Least-cost 100% Renewable Electricity Scenarios

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***Abstract*—Renewable energy sources (RES) are becoming the main players for the sustainability of the planet and achieving a 100% RES energy system has been attested as a good strategy to go forward in many countries. This target however defies the system to integrate highly variable RES in a system that does not allow for shortage on the energy supply. This work presents a possible 100% RES scenario for an electricity system close to the Portuguese estimating and analysing the economic and technical impacts. The sensitivity of the results to aspects related to RES availability, electricity demand, peak load and interconnection capacity for electricity trading were also analysed. The results highlighted the excess of electricity produced in 100% RES systems and the importance of including interconnection capacity to contribute to overcome this problem.**

***Index Terms*—100% RES system, electricity power planning, renewable energy sources, scenarios**

I. Introduction

Accounting for gradual integration of renewable energy sources (RES) in the national energy system is a reality today, an obligation and an opportunity. In fact, sustainable power planning is highly associated to high renewable energy system integration and even to the 100% RES system. In truth, a feasible 100% RES system can be achieved but the system structure will have to be dramatically transformed. In the electricity sector, renewable power generators will replace thermal power plants; in the heat sector, heat pumps will replace individual boilers; and in the transport sector, electric vehicles will replace oil fueled vehicles [1].

The transition from a traditional energy system to a 100% renewable one can be a good strategy to simultaneously mitigate CO_2 emissions, reduce external dependency and increase the security of supply [2]. The impacts also reach the dimensions of social welfare and economic development, namely through the reduction of harmful pollutants for public health, such as NOx, SO_2 and particulate matter, and the generation of opportunities for local incomes and job creation [3].

Notwithstanding, a 100% renewable system introduces several challenges for planners and decision makers, particularly deriving from intermittent RES, such as wind and solar, characterized by their low controllable variability and high unpredictability [4]. Therefore, it is desired to consider strategies capable of guaranteeing that electricity supply and demand can be effectively balanced at all times. Storage technologies combined with wind and solar power plants, interconnection capacity to import or export electricity with neighboring countries and end-use side management have demonstrated to be possible support actions to implement a robust 100% RES system.

In this work, a 100% renewable scenario for an electricity system closed to the Portuguese one is presented for a 20 years planning period, and compared with a business-as-usual scenario, taking 2014 as the departing year. Sensitivity analysis was carried on several variables, namely on the demand, peak load, capacity factors of RES technologies and system configuration – island and connected, in order to evaluate the techno-economic impact on the 100% RES system. The contribution of this work is oriented to the theme of economic analysis of 100 % RES systems, which is recognized by reference [2] as one of the dimensions that need further investigation on scenario analysis of future 100% RES systems.

The paper is organized as follows. A literature review of developed works on the theme of 100% RES scenarios follows this introduction. Then, the methodology used in this study is presented and, subsequently, the results and discussion are detailed. At last, the main conclusions of this work are shown.

II. Literature Review

Several research has been undertaken in order to evaluate the potential of 100% renewable systems in climate change mitigation and efficiency of resource use, or simply to obtain insights of the technical challenges imposed by the transition to 100% RES system [2].

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Ćosić et al. [5] simulated a 100% renewable scenario for the energy system in Macedonia, for the year of 2050, using the EnergyPLAN model. They demonstrated that a 100% RES scenario, operating in a closed system, i.e., not including the import and export capacities, is possible but different storage technologies, such as heat pumps and electric vehicles, are required to compensate for the critical excess of electricity produced (CEEP). In this work, CEEP is referred to the amount of electricity generated exceeding the demand and that cannot be absorbed by the energy system. However, the original concept is applied to the electricity generated exceeding the exports capacity, and thus it is a particular criteria of open system scenario analysis [6].

Another interesting analysis was carried by Elliston et al. [7] which compared a 100% RES scenario with low emission fossil fuel scenarios, for the Australian electricity system in 2030, using the simulation tool NEMO. Low emissions fossil fuel scenarios induces high investments on carbon capture and storage (CCS), a technology that combined with thermal power plants, allows the reduction in 90% of the CO_2 emissions released to the atmosphere. Even though, CCS was demonstrated to have higher technological and investment risks than available RES technologies, concluding that any of the fossil fuel scenarios will hardly compete with a 100% renewable system in a carbon constrained future.

Krajačić et al. [8] presented a possible solution for introducing a 100% renewable electricity system in Portugal for the year 2020, using the H2RES model, a simulation energy-planning tool. They argue that for both electricity system' configuration, open system and closed system, a 100% renewable system can be achieved in the near future with the ancillary of pumped hydro and other storage techniques. They also stated that power planning in closed system enables a better overview of the energy technologies accessible, but on the other hand, is more financially demanding because it forces the installation of more power units and storage that will be operating for a small numbers of hours.

A 100% renewable scenario for the Portuguese electricity system was also simulated by Fernandes and Ferreira [9], using the EnergyPLAN model. The main focus of this work was to analyze the impacts of renewables scenarios under a technical optimization procedure, and so the analysis does not account for the electricity market economic parameters. One of the main findings was that high rates of CEEP would be generated in a 100% RES system and thus, to achieve a resilient system, proper backup strategies are required, namely the inclusion of interconnection capacity between Portugal and Spain in the planning model along with storage systems.

III. Methodology

To evaluate the potential of a 100% renewable electricity system, for a similar case to the Portuguese one, a generation expansion planning model was applied to the study. Sensitivity analysis on the electricity demand, peak load and capacity factors of RES technologies were undertaken in order to evaluate the impacts of these variables on the 100% RES system economic and technical characteristics. The effects of including the electricity interconnection capacity with Spain was also investigated. All scenarios were compared according to specific economic and technical indicators.

A. The optimization model

The model used to create the scenarios is a generation expansion planning model fully described in [10], and, for the purpose of this work, it was expanded to a 20 years' time horizon using monthly intervals. As an optimization problem, the model seeks for the best least cost solution, constrained by the inputs introduced and by the system characteristics. The main outputs of the model are total costs and total emissions released by the electricity production system for the entire period analyzed, as well as a combination of different electricity generation options and their contribution to the electricity production. The assumptions included in the model follow:

- Electricity demand and peak load increase at a constant rate of 1% per year until 2035, an average value projected by REN in the national report "Development and Investment Plan of the Electricity Transmission Grid 2014-2023" [11].
- The technologies included in the model are coal, CCGT (combined cycle gas-turbine), wind onshore, wind offshore, large hydro with reservoir, run-of-river, minihydro, solar PV and biomass. Pumping hydro technology is also included in the model as the energy storage option.
- Cogeneration, geothermal and wave power were included in the model as a parameter and their share are assumed to grow at the same rate as the demand. These technologies, along with the other renewables except large hydro, composed the denominated "special regime production" and, for this work, they will be presented as a parameter designated "srp".
- All costs related issues were collected from [12] which provides a relatively recent survey of current and future cost estimates in the electricity sector, covering renewable and non-renewable generation. All costs are assumed to remain constant for the next 20 years and so, the technology learning effect and the variations in fuel prices are not considered.
- The potential for each RES until 2035 were obtained from the project "New Energy Technologies – Roadmap Portugal 2050" [13].
- CO_2 emissions allowances are assumed to remain unchanged at 25€/ton CO_2, as well as the discount rate, which was set at 8% [14].
- The reserve margin used in this study was defined to be 5% [15].

B. The scenarios

A business-as-usual (BAU) scenario was designed according to the actual pattern of electricity demand and supply, using 2014 as the reference year. Technical data of the electricity matrix was provided by REN, namely power generation, installed capacity, peak load and monthly inflows.

The monthly availability of each technology to generate electricity was assumed to follow the average of the 2008-2014 period in Portugal. The minimum renewable share in total production is assumed to be not less than 62%.

A 100% RES scenario was designed under the same assumptions of BUS scenario but the minimum renewable share in total demand was set at 100%.

C. *The sensitivity analysis*

The electricity demand is the main driver for the system power planning and a balance between electricity demand and supply must be matched at all time. Since 2011, Portugal has seen a decrease in the electricity consumption [16] but, in fact, other aspects such as the growth of the electric vehicles can change this trend and additional electricity would have to be produced in order to accompany this evolution [2]. Thus, a sensitivity analysis was conducted by doubling the electricity demand growth rate assumed in the model.

The potential of solar and wind energy is substantial in the Portuguese territory and considering that renewable technologies are being intensively developed in order to provide the maximum efficiency and reliability, an investigation was carried to analyze the economic and technical impact of assuming higher capacity factors (CF) of RES technologies. These capacity factors were collected from a recent work that had considered a similar case study [17].

Demand response is a measure or action applied at the electricity end-users side in order to reduce peak demand and system's emergencies. Demand response is being demonstrated as an important strategy to load levelling and decrease the backup supply requirements [18]. To analyze the impact of the peak load growth rate in the 100% RES system, a sensitivity analysis was carried reducing the peak load to an half of the previously assumed under the base case scenario.

Finally, the interconnection capacity for electricity trading was investigated and compared with the results for the island system configuration. For the connected system, the model includes some constraints about the imports and exports capacity, as well as a balance constraint and assumes average MIBEL market prices from 2014 to 2015 period. The interconnection capacity was assumed to be 3000 MW [7].

IV. Results and Discussion

The results for the two scenarios analysed are presented in Table I and Figure 1. The values for cost and CO_2 emissions were obtained directly from the planning model representing the average cost and average CO_2 emissions for the entire planning period. RES share is computed as the ratio between total RES power output and total production in the last year of the planning period. CEEP is computed as the difference between total electricity production and total demand also in the last year of the planning period.

TABLE I. Main Indicators for Scenario Analysis

Scenario	***Cost of electricity (€/MWh)***	***CO_2 emissions (ton/MWh)***	***RES share (%)***	***CEEP (%)***
BAU	5,36	0,131	64	0
100 RES	16,28	0	100	4

The BAU scenario demonstrates a very conservative future, with just 2% more RES share in the total electricity produced in 2035 than the actual share today. In fact, within a period of 20 years, only 1000 MW of additional installed capacity is required to fulfil the electricity needs, composed exclusively by combined cycle gas-turbine (CCGT) and biomass power plants. Thus, for a system still relying at a great extent on conventional thermal power plants, which can be highly predictable and work at high capacity factors, the cost for BAU scenario is expectable to remain low as the new investments costs are low and the model does not account for the costs of the investments already incurred. The system costs will then mainly reflect the fuel costs of thermal power plants. The electricity supply is also expected to remain well balanced with the electricity demand, as shown by a CEEP equal to 0%.

For the 100% RES scenario, due to the total replacement of fossil fuel sources by renewable power production, the total costs of the system becomes 3 times higher than the one obtained in BAU. Moreover, it is generated 11% more electricity than is needed to meet the system demand in the last year of the planning period. It is interesting to see that the transition to a 100% RES system will lead to a high reliance on wind power production, as concluded in several works [8], [9], [19], but solar power will also play an essential role since all the solar potential would be installed.

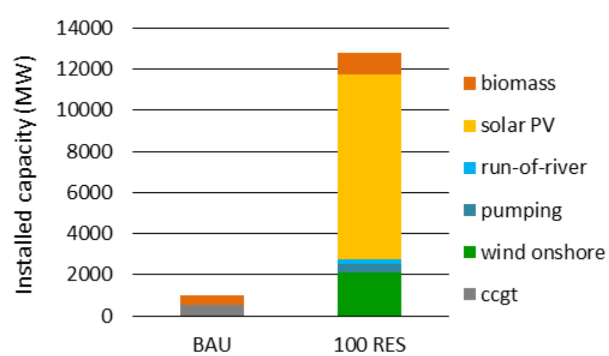

Figure 1. New installed capacity for the planning period for each scenario.

The results for the sensitivity analysis of the 100% RES scenario to a higher electricity demand growth rate as well as to higher capacity factors for RES technologies are presented in Table II.

As expected, the cost obtained for a demand growth rate of 2% is higher than the one obtained for 1%, due to the need to install additional renewable power units to fulfil the electricity demand until the end of the planning period. Regarding capacity factors of RES technologies, assuming higher values, particularly for wind and solar power plants, considerable cost reductions can be achieved. The values assumed for the higher capacity factors were obtained from optimistic projection and aimed to show the importance of technological development to reach highly efficient RES technologies as a strategic route to ensure the economic competitiveness of these 100% RES systems.

A common characteristic to all these scenarios is the excess production, which is higher for higher electricity demand growth or higher capacity factors for RES technologies. Forcing the system to install only renewable technologies will lead inevitably to produce excess electricity. The excess of electricity was also demonstrated in previous works for 100% RES scenarios for the Portuguese electricity system [8], [9]. These results strengthen the role of energy storage, demand response and interconnection capacity in the power planning models, promoting the balance between electricity supply and demand at all time.

TABLE II. SENSITIVITY ANALYSIS TO THE IMPACT OF ELECTRICITY DEMAND AND CAPACITY FACTORS OF RES TECHNOLOGIES

Demand	**CF**	***Cost of electricity (€/MWh)***	***CEEP (%)***
1%	Mean	16,28	4
2%	Mean	19,53	11
1%	High	2,11	10

The results for the sensitivity analysis to the system configuration, as well as for the peak load, are presented in Table III.

It is observed that there is no significant impact in the costs of electricity produced from the assumed value for the system's peak load. The fact that the same electricity generation options are selected by scenarios with different peak loads may be attributed to the reserve margin required for the electricity system and computed into the model.

TABLE III. SENSITIVITY ANALYSIS TO THE IMPACT OF PEAK LOAD AND SYSTEM CONFIGURATION

Scenario	***Peak load***	***Cost of electricity (€/MWh)***	***CEEP (%)***	***Imports (%)***	***Exports (%)***
Island system	1%	16,28	4	-	-
	0,5%	16,28	4	-	-
Conneted system	1%	6,85	-	33	0,5
	0,5%	6,71	-	34	0,4

Including the capacity of 3000 MW of electricity interconnection with Spain and thus, the possibility of trading electricity in the market, will lead to a considerable decrease in the total costs. However it is noteworthy to observe that instead of encouraging the exports of renewable electricity, the system would rely greatly on the imports, in order to reduce the investments on new power plants. This should be related to the assumed MIBEL values, lower than the levelised cost of new RES power plants.

The electricity production profile in the last year of the planning period is presented in Figure 2 for an island system configuration and in Figure 3 for a connected system configuration.

For an island system scenario, a value of CEEP of 4% was previously shown. From Figure 2 it can be seen that only for summer and early autumn seasons' the electricity production would match equally the electricity demand. For the rest of the entire year, electricity production exceeds demand. This is due to the installation of power units, mainly solar PV, which can produce significant amounts of electricity during sunny days but whose production becomes zero or very low by night or in cloudy days. Therefore, hydro and wind power units will also have to be installed to compensate for low solar power output, originating an excess of electricity produced during, mainly, low solar radiation months.

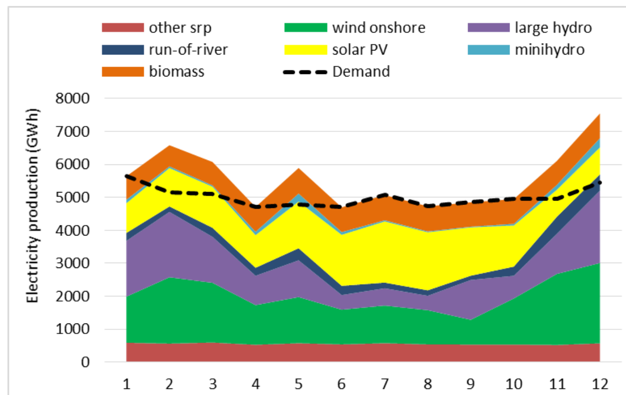

Figure 2. Electricity production for the last year of the planning period. Island system configuration, 100 RES.

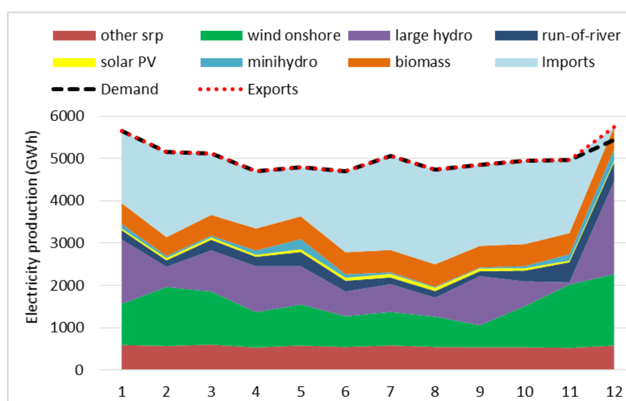

Figure 3. Electricity production for the last year of the planning period. Connected system configuration, 100 RES.

Considering a connected system scenario, the problem of the excess of electricity produced could be theoretically overcome but the system would rely heavily on the imports capacity. Under the assumed conditions, the system would install biomass and no advantage of the solar potential would be taken. A very little amount of the total electricity produced would be exported and only in December, due to the high electricity production from large hydro and wind onshore power plants. This poses important challenges to the decision makers related to the security of supply of the system if a simple cost optimization approach was undertaken relying on the historical time series of MIBEL prices. In addition, another important drawback arises from this situation. It is certain that internal production of electricity would come from RES only but the total supply would be also supported on imports, which have no guarantee of origin, as referred also in [8]. In this case, should it be wise to designate such scenario as a 100% RES scenario?

V. Conclusions

RES are in the spotlight of the policies for future energy supply and the potential of 100% renewable systems are under research in many regions and countries. For countries like Portugal, whose only energetic endogenous resources are the renewable ones, 100% RES system may represent an interesting solution to achieve electricity sell-sufficiency. The implementation of such a system would impact society, environment and economy, namely through the reduction of pollutants emissions, creation of opportunities to increase employment rate and income for local communities, and through the reduction of the system's costs that would lead to a decrease in the end-use energy costs. However, the challenge relies on how to integrate intermittent sources in the system while continuously maintaining the balance between energy produced and energy demanded.

This paper addresses the topic of least cost optimization of 100% RES scenarios and intends to evaluate the potential of implementing a 100% renewable electricity system in a 20 years planning period in a system close to the Portuguese one. One reference scenario and a 100% RES scenario were designed using [10] model and the impacts on economic, environmental and technical parameters were analyzed. Sensitivity analysis to the technical-economic parameters of the 100% RES scenario was undertaken for an increase in the electricity demand, increase in the capacity factors of RES technologies, reduction of peak load and system configuration – island or connected electricity system.

The results of this work lead to conclude that a 100% RES electricity system is theoretically feasible. Wind onshore and hydro power production would have the highest shares on electricity generation in a 100% RES system but solar power would also have a very prominent role in the electricity system, highlighting the potential of this energy source and the opportunity for cells PV efficiency development.

A common feature among 100% RES scenarios was the excess of electricity produced, more pronounced when increasing the electricity demand growth rate. In the optimization model, only pumping hydro units were considered as the energy storage option and therefore additional storage technologies must be considered in future approaches to the planning model. Another strategy to tackle the issue of excess of electricity production could be the exportation of that excess, through the electricity grid interconnections with neighboring countries. This was demonstrated to be a cost-effective solution as the results from the sensitivity analysis conducted on the system configuration showed that it is possible to obtain economic savings and improve production efficiency, operating in an interconnected electricity system. However, the increase on electricity importations should be seen as an important aspect to be considered due to security of supply considerations, rising also doubts about the possibility of ensuring an effective 100% RES supply. The results of this work put in evidence the need of complementing electricity storage units and interconnections capacity to achieve a feasible 100% RES system.

This paper should be seen as a precursor of future research projects aiming to address the topic of 100% RES systems for the Portuguese case overcoming some of the main limitations of the proposed model. Under the scope of economic analysis, the effect of technology learning rate should be evaluated in order to access the competitiveness of available and emergent RES and storage technologies and their potential of integration in the future electricity system in Portugal. Interconnections capacity should also be included as a crucial element for continuous balance between electricity demand and supply in 100% RES systems, but some measures must be applied in order to guarantee the renewable origin of electricity imports. Also, it should be underlined that the present model relied on oversimplification of the market, departing from average monthly electricity prices without taking into consideration the strategic behaviour of the market players or the prices elasticities. The integration of a market trading environment in electricity power planning increases the complexity of the model and represents an important source of uncertainty to be addressed in future research. For this, modelling of power system with a short-term optimization model such as the one presented in [20] is particularly well suited, in order to account for the intra--daily profile of resources and demand. Finally the issue of security of supply focusing in particular the assumed reserve margin should be a matter of in-depth analysis for the design of 100% RES systems in both island and connected configurations.

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