# Modelling Interconnected Renewable Electricity Systems

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**Abstract.** This paper addresses the long-term power planning in interconnected system with high renewable share. A case close to the Portuguese electricity system was modeled to assess the relevance of the interconnection with Spain in future scenarios. The results show that the increase on the renewable energy share will lead to a higher total cost of the system mainly due to investment costs. On the other hand, $CO_2$ emissions will be significantly reduced for each scenario in question. Another significant result is that the increase on renewable power, will lead to an excess of electricity production mainly during winter. For a 100% renewable scenario, the importance of interconnection is demonstrated, in particular, for the summer months for which importation can compensate the reduction of wind and hydropower output.

**Keywords:** Electricity planning · Renewables · Importations

## 1 Introduction

The sustainable use of energy and production of electricity are essential for the reduction of carbon dioxide ($CO_2$) emissions. Different energy strategies have been emerging and amongst which the development of renewable energy sources can be highlighted. The gradual integration of renewable energies leads to changes in the operation of the electricity grid as production tends to be seasonal and variable, but the security of supply remains essential. Electricity planning using optimization models has proven to be an effective tool in recognizing the level of impact that renewable technologies have on the electricity sector and for the definition of future strategies.

According to Pina et al. [1] modeling of energy systems has become more complex and realistic as new opportunities in the energy market have emerged, allowing the combination of two or more models. The complexity of optimization problems results from the diversity of existing production technologies, the temporal and/or spatial evolution of the parameters included in the model and the social and environmental arguments integrated in the model. In short, with the increasing contribution and integration of renewable energy sources (RES) in the grid, the complexity in idealizing an electric planning becomes bigger and for that reason, the optimization models are essential


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tools for the decision making, since they can include technical restrictions, economic, environmental and system ones [2].

This paper aims to contribute for the modeling and analysis of electricity system with a high RES share. The study will outline a long-term planning model for possible 100% renewable electricity system in Portugal, either isolated or interconnected with Spain. A model previously developed for long-term sustainable electricity planning was adjusted and applied to the Portuguese power system to include different renewable technologies, with the aim of minimizing the cost and also allowing to assess the impact on $CO_2$ emissions, throughout a planning period of 20 years.

## 2 Modelling and Electricity Planning

The modeling of energy systems operates as a tool to transform a complex reality into a simpler reality, making it possible to understand and analyze a problem. There is a wide variety of models in which the mathematical formulas allow to simulate or optimize a system [3]. Mathematical optimization models have been used for planning, operation and control problems of the power system and may have as their main objective to minimize, for example cost, operational errors and energy losses, or to maximize, for example, quality and efficiency of the system [4]. According to [5], models can guide the search for electricity and energy systems by comparing different modeled scenarios in order to apply the lower cost scenario and account for the efficiency and safety of the system.

Ringkjob et al. [6] reviewed 75 tools commonly used to analyze energy systems. The authors, with the help of the creators of the tools presented in the article, updated them in key points so that most of the current challenges related to electrical planning could be assessed. According to [2], optimization models remain as essential tools to aid in energy decision-making, but constraints and impacts must be integrated into these models reflecting the market conditions and specificities of each system under analysis. The case of the increasing integration of RES in the systems are gaining a remarkable importance, as the transition from fossil energy sources to RES has several impacts on the energy system. In addition, energy systems can also be analyzed as isolated systems (islands) or as systems interconnected to other areas. The interconnection between distinct systems allows for the import/export of electricity increase the complexity of the models, but represent also an important aspect to be taken into account.

The increasing importance of RES gave rise to several studies including the projection of a 100% renewable energy system with a great mix of energy sources but its implementation remains a challenge [7]. In addition to economic issues, the technical problems can challenge an energy system to become 100% renewable. These problems are frequently related to the variability of some renewable (wind and solar) which are not necessarily correlated to demand. On the other hand, if some RES present greater intra-daily variability, RES such as hydro and biomass can be more variable at a seasonal level [7].

According to Santos et al. [8], a number of studies have been conducted to assess the potential of a 100% renewable system in terms of climate change mitigation and resource efficiency, or to gain an understanding of the expected technical challenges. Despite all the information available and studies on 100% renewable system, this subject is still not absolutely consensual. In energy systems with high integration of renewable energy in order to obtain the maximum use of these sources of production, the electric system must somehow balance the intrinsic variability of its energy production [9]. According to Deason [9], flexibility options for the efficient integration of variable RES to reach a 100% renewable scenario can be added in different ways to the electricity system through energy production (e.g. hydroelectricity, biofuels and solar thermal energy concentrated storage), interconnected power grids, energy storage (e.g. thermal storage, compressed air, pumped storage, or batteries) and flexible demand. Thus, the extent of the real cost of integrating variable sources depends on the flexibility of the specific energy system, i.e., to what extent the supply side and demand side can deal with this variability.

In conclusion, Heard et al. [10] pointed out that strong empirical evidence must be demonstrated for any study attempting to construct or model a future low-carbon system by combining renewable technologies. For the authors, the desire to promote the 100% renewable ideal, without critical evaluation, delayed the identification and implementation of efficient ways of decarbonising. In contrast, Brown et al. [11] argued that energy systems 100% based on renewables are not only feasible, but also already economically viable and decreasing in cost every year.

For the case of Portugal, the results obtained by Krajacic et al. [7] found a solution for a 100% renewable system, which would be theoretically possible to achieve if there is an additional expansion of the grid to allow for a greater exchange of renewable electric energy (import-export). In addition, the authors emphasized that the incorporation of storage systems such as batteries and hydrogen, together with the existing pumping hydraulics, would allow the combination of these with the transport system and would contribute for the implementation of the electric vehicles. In Fernandes and Ferreira [12], the results also showed that it is theoretically possible to implement a 100% renewable system. Hydro and wind energy would have a dominant role in the system but the authors underline the need to complement it with other technologies (such as biomass, solar and wave), due to the seasonality and in order to reduce the required installed capacity. Santos et al. [8], investigated the economic component of the implementation of a 100% renewable system with energy interconnection and storage. The results showed that both the export and the storage by hydro pumping could be two viable solutions for dealing with the excess of electricity production from RES. According to the authors, the interconnection capacity would allow to save costs and improve production efficiency.

## 3 The Portuguese Electricity System

In Portugal, the RES power has been gradually increasing and represented in 2017, close to 70% of the total installed power. Figure 1 shows the evolution of the installed RES power in Portugal between 2005 and 2017. Figure 2 represents the contribution of each renewable and non-renewable technology to the production of electricity in 2017.

The figures clearly show a remarkable increase on RES in particular in what concerns wind. This strategy allowed to increase RES power output and make the system less dependent on the hydropower. Nevertheless, the importance of hydropower remains unquestionable as for example RES share in reached 2016 about 57% of the total electricity production against the 42% for 2017. This difference was mainly driven by the rain conditions, as 2016 was a wet year (well above the average) and 2017 was a dry year (well below the average).

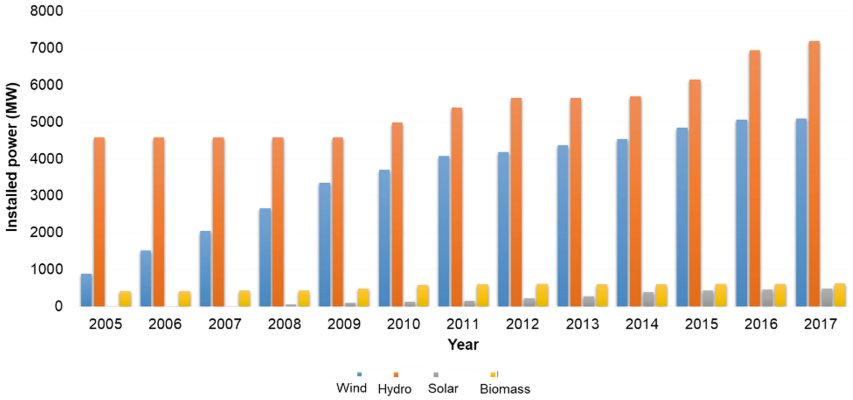


**Fig. 1.** Installed RES power in Portugal (source: data from [13, 14])

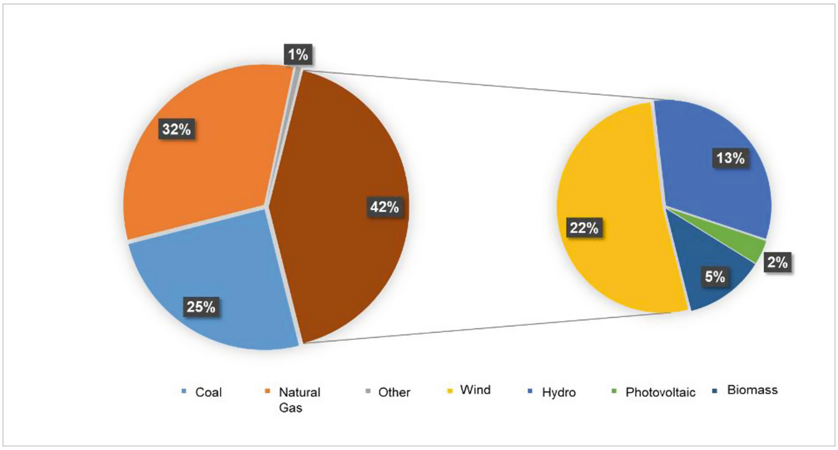


**Fig. 2.** RES and non-RES share of electricity production in Portugal, 2017 (source: data from [14])

Future projections for Portugal point to further investment on RES, with high focus on solar technologies. According to the Monitoring Report on the Security of Supply of the National Electric System 2017–2030 [15], the trajectories traced to 2025 and expanded for 2030, indicate that RES output will represent about 80% of the total electricity use in Portugal. More recently, the Roadmap for Carbon Neutrality in Portugal (RNCP) for 2050 was presented with the objective of reducing greenhouse gas emissions, i.e. the balance between emissions and their removal from the atmosphere should be zero. This Roadmap [16] presents ambitious goals for the power system since it has a fundamental role to carbon neutrality. The objectives of this document reinforce the predominant use of renewable endogenous resources that will significantly reduce energy dependence, as well as allowing for more than 80% of primary energy consumption by 2050. As for the final energy consumption, the Roadmap states that by 2050, more than 65% of final energy consumption will be electricity, which reinforces the sharp reduction in consumption of petroleum products [16]. The scenario outlined for 2050 assumes that electricity will be exclusively obtained from RES, including decentralized production, namely solar, as well as an investment in different storage options. Interconnections with neighboring power grids and consequently other electric markets will allow the transition to a renewable-based electrical system [16].

The Portuguese electricity system is interconnected to the Spanish territory and this interconnection has been increasing in recent years. In 2017, in Portugal-Spain (export) direction, the interconnection capacity reached 2600 MW, while in the Spain-Portugal (import) direction, this limit was 2000 MW [17]. Energy exchanges between Portugal and Spain have increased significantly through the years. Figure 3 shows the evolution of energy exchanges by interconnection between Portugal and Spain, from 2008 to 2018, as well as the average price (€/MWh).

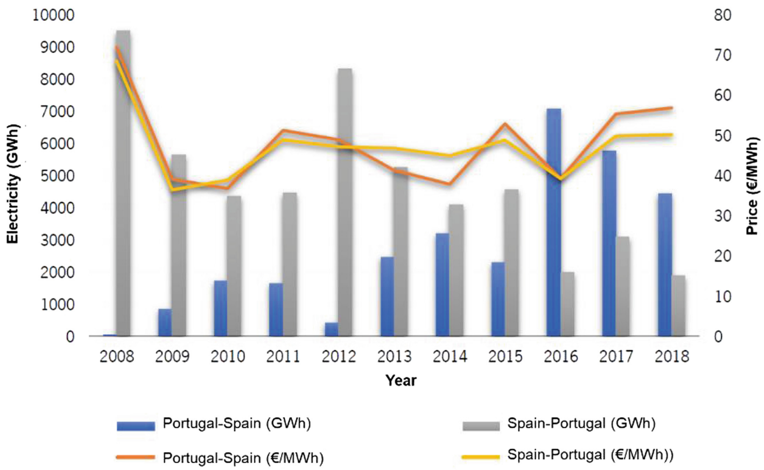


**Fig. 3.** Interconnection Portugal-Spain (source: data from [17, 18]).

## 4 Modelling Approach

The model implemented departed from a previous version from Pereira et al. [2], also developed for long-term power planning in Portugal using a cost minimization approach. The model was adapted for this particular study, with the inclusion of additional technologies, the extension of the planning period and the inclusion of the interconnection possibility. This resulted in a Mixed Integer Linear Problem (MILP), which was programmed in GAMS (General Algebric Modeling System) language. The solver CPLEX was used to obtain the numerical results of the cost minimization problem.

Besides the cost equation (objective function), a set of equations was included to reflect the constraints of the model. These constraints are imposed conditions in the formulation of the model and allow defining viable values of the decision variables for the specific case of the Portuguese electricity system. As such, the input information for the problem includes the mathematical formulation of the objectives and constraints. These constraints addressed:

– Demand, ensuring that the demand for electricity is always met over the planning horizon.
– Renewables, representing the minimum renewable shares for each scenario.
– System, which take into account the technical characteristics of the system and of the power plants (capacity, reserve, hydro and natural gas).

The input data describe the technical and economic characteristics of the existing and candidate power plants and the expected load (demand) pattern. The proposed model includes the following data modules:

– Information on all the generating units in the system at the start of the study and a list of retirements and fixed additions to the system.
– Information on the various generating units to be considered as candidates for expanding the generating system.
– Information on monthly demand, peak load for the planning period and the previously committed production (non-modelled).

The model does not deal with individual power plants but with technologies. Average values for the efficiency, $CO_2$ emission factors and specific fuel consumption are considered for each technology based on the average operating conditions occurred in previous years (for existing power plants) and on the expected performance of future power plants. It should be also underlined that the model does not foresee compensation payments for plants that although not producing or producing very little during the planning period would still be available as reserve. The model assumes that the fixed O&M will always be incurred even for these non-operational power plants.

The assumptions used as well as the source of data collection were presented, and according to the state of the Portuguese electricity system in 2017, three scenarios are established for further analysis:

– Scenario 1: "Base", assumed the minimum 80% share of renewable according to the "Monitoring Report on the Security of the National Electric System Supply 2017–2030", set as a restriction to the model.
– Scenario 2: "Maximum Renewable" (MAX-REN), is based on the year 2017 and provides for the maximum integration of renewable energy supply (100% renewable system), with no interconnection. This 100% RES share was also set as a restriction to the model.

– Scenario 3: "Interconnection System" (S-INT), 100% renewable system with the possibility of interconnection with Spain. The 100% RES was set as a restriction and the interconnection possibility was included on the cost objective as virtual generator with no investment or fixed costs.

## 5 Results

The optimization results for the three different scenarios in terms of total cost and $CO_2$ emissions for a 20-year planning period are shown in Table 1.

For the "BASE" scenario and for the "MAX-REN" scenario, the total cost assumes different parameters such as the cost of new units, i.e. new investments in renewable technology, fixed and variable cost of operation and maintenance (O&M), the fuel cost used in each production unit and the license cost for CO2 emissions.

**Table 1.** Characterization of the 3 scenarios

| Scenario | Cost (€/MWh) | Emissions (t/MWh) | RES share (%) |
|---|---|---|---|
| Base | 6.41 | 0.031 | 80 |
| MAX-REN | 9.03 | 0.019 | 100 |
| S-INT | 7.87 | 0 | 100 |

In the "S-INT" scenario, in addition to the previously mentioned parameters, the importation costs are also included in the objective function. A low importation cost of around € 9/MWh was assumed, which, despite being lower than the average value observed in the Iberian Market (MIBEL) will ensure that importations will be included in the model, albeit with optimistic costs. In fact, given the investments already made and the constraints imposed by the minimum share of renewables, it appears that with higher cost values the model would tend to reduce imports or even avoid them. This result comes

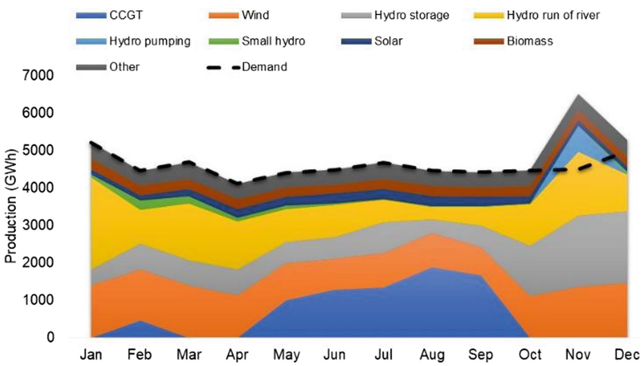


**Fig. 4.** Production and demand, year 20, Base Scenario

mainly from the use of monthly average values which do not allow for capturing strategic decisions and short-term needs, which are often related to import/export decisions.

Figure 4 illustrates the evolution of monthly energy production and consumption forecast in the "Base" scenario in year 20 of the planning period.

The analysis of electricity production per month allows observing the seasonality of each technology in production, in particular for hydro and wind power. The production highly relies on RES with the exception of the summer months for which combined cycle gas turbines (CCGT) would be called to operate and compensate the low hydropower production. As for winter months (November and December), some excess production may be observed given the more favorable wind and hydro conditions.

Figure 5 shows the evolution of energy production and consumption for the "MAX-REN" scenario in year 20 of the planning period.

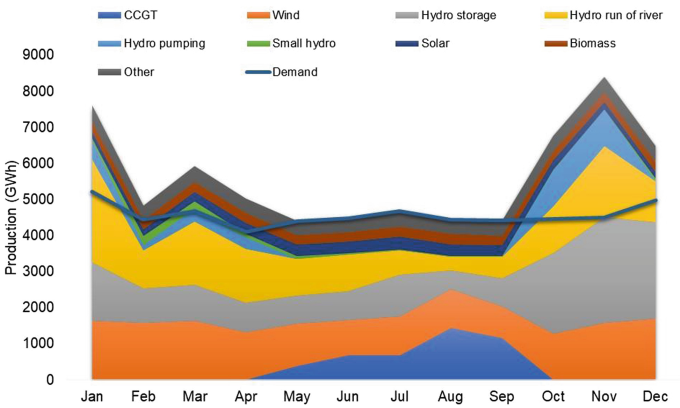


**Fig. 5.** Production and demand, year 20, MAX-REN scenario

The results are quite similar to the ones presented in the previous scenario, although with the seasonality being even more evident, which leads to higher installed capacity of RES and consequently to higher excess production during the winter. Given that the restriction imposing a 100% RES share was set on an annual basis as ratio between production and demand, the model tends to use CCGT during the summer which would be compensated by the excess of electricity production in the winter. As such, the yearly demand equals RES production but the system does reach the full decarbonization.

As for the "S-INT" scenario, it represents also a 100% RES system but now with the possibility of trading with Spain. Imports would occur in months of lower RES production, such as May, June, July, August and September, which reflect the lower hydro availability. The importation of electricity allows the consumption to be satisfied in these months, without recourse to the gas technologies as verified in the previous scenarios and allowing also for a reduction of installed power of new wind power plants, as presented in Fig. 6. The system would then be fully decarbonized.

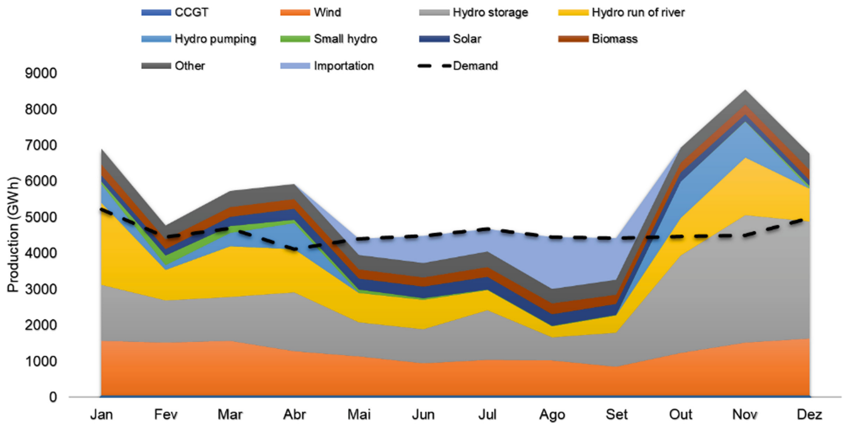


**Fig. 6.** Production and demand, year 20, S-INT scenario

## 6 Conclusions

This paper addressed the importance of interconnection capacity to deal with renewable electricity systems. The three scenarios analyzed reinforce that high RES system tend to be strongly affected by the seasonality of the resources, which can result in either curtailment or excess of production. The results shows the relevance of interconnected electricity system to tackle this problem. The interconnection allows excesses not to be wasted and the system does not fail when there is a production shortfall. It is clear that imports should be considered as a strategy for security of supply of electricity as well as investment in different storage systems to balance the supply of electricity in months of lower production.

Although a simplified approach was used in this study, it became evident that the interconnection can have a positive impact is what concerns costs, emissions and security of supply. However, the cost impact of this strategy is yet to be properly assessed as the proposed approach relied on a simplification of the market assuming only the possibility of importations and at a very low price. In fact, when considering exportations as well, the model would tend to converge to solutions of profit maximization through the increase on production of electricity. This solution, although mathematically sound would not reflect the restrictions associated to the market operation. It also would not take into account the strategic options of market agents Thus, the cost function can reflect the costs of importation, but not the possible revenues of the possible exports that would always be dependent on strategic decisions and the interest of the Spanish market in this excess of electricity produced in Portugal. This open avenues for important research for the inclusion of the short-term market operating model in the long term generation expansion problems and for the assessment of the best options for the decarbonization of the electricity system.

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