing to an installed capacity of about 9 GW by 2030 in the Portuguese electricity system, which makes the scenario proposed in this work coherent with those roadmaps. It is also noted that an installed capacity of 8 GW corresponds to an average PV capacity of 774 W per capita (Bank, 2016) – Germany, less sunny, had already 484 W per capita in 2016 (Harry Wirth, 2018; The World Bank, 2016). Besides the favorable conditions for photovoltaics already mentioned (the high solar potential and its cost competitiveness in Portugal), the focus given to this technology over other renewables is also supported by the fact that in Portugal onshore wind and hydro generation potential is almost tapped, which leads to a less growth potential compared to solar.

Figure 7 shows the hourly imports and exports of the SOLAR scenario for the entire year. The SOLAR scenario reduces import needs (-70%, Figure 9) to 3.0 TWh, but still above the current BAU imports of 2.1 TWh. The hours along the year in which the interconnection capacity is not enough to accommodate imports or exports (0.4% and 2.6%, respectively) is below the model uncertainties, but this electricity system configuration leads to a significant increase in exports, from 0.1 to 3.2 TWh (Figure 9). This could lead to an imbalance on the regional electricity market, where Portugal could end up paying to export the excess energy. This consequence has already been observed in Germany in 2017, where the increasing penetration of variable renewables lead to about six whole days with negative electricity wholesale prices (Rupert Darwall, 2018). It follows that a high share of PV penetration must be complemented by technologies to accommodate its variability.

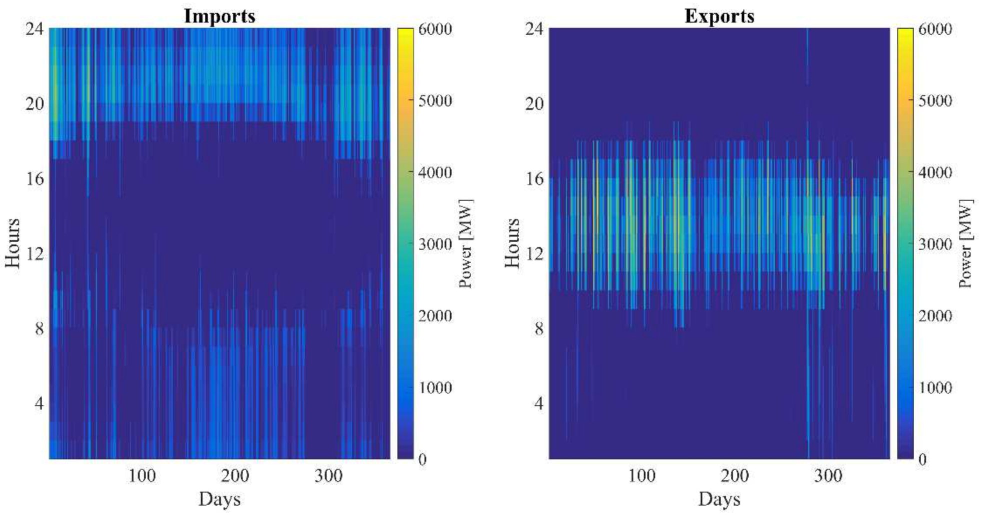


Figure 7 – Heatmaps of import and export needs during the year for the SOLAR scenario.

The existent hydro pump absorbs a significant part of the added photovoltaics' generation, as its operation increases almost six times when compared to the BAU and NoCOAL scenarios (from 0.78 in those two scenarios to 4.52 TWh), being used at its nominal capacity during 24% of the time (Figure 11). Increasing the energy stored in existing hydropower dams by reverse pumping during low demand periods would enable some of the excess energy that needs to be exported to be used later during peak time. To identify how to decrease the imports to the BAU scenario levels, a sensitivity analysis was performed for the hydro pump capacity.

The resulting hydro pump capacity needed to decrease the imports to the BAU import level was found to be 2.75 GW, which is the basis for the SOLAR-STORAGE scenario. In 2007, the Portuguese Government approved the National Program of High Hydroelectric Potential Dams, which aimed to increase the hydropower electricity generation by upgrading the capacity of existing dams and building new ones. To increase the storage capacity and enable a higher penetration of variable renewables, the program also included the upgrading of the hydro pump capacity, increasing it from 1 to 2 GW (Water Institute et al., 2007). In 2017, with an installed capacity of 2.7 GW, that goal had already been exceeded (National Energy Networks (REN), 2017a). For these reasons, the authors believe that the suggested capacity of 2.75 GW is an achievable and realistic goal.

This scenario allows energy exports to decrease 60% compared to the SOLAR scenario, as Figure 7 and Figure 8 show. Again, the hours during which the interconnection capacity is exceeded (about 0.7%) is below model uncertainty.

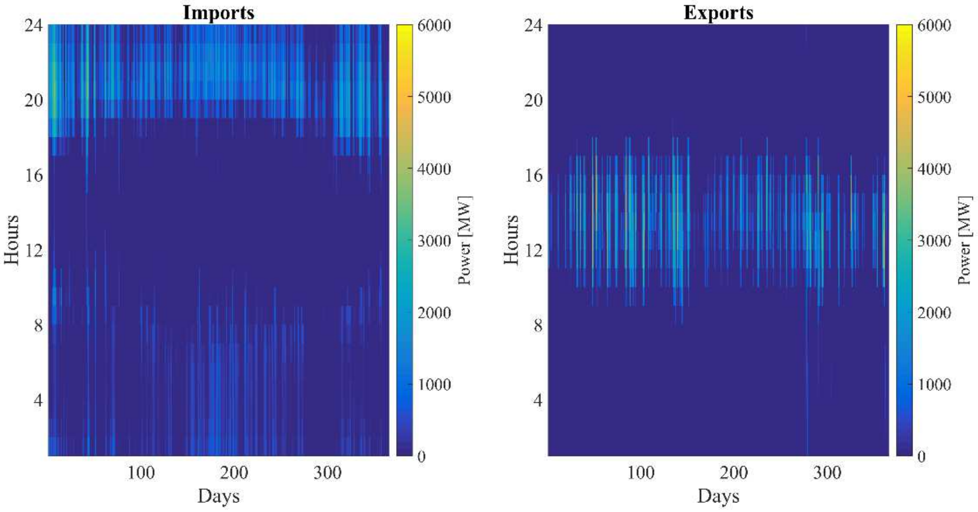


Figure 8 – Heatmaps showing import and export needs during the year for the SOLAR-STORAGE scenario.

Table 3 summarizes the distinguishing features of each scenario. Figure 9 shows the annual import and exports needs, while Figure 10 shows the load duration curves for the imports and exports during the year. Figure 11 shows the hydro pump load duration curve.

Table 3 – Summary of the distinguishing features of each scenario in relation to the BAU scenario. All other features remain the same.

Distinguishing features of each scenario	
BAU	1.7 GW of coal-fired power plants
NoCOAL	0 GW of coal-fired power plants
SOLAR	0 GW of coal-fired power plants + 8 GW of photovoltaics
SOLAR-STORAGE	0 GW of coal-fired power plants + 8 GW of photovoltaics + 2.75 GW of hydro pump

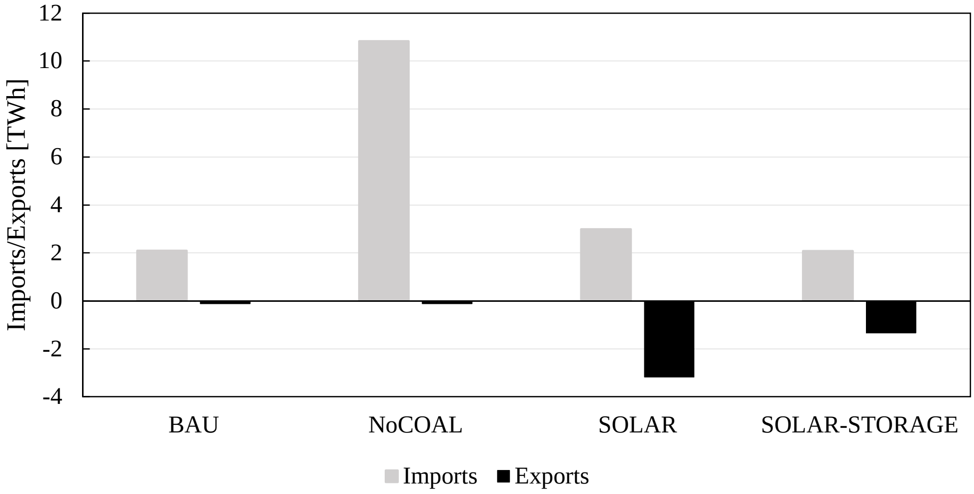
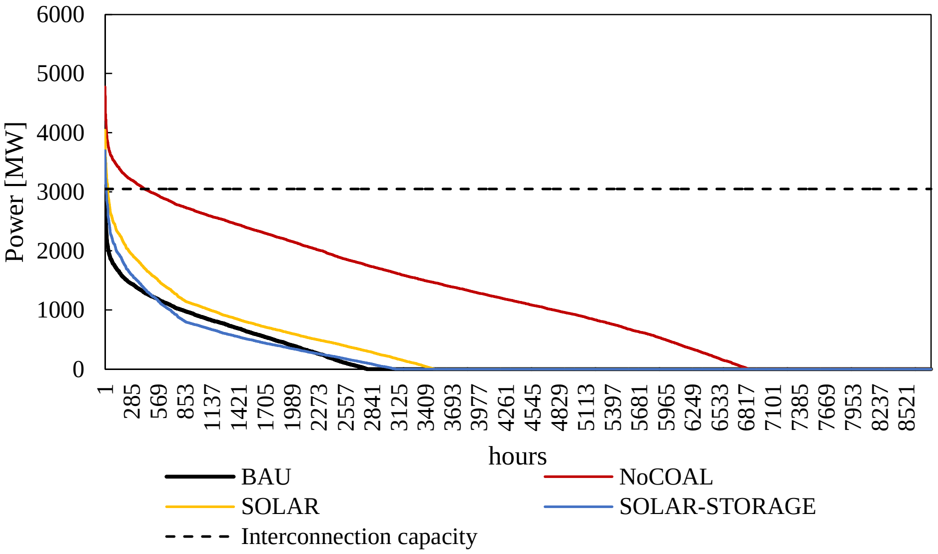


Figure 9 - Annual import and export needs for each scenario.



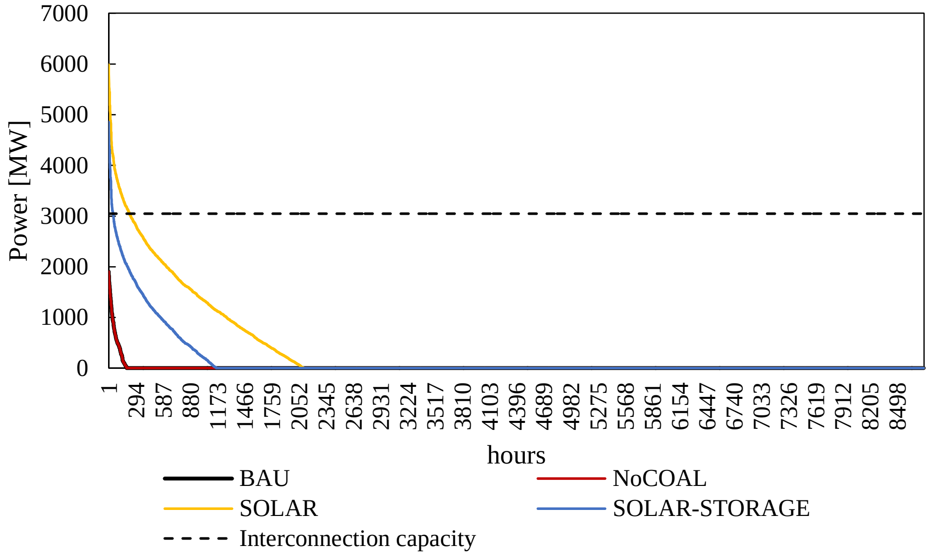


Figure 10 - Load duration curves for imports (above) and exports (below) needs.

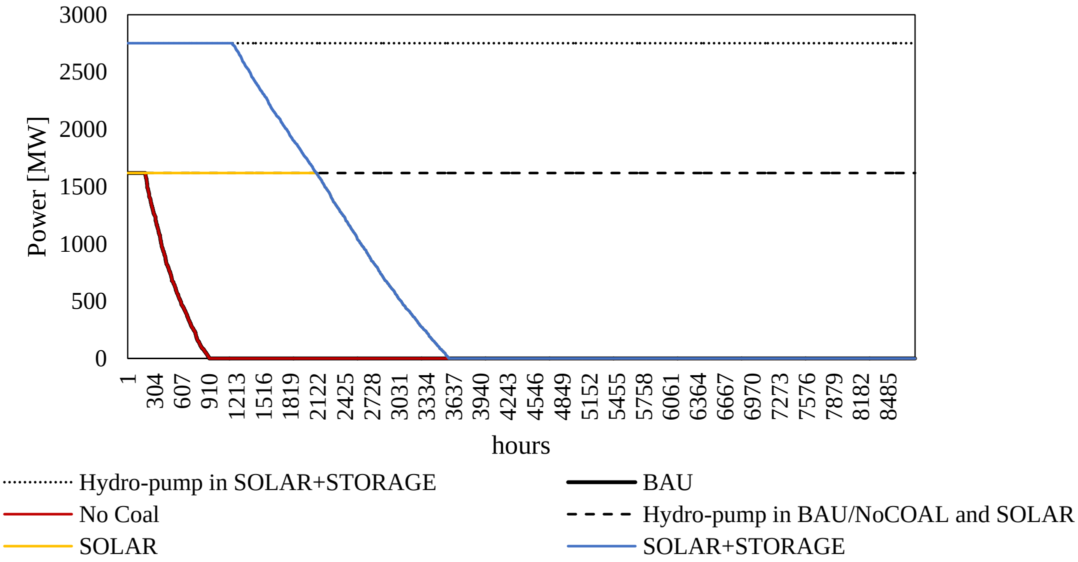


Figure 11 - Load duration curves for hydro pump.

Table 4 summarizes the impacts of the proposed systems. The renewable electricity share reaches 77% in the SOLAR-STORAGE scenario, a significant increase from the 50% of the BAU. In a wet year, it could exceed 80%.

When considering imports coming from coal-fired powerplants, the NoCOAL scenario leads to a slight increase in CO_2 footprint in the electricity system (+1%) since the added imported energy is assumed to be produced in less efficient power plants, as discussed in Subsection 3.2.2. A displacement of the CO_2 emissions from Portugal to Spain takes place, resulting in an increase of 9.86 Mton of CO_2 emissions in the neighbor country, which corresponds to 48% of the Portuguese electricity system emissions in 2015. However, when considering imports based on the average Spanish electricity mix, the CO_2 footprint decreases 36% compared to the BAU, given that this electricity is assumed to be 36.8% renewable (*Spanish Power Systems 2017*, 2017). Increasing PV capacity coupled with storage availability (SOLAR-STORAGE scenario) leads to significant CO_2 footprint decrease (-56%), relevant to meet the CO_2 emission targets.

The capacity factor of gas-fired power plants increases with the coal phase-out. When other supply solutions are introduced on the system, their capacity factor decreases compared to the NoCOAL scenario, but not significantly. This means that burning coal is partially replaced by gas-fired power plants, which could be economically interesting for some actors in the energy market. Nevertheless, their capacity factor will continue rather low, due to excess installed capacity and the priority given to renewables entering the grid, maintaining the economic viability challenges for these power plants.

Table 4 - CO_2 footprint, RES share and capacity factor, for all the scenarios.

	RES share [%]	CO_2 footprint amount or relative difference to the *BAU*		Capacity factor of natural gas power plants [%]
		Coal	Spanish el. mix	
BAU	49.9	20.4 Mton		15.9
NoCOAL	61.0	+1%	-36%	30.1
SOLAR	75.5	-51%	-54%	24.2
SOLAR-STORAGE	76.5	-56%	-56%	23.2

5. Economic implications

Portugal no longer explores coal, thus no volume of exports is present, which also implies that all gross inland coal consumption results from imports. Portuguese coal exploration ceased in 1994, and since then the country dependence on imported coal, the vast majority to secure energy needs, have increased (Miguel et al., 2018). This coal supplies Sines and Pego power plants, which act as baseload and backup in the electricity system, ensuring the fulfilment of power demand during low renewable power generation periods. These two power plants alone account for more than half of the thermal electricity production in Portugal.

While coal represented 28% of the electricity mix in 2015 (c.f. Section 2), in 2016 accounted for 21% and in 2017 for 26%, a variation that has to do with the interannual hydro energy resource available. This means that the quantity of coal imported (bituminous) and the price payed for it varies significantly between years: while in 2017 was 5.9 Mton e.g. in 2013 was 4.3 Mton, amounting to 444 M€ and 254 M€, respectively, as Figure 12 shows. This puts the Portuguese energy budget reliant on the amount of coal required by the country, and on the price fluctuation of this raw material in the international markets – in 2017 the average price paid was 75.3 €/ton, 47% higher than in 2016, increasing the weight of coal in the energy budget from 4.0 to 5.4%, respectively (National Department of Energy and Geology (DGEG), 2018). Since 2008, when the Portuguese power fleet started to have its present structure, coal imports weighted negatively on average c.a. 300 M€ per year on the Portuguese external balance of payments (National Department of Energy and Geology (DGEG), n.d.).

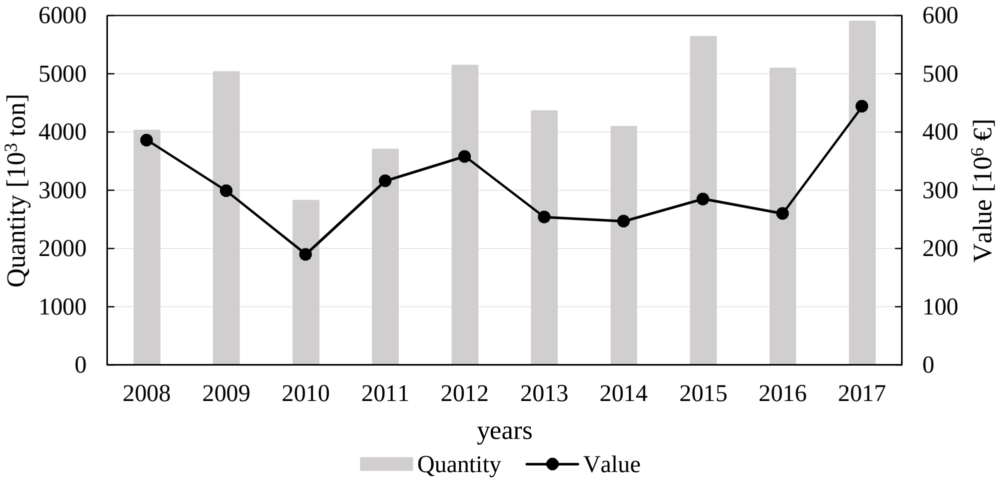


Figure 12 – Evolution of coal (bituminous) imports in Portugal in the period 2008-2017 (National Department of Energy and Geology (DGEG), n.d.).

Despite detrimental budgetary penalties related to an electricity system highly reliant on imported coal, shutting down the coal-operated power plants in Portugal without replacing them by other technology should overall lead to negative economic consequences, as (Pereira and Pereira, 2018) concluded. The authors studied the macroeconomic and distributional effects of this scenario, showing that, due to increased reliance on electricity produced in Spain and on domestic natural gas electricity production, it leads to an increase in electricity prices, with implications throughout the economy. The authors argue that the policy and market conditions in Spain are pivotal at understanding the exact effects, and that a decrease in domestic power production correlates with an increase in coal based imported electricity produced in Spain, provided that this country maintains these power plants in operation for a longer period than in Portugal – which is unlikely, increasing the uncertainty of the economic consequences of this scenario for Portugal (LUSA, 2018). The authors finish arguing that investments in renewable energy technologies should offer a cost-effective mean to address the capacity loss related to the closure of the coal-fired power plants, and that a marked-based approach based on a tax over carbon could be key to the market adaptation. The authors did not evaluate however the economic effects of a scenario where coal fired power plants are replaced by an alternative technology.

This was done in a different study, although from the standpoint of the economic value of human lives. (Prehoda and Pearce, 2017), based on an existing geospatial correlation between coal fired power plants and mortality related to air pollution in the United States, quantified how much PV is needed to offset these casualties. The results show that 755 GW of PV could avoid the death of c.a. 52,000 people per year, costing about 1.1 million dollars per life, which compares well with the value attributed to human life in other studies. This figure does not include however the value of PV generated electricity – when the revenues of it are included, the PV based solution proposed also saves money. The authors, however, did not assessed how the power systems would be impacted by this proposal from a more technical standpoint, e.g. of energy balances.

In the basis of these results is the price of photovoltaics; its evolution in the last decades shows that each time the cumulative installed capacity doubled, the price fell 24% (Bruno Burger et al., 2018). Only in the period 2010-2017, the levelized cost of electricity (LCOE), as defined in Equation 4 (where *n* is the year of the project and *N* is the lifetime of the project), of utility-scale PV dropped 40-75% (IRENA, 2018), depending on plant size, on annual irradiation at the power plant location (e.g. in kWh/m²) and on country specific conditions. Current PV LCOE of ground mounted PV systems in places of high solar irradiation (1500-1800 kWh/m^2), as Portugal, is between 31 and 48 €/MWh, which may be countered with the coal-based LCOE, in the range of 63 to 99 €/MWh (Kost et al., 2018), i.e., solar is already cheaper than coal.

$$LCOE = \frac{\sum_{n=0}^{N}(Investment\ (CapEx) + Operation\&Maintenance\ (OpEx) + Fuel\ cost)_n}{\sum_{n=0}^{N}(Electricity\ generation)_n} \tag{4}$$

In fact, if the cost of CO_2 emissions allowances in the EU Emissions Trading System (EU ETS) is included (assumed as 20 €/ton (“Carbon Assets,” 2018)), the marginal cost of producing coal jumps to about 49 €/MWh, assuming 76.8 €/ton as the price paid for coal, which corresponds to the average that Portugal payed for it since 2008 (National Department of Energy and Geology

(DGEG), n.d.). Based on this cost tendency, (Wiśniewski and Pejas, 2018) shows that installing 5-6 GW of dispersed PV farms in the period 2019-2024 could replace the power generated at a planned 1 GW coal power plant to be deployed in Ostroleka, north-eastern Poland, while also providing lower power prices.

It is out the scope to examine in detail the economic effects of the counterfactual scenario proposed in this article of substituting the Portuguese coal power production by 8 GW of photovoltaics in the short/medium term. However, given that renewable energy tenders are about to begin in Portugal with an anticipated top price of 45 €/MWh (Ana Brito, 2018), the proposed scenario will likely lead to cheaper energy to consumers, even considering the economic impact of the investment in the electrical network imposed to the TSO, which should be able to absorb all the new distributed energy that will be produced – an expenditure that has to be made in any case. Moreover, the scenario proposed will improve Portuguese foreign accounts, reducing the total budget for energy, decreasing the energy financial burden while also improving security of supply and the final consumer situation. The necessary investment in PV will depend on the type of model that will prevail (centralized, distributed, residential), as whether these investments are taken by families or companies. In case they are taken by solar promotors, the firms will increase their total assets, while increasing liabilities. However, performing a cost-benefit analysis should reveal that total costs will be exceeded by total benefits.

6. Policy implications

These results outline a possible path for the phase-out of the coal-fired power plants in Portugal. The vision proposed is built on a significant increase of PV penetration which, considering recent developments with widespread deployment of subsidy-free large-scale PV power plants in particular in the southern region of the country, is expected to be attainable in the relative short term, i.e. within a five-year period or even less. Nevertheless, such a ramping increase in PV deployment requires addressing a number of critical issues.

Firstly, the power grid requires update to host the deployment of large-scale PV power plants in the sunnier southern regions of Alentejo and Algarve. Historically, most of the supply capacity is located in the central and northern regions (where hydro and wind power are more abundant) while most of the demand occurs in the coastal urban regions. The national energy regulator has recently published a roadmap for grid expansion towards the southern regions to address this concern (Emiliano Bellini, 2018; National Energy Networks (REN), 2017b).

On the other hand, the rapid increase in PV power capacity before the closing of the coal-fired power plants would lead to a transitory situation of excess power during day-time hours. The need to export this excess power highlights the need to rapidly increase interconnection capacities both with Morocco and, across Spain, towards France and central Europe.

Finally, this deployment of PV requires massive private investment that requires a high level of confidence of stake holders in the energy market. It is thus critical that the Portuguese government and parliament address the current debate on removal of historical renewable energy subsidies without retroactive effects.

7. Conclusions

This work envisages a short- to medium-term scenario of further decarbonization of the Portuguese electricity system contributing critically to achieve the existing climate-energy targets. It implies removing coal from the electricity system, currently generating a fifth of the electricity consumed in the country. A coal phase-out without any additional power capacity installed results in a five-fold increase of imports, which highlights the need for adding alternative power capacity to the system. Preferably, such added capacity requirement would be fulfilled by renewable energy, which seems to have beneficial impact on the electricity cost given that the current cost of utility scale photovoltaics-based electricity is already on par with the coal-based electricity, and in some cases below. Even though several clean alternatives could be discussed, in this work the proposed vision for a cleaner electricity system was the increased penetration of photovoltaics and of hydro pumping. In this sense, it was shown that coal-fired power plants can safely give place to about 8 GW of PV coupled with 2.75 GW of hydro pump capacity, about 2% more than the presently installed pumping capacity in Portugal, without significantly affecting the dependence from the outside and complying with technical constraints of the system.

The renewable electricity share on a dry year will increase from 50 to about 77%, whilst CO_2 footprint emissions will drop 56%, a significant contribution to meeting overall national targets.

The final remarks show that the sudden shut-down of coal-fired power plants is not appropriate and it should be followed by an increased penetration of renewables and storage technologies. The proposed high penetration of photovoltaics can easily be attained before 2025 considering the very competitive costs of the technology, especially under favorable insolation conditions, as in Portugal. The policy makers should create the optimal conditions for this to happen. In a time of urgency to reduce CO_2 emissions to tackle climate change, accelerating the displacing of coal-fired electricity generation with renewable energy seems to be of elementary prudence.

In this work, the simulation of the electricity system is based on an hourly optimization of energy balances, not discarding some existing technical constraints that the real system has. In the future, the work could be enhanced by performing a more robust analysis, including a detailed spatial, economic and technical simulation of the electricity system. Moreover, it should also comprise a refined simulation of the transmission network, as well as a dynamic analysis of power flows.

Acknowledgments

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Figure Captions

Highlights

1. Coal power plants still supply a fifth of the Portuguese electricity demand.
2. Coal power plants phase-out is tested, considering alternative supply sources.
3. Coal phase-out slightly increases CO_2 emissions assuming carbon intensive imports.
4. Photovoltaics coupled with hydro pump can replace coal (-56% of CO_2 emissions).
5. Photovoltaics with storage increases renewable electricity share from 50 to 77%.