Development of a modelling tool for analysis of specified renewable energy penetration scenarios. Case study of Porto Santo, Madeira

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June 2018

Abstract

Climate change, security of energy supply and fossil fuels depletion are well-known issues that determine the need of finding pathways for sustainable energy production. These pathways include energy efficiency and renewable energy production. However, the worldwide current energy infrastructure was designed for conventional technologies, based on fossil fuels that have provided large and cheap energy storage. This flexibility of fossil fuels enables the production of energy whenever is required. On the other hand, variable renewable energy sources (RES) as wind or solar are not flexible since energy production from these sources is intermittent. This intermittent nature introduces barriers to the penetration of energy from these sources into the power supply system, like the struggle to match demand with supply. Moreover, in some regions, the water supply is already limited, and the situation can become worse due to climate change. Hence, it is important to study if there is a significant synergetic relation that can be obtained by coupling these two sectors. The objective of this study is to develop a techno-economic modelling tool to conduct an analysis of specified renewable energy penetration scenarios, focusing mainly on the power and water sectors and considering the integration of the most suitable RES conversion technologies. Finally, the developed modelling tool will be applied to the Island of Porto Santo, in Madeira.

Keywords:

Energy in Islands; Energy Planning; Isolated Power Systems; Renewable Energy Integration; Intermittent Renewable Energy; Desalination

1. Introduction

In 2015, the Climate Change Agreement (Paris Agreement) was signed, where countries committed to reduce their emissions. The biggest aim is to hold bellow the global average temperature 2ºC above pre-industrial levels [1]. Unfortunately, 2016 was the hottest year since the first records in 1880 [2]. A substantial portion of the world population lives in cities in coastal zones [3], and while the sea levels rising rate per-se might not seem so alarming, that combining with increasing incidence of extreme weather events can just be the right match for unprecedented floods to cause billions in material damages. Another major consequence of climate change are perturbations to the hydrological cycle, which in turn affect the water system and the access to potable water sources [4]. In this way, the energy and non-energy infrastructure may benefit from an integration, so that it can be robust, reliable and smart enough for the next decades.

Islands are especially vulnerable, and several authors have been studying these impacts and proposing solutions over the years. In Segurado et al. [5] an in-depth analysis is made to one of the islands of the Cape Verde archipelago, S. Vicente. It is concluded that the coupling between the energy and water sector is indeed very profitable. All the excess wind power that is produced during the night can be used in the desalination plant and then also to pump water to an upper reservoir (pumped hydro system - PHS). It is shown that, compared with the business as usual (BAU) for 2020, a renewable energy sources (RES) electricity share of about 70% is realistic, with more than 90% of wind powered desalinated water, as also about 20% decrease in costs and 50% of CO_2 emissions. Stenzel et al. [6] performed a life-cycle assessment on the electricity generation in Graciosa Island in the Azores Archipelago. By assuming a decrease in the conventional share of electricity production from 100% diesel to 35% (integrating more wind, PV and batteries) the authors conclude that a decrease of 43% in the total environmental impacts is achieved, since the great majority (over 60%) of these environmental impacts are caused by the transportation and combustion of diesel. Finally, Chen et al [7] point out that every island has its specific needs and resources, and thus in each one the optimal mix of RES must be carefully chosen. It is further acknowledged that the integration of the water sector in the electrical system depends if the water resource is scarce or abundant. For high RES penetrations, energy storage (ES) is needed. Excess wind power is usually stored in a PHS if the island topography allows it, and if not possible, batteries or hydrogen storage could be the solution.

The objective of the present study is to develop a techno-economic modelling tool to conduct an analysis of specified RES penetration scenarios, focusing mainly on the power and water sectors and considering the integration of the most suitable RES conversion technologies.

Porto Santo is an island that depends heavily on fuel imports, however more recently the Regional Government became very determined in reversing this so-far inevitable fact [8-10]. The modelling tool developed is used to study different possible scenarios for Porto Santo's power system with the aim of increasing RES penetration. In addition, specific RES penetration scenarios are analyzed for Porto Santo.

2. Methodology

For this study, a new modelling tool named Renalyst (Renewable Energy Analysis Tool) was developed. This tool was developed in Excel spreadsheets and it is specifically designed for application in isolated power systems as usually are islands.

The main inputs include the hourly electricity supply from different sources, the hourly demand of electricity for desalination or the hourly potential electricity production from RES (all from previous years). Other important inputs are the percentage of RES penetration that is desired to be achieved and/or the amount of available capital for investment, and the target year for that desired RES penetration.

The intermittent RES conversion technologies considered by Renalyst are: wind, solar PV, wave, tidal, run of river hydro, ocean thermal energy conversion and an unknown future technology, presently filled in blank by default. Non-intermittent RES include biomass, hydro, geothermal and waste. Additionally, the tool considers electrochemical storage (e.g. lithium-ion batteries) and a PHS as the two main ES technologies.

Additionally, the user has several options for the target year. For example, if the desalination mode is activated, the user can choose what is the maximum hourly share (in %) of RES electricity that can be used in the desalination plant. Furthermore, if the PHS mode is activated, the tool uses excess RES electricity to both produce water from the desalination plant and then to pump the available excess water (the part not used by the population) to an upper reservoir, to be later turbinated producing RES electricity. All these options allow the user to analyze if the integration of the power and water systems make economic and technical sense, i.e. if the new system is more resilient, efficient and with a higher RES penetration then the current one. The final year, where all this information is computed and shown, also presents an important set of data – the spinning reserve. Renalyst computes how many thermal groups are operating every hour of the year to ensure a (n-1) security criterion[1], and it presents the loads of the thermal groups and their respective yearly working hours.

Renalyst investment criterion was inspired in a GE-McKinsey matrix model to allocate the investment across the different RES technologies, and with the resulting installed power for each technology [11].

Main outputs of Renalyst include the RES penetration achieved, loads in the PP thermal groups, total RES electricity curtailed, and the correspondent installed power of each RES to achieve the desired scenario proposed.

The financial outputs of Renalyst are provided in differential terms, i.e. they represent additional costs that are a consequence of implementing a new proposed system relatively to the present situation. One of these outputs is the differential levelized cost of electricity (ΔLCOE) which is calculated according to (1),

$$\Delta \text{LCOE [€/kWh]} = \frac{\sum_t (I \cdot CRF + O\&M) + (I \cdot CRF + O\&M)_{PP}}{E_{Sup}} \tag{1}$$

where I represents the total investment in the renewable energy generation system, $O\&M$ are the operation and maintenance costs (assumed as a fixed percentage of the former), $(I \cdot CRF + O\&M)_{PP}$ representing cost variations in the PP (here the operation also include the fuel[2] used and CO2 licenses costs; preferably this parcel will be negative as less fuel will be used), E_{Sup} is the total electricity produced by the power system and CRF being the capital recovery factor, calculated according to (2),

$$CRF = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \tag{2}$$

where i is the discount rate and n represents the expected lifetime of the equipment (in years). The annualized costs for each scenario is given by the numerator from (1), with units in [€]. Regarding the variations in fuel and CO2 costs ($\Delta fuel$ and $\Delta CO2$), these represent the cost difference in fuel use and CO2 licenses for the new systems that were proposed in comparison to the present situation, for the target year.

[1] A (n-1) security criterion means that if the largest producing source suddenly fails, all the other sources must have the capacity to generate enough power to guarantee the supply.
[2] It is assumed that the specific fuel consumption is the same regardless of the engine load.

Finally, some of the results provided by Renalyst are compared with the results from EnergyPLAN, a widely used energy modelling tool [12], to ensure their reliability.

3. Porto Santo characterization

Porto Santo is a small island (42 km^2 of area) part of the Madeira archipelago, an autonomous region of the Portuguese Republic. It is located in the Atlantic Ocean, at about 40 km from the main archipelago island (Madeira island) and about 600 km from North Africa. Opposite to the Madeira island, this island has a very low relief, as it is predominately flat (maximum altitude at 516 m) and characterized by a very warm climate especially in the summer period. The main economic engine is indeed the touristic activity of the summer period, especially in the month of August. One of the major issues of this island is the water resource though, since it is very scarce due to the semi-arid nature of this island. Because of that, a desalination plant was installed in 1980 to guarantee the production and supply of fresh water to its current 5,000 inhabitants [13].

3.1. Power and water sectors

The power sector is composed of one thermal power plant (with four groups running on fuel and diesel), one wind park (with only one wind turbine working, two stopped due to malfunctioning and not likely to be repaired), one PV park and few distributed PV microgeneration. The electricity demand from the past years has been in the 30-32 GWh range, with a RES electricity share between 11 and 15% [8-9] and the RES curtailment is about 0.2 GWh. The main constraint of the power sector is the significant difference in power consumption between the winter and summer periods, with peak demands of about 3 MW in the winter period and 8 MW in the summer [14].

Table 1 shows the current characteristics of the power system, the foreseen ones for 2019 (when a 3 MWh lithium-ion battery system is foreseen to be installed, and for 2027, the target year of this study. According to [15], the main objectives of installing the battery system are: (i) reduce permanently one thermal group in the power plant operation (as the battery system will provide spinning reserve all the time); (ii) Enhance the integration of RES, cooperating with conventional technology when the intermittency of RES happens; (iii) Improve the efficiency of the thermal power plant operation (higher loads in the groups). With this, RES penetration is expected to grow from 14% to 20%.

Table 1. System characterization – present situation and BAU.

		Present Situation - 2017	BAU - 2019	BAU - 2027
Installed capacity	Power plant [kW]	15,200	15,200	15,200
	Wind power [kW]	660	660	660
	PV power [kW]	2,340	2,340	2,340
	Lithium-ion batteries [kWh]	-	3,000	3,000
Electricity demand [GWh]		32.4	33.1	35.8
RES penetration		13.7%	20%	-

The water sector is characterized by a desalination plant located in the beach line in the south part of the island, with a maximum production capacity of 6,900 m^3/day of fresh water [13]. In the last five years, the yearly average production has been almost 1,000,000 m^3 (or 40% of the maximum capacity) [16]. Since this plant produces 1 m^3 of desalinated water using about 5.65 kWh of electricity, the production of water in this island alone accounts for almost 20% of the total electricity consumption, which is significant.

3.2. Scenarios considered

Table 2 shows the several scenarios studied. In addition to the BaU, three other scenarios are proposed, all considering further installations in wind and PV power. Table 4.2 presents the scenarios considered. For the BaU scenario, the only difference respective to the present situation is the installment of the batteries system. For the other scenarios, more wind and PV power installations along with batteries and a PHS are considered. Additionally, scenarios 2 and 3 will be tested for very high penetrations (scenarios 2a and 3a). For this, the minimum hourly production from the power plant will be set to zero and the installed capacities of wind, PV, batteries and PHS will be further increased.

Table 2. Scenarios considered

Scenario	*Further wind power*	*Further PV power*	*Batteries*	*PHS*	*Desalination mode*	*Minimum PP load*
BAU	No	No	Yes	No	No	Yes
Scenario 1	Yes	Yes	No	No	Yes	Yes
Scenario 2	Yes	Yes	Yes*	No	No	Yes
Scenario 2a	Yes	Yes	Yes*	No	No	No
Scenario 3	Yes	Yes	Yes	Yes	Yes	Yes
Scenario 3a	Yes	Yes	Yes	Yes	Yes	No

*For scenarios 2 and 2a two batteries are considered: the one that is expected to be installed in 2019 (a 3-MWh battery) which will function with the main purpose of providing power quality services and another battery with the capacity proposed by Renalyst (which changes from point to point) with main purpose of storing and providing bulk power. For the BaU and scenario 3, only the 3-MWh battery is considered.

In the present study different scenarios were studied and the two RES considered were PV and wind technology, as other RES1 are not mature yet (especially when compared with these two). Additionally, it is not viable to consider installation of RES2 (e.g. biomass, hydro) as those resources are not readily available in the island.

The electricity demand growth is an important input, although also difficult to estimate. A value of 1% growth per year for this parameter was assumed based on the recent positive trajectory in economic growth and more electrical appliances, resulting in an electricity demand of about 36.6 GWh for 2027, a value last observed in this island in the period of 2005-09 before the financial crisis. However, a sensitivity analysis will be conducted assuming 0% and 2% for this parameter, so that a range of 32-39 GWh in electricity demand is modelled for 2027, which covers all electricity demand's historical values since 2002.

The target year was chosen to be 2027, which represents 10 years from the available data. This year was done so that all scenarios could be compared in the same year, and if scenarios 1 and 2 could be implemented in less than a 10-year time frame, a PHS considered in scenario 3 would take no less than that time to be fully implemented in the island.

The water demand growth was also assumed to grow 1% per year from 2017 to 2027. To what concerns the hourly maximum share of RES power in the grid, a value of 30% was attributed from the knowledge of [17-18], of which considered 20% for wind power and 10% for PV power although with the possibility of one (e.g. wind) being 30% in the case of the other (e.g. PV) do not supply any electricity in a given hour (e.g. at night). For scenarios contemplating the water integration with the power sector (1, 3 and 3a), a value of 100% is attributed to the share of RES power in the desalination plant and in the PHS in the case of scenarios 3 and 3a. This is done to study the potential synergistic relation between the power and water sector. However, it also assumes a technology progress until 2027 to achieve this, since it may not be possible to use only excess RES power presently to do this.

Since the island is very limited in terms of space, it was assumed a maximum of 30 MW for wind and PV power that could be installed in the island. Finally, an hourly minimum of 800 kWh was set to the power plant operation, common to scenarios 1, 2 and 3, as this represents the required minimum load of one working thermal group [139]. This means that at least this amount of electricity must come from the power plant each hour of the year.

Regarding scenarios 1 and 3, where the desalination is considered, a value of 5.65 kWh/m^3 for producing and distributing water was computed from knowledge of [16, 19-23] and a maximum daily production capacity of 6,900 m3 from knowledge of [13], and for scenarios 2 and 3 (and the BaU) where the lithium-ion batteries are installed, a roundtrip efficiency of 90% was also assumed (with equal charging and discharging efficiencies) [24-25]. For the scenario 3, comprising the PHS, a specific set of inputs were also specified. Since the available head in this island will be in the range of 200 to 300 m and with small flow rates, the type of turbine chosen was a Pelton turbine with an available head of 250 m [26]. The round-trip efficiency for these systems usually ranges from 65-85% [27-28], and a value of 75% was assumed, with equal efficiencies of the pump and for the turbine-generator system.

3.3. Economic inputs

Furthermore, there are also economic parameters that need to be specified so that the model can be able to compute the variation in the differential LCOE. Table 3 summarizes the assumed economic and financial parameters.

Table 3. Economic inputs

Wind power, total costs	1,000 €/kW for 2017 and decreasing 1%/year [29-30]
PV power, total costs	1,300 €/kW for 2017 and decreasing 4%/year [29-30]
Lithium-ion batteries, total costs	500 €/kWh for 2017 and decreasing 4%/year [29-31]
PHS, total costs	Pump/Turbine: 500 €/kW for a single penstock and 1,000 €/kW for a double penstock system; Reservoir: 7.5 €/kWh [30, 32]
PP fuel cost	350 €/ton$^{(1)}$ [9, 33]
RES & ES useful lifetime	Wind: 20 yrs. [32, 34] PV: 25 yrs. [34-35]; Batteries: 4,500 cycles [36] $^{(2)}$; PHS: 50 yrs. [32, 36]
Discount rate	r=7% [37]
O&M (RES and ES)	2% of the investment [30]
CO2 license costs	5.90 €/ton$^{(3)}$ [9]

(1) This cost represents a weighted average between diesel and fuel use in the PP.

(2) The lifetime in years is estimated from: $Batteries\ lifetime\ [years] = \frac{Max_{cycles}}{Number_{cycles}}$, being Max_{cycles} the assumed input of 4,500 cycles for the useful number of cycles during the batteries lifetime and $Number_{cycles}$ the number of cycles performed in the simulated year, which corresponds to the total energy discharged by the batteries divided by its total capacity simulated in the hourly spreadsheet in the target year.

(3) For each ton of CO2 emitted, a license must be acquired.

4. Results

Scenario 1 explores how a close tie between the excess RES power production and the desalination plant could benefit both sectors, using the desalination plant as the main demand-side management strategy and increasing the RES penetration at lower costs respective to the other scenarios, since no expensive ES technologies would be needed. In scenario 2, the 3-MWh battery is considered, along with another battery proposed by Renalyst. The first battery mentioned will be function in power quality mode, providing mainly spinning reserve, and the former battery will be function in bulk power mode, making a high number of cycles. It was studied how a system with these batteries could achieve higher RES penetrations at reasonable costs. Figure 5.3 shows the results obtained for this scenario. Scenario 2a corresponds to the above scenario 2 without the PP minimum load. Without this limit, a 100% RES penetration mark could in theory be achieved. Scenario 3 considers two ES technologies – the pumped hydro system, where excess RES power is used in the desalination plant and after in the PHS as the main demand-side strategy, and the 3-MWh battery. Here, the PHS will "substitute" the second battery from scenario 2 which works in bulk power mode, so that it can be compared what is the system, batteries or batteries and a PHS, that allows for higher RES penetrations at lower costs. Finally, scenario corresponds to the above scenario 3 without the PP minimum load. Without this limit, a 100% RES penetration mark could in theory be achieved. Figure 1 presents the results obtained for these scenarios and the BaU also.

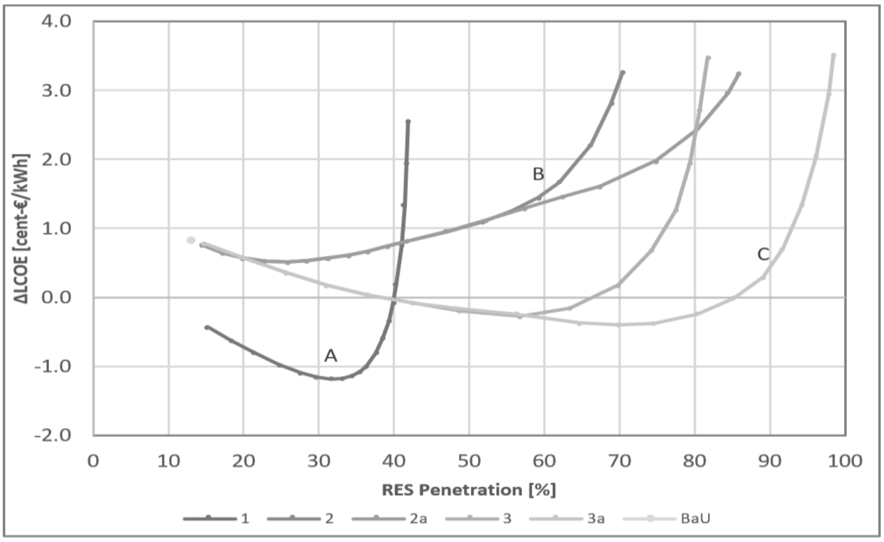

Figure 1 – All scenarios results

Three points were considered for a more detailed examination. Table 4 presents the main characteristics of those points.

Table 4 – Summary of the three points from Figure 1

Point in Figure 1	RES penetration [%]	Wind power [kW]	PV power [kW]	Batteries [kWh]	PHS – Pump power [kW]	PHS – Turbine power [kW]	ΔLCOE [cent-€/kWh]
A	31.6	3,467	2,874	-	-	-	-1.18
B	59.2	9,081	3,942	2,631 + 3,000	-	-	1.45
C	89.1	14,226	4,921	3,000	4,810	3,599	0.29

Furthermore, figure 2 summarizes the energy produced and supplied by source for the same three points considered in figure 1.

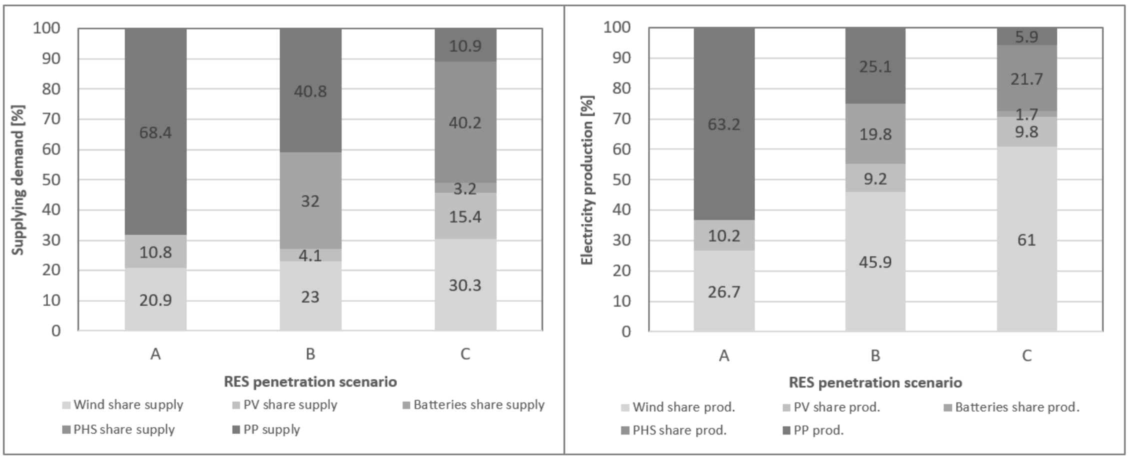

Figure 2 – Supplying demand and electricity production by source for each point highlighted in Figure 1

4.1 Sensitivity analysis

The sensitivity analysis conducted revealed that the most sensible parameters, i.e. the ones that can mostly affect the results when variated, are the fuel price (used in the PP) and the maximum hourly share of RES power that can be injected into the grid. Figures 3 and 4 present the results obtained for all scenarios when these parameters were variated.

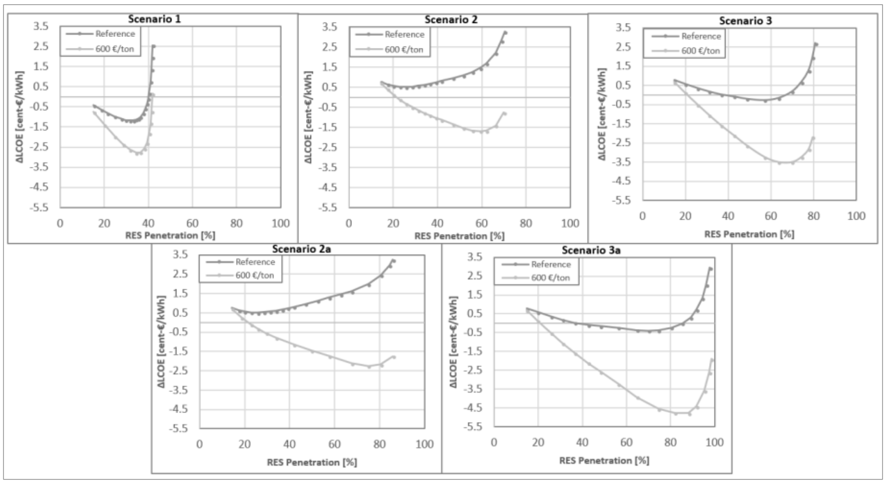

Figure 3 – Sensitivity analysis to the fuel cost for all scenarios

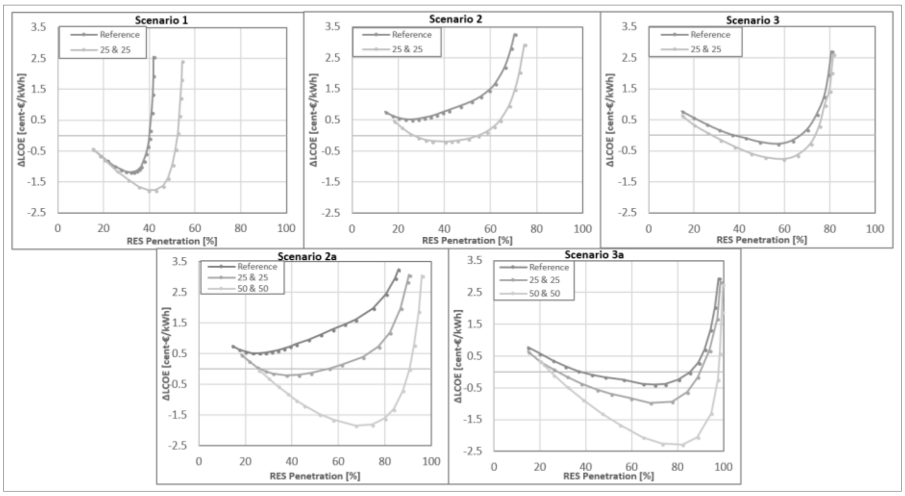

Figure 4 – Sensitivity analysis to the maximum hourly share of RES power for all scenarios

Also, regarding scenarios 2 and 2a, results suggest that the annualized costs of the batteries system have a great impact in total system costs. The sensitivity analysis was performed considering the useful number of cycles of the batteries to be 9,000 cycles instead of the assumed 4,500 cycles. Results are presented below in figure 5.

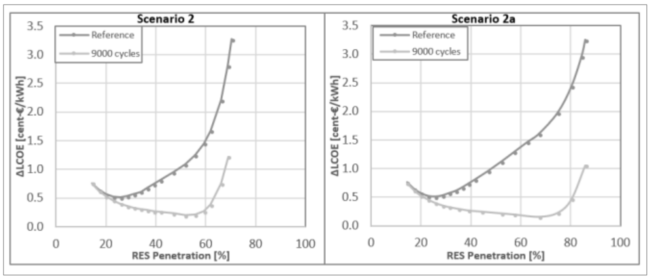

Figure 5 – Sensitivity analysis to the maximum number of cycles of the batteries system for scenarios 2 and 2a

5. Discussion

5.1 Scenarios discussion

The BaU proposal proves to be insufficient without further installations in RES technologies, namely wind power. Since the only power that is presently being curtailed is 0.2 GWh from the wind turbine, this also corresponds to the only additional RES electricity that can be used. For 2027, since the electricity demand is assumed to grow 1% per year, and with no further RES installations, the RES penetration will be lower than presently, or 12.9%. installations projected, the RES penetration decreases as the electricity demand continues to increase. Unless further RES installations are made, the only major benefits from the batteries system will be related to the increase in the thermal groups load (saving fuel and O&M costs) and by providing grid stabilization services when the intermittency of the RES happen. When the batteries study was made, all three wind turbines were working, hence the expected result of increasing the RES penetration from 14% to 20%. However, with only one wind turbine working, there is no potential to achieve this target only with the batteries system.

Scenario 1 attempts to maximize the synergy between the power sector and the water sector. For this scenario, RES penetrations with a negative differential LCOE respective to the present situation are possible up to 40%, and with more than 1 cent-€ in this cost in the range of 25-35%, which shows how strong can be the link between the RES installed power and the desalination plant. However, for this it is assumed that in 2027 the technology progression is such that the desalination plant can use 100% RES power, which might not be possible presently. Furthermore, the costs associated with this technology progression were not included. To sum up, this is the scenario that allows for the lowest differential LCOE and still achieve RES penetrations up to 30pp higher than the present situation.

Scenario 2 considers the integration of an ES technology: batteries. With this, RES penetrations situations are available up to 50% at realistic costs (one cent-€ more in the differential LCOE). From here, costs start to mount heavily as: i) the batteries are required to perform higher number of cycles since no more RES power can be injected into the power grid (due to the 30% limit), increasing the annualized costs for the batteries; ii) more wind and PV power does not imply higher RES penetration, and thus not extending fuel and CO2 savings, since the system starts to lose flexibility as it approaches the minimum load of the PP and the batteries system are not large enough in capacity to serve as seasonal storage.

On the other hand, scenario 2a was tested without this minimum load from the PP, allowing for higher RES penetrations. Both curves (2 and 2a) are identical up to a 55% RES penetration mark, which tends to suggest that this minimum load does not impact the system until this point. From there onwards, scenario 2a is more flexible relative to scenario 2, since more RES power can be injected hourly. However, the reasoning is the same in the sense that this RES power is injected through the batteries, meaning very high annualized costs for the batteries system due to their high number of cycles performed. Furthermore, more wind and PV installed power aggravate the costs as the batteries are not large enough in capacity to serve as seasonal storage, shifting the excess production from the winter period to the summer.

Scenario 3 considers the use of the PHS as the main ES technology, along with a 3-MWh battery serving mainly as spinning reserve. Like scenario 1, it is assumed that 100% RES power can be used in the desalination plant and, in this case, in the PHS also. With this, situations of negative differential LCOE are available from 40% to roughly 65% RES penetrations, which suggest that such a system would be ideal for this range of RES penetrations. Configurations with higher RES penetrations start to compete with the minimum load of the PP, thus not extending fuel and CO2 savings, and increasing system costs.

For scenario 3a this minimum load of the PP is removed, and RES penetrations close to 100% are achievable at not absurd costs. Again, the curve from this scenario departs from the one from scenario 3 at roughly 55% RES penetration, like scenario 2 and 2a, which suggests that the minimum of the PP is important from this 55% RES penetration figure upwards. Still, RES penetrations with a negative differential LCOE are found up to 85%, which makes this the scenarios capable of higher RES penetrations at the lowest costs. The steep increase from the 90% RES penetration mark upwards suggest that the RES system needs to be oversized in terms of RES power and ES capacity to accommodate the peak in the summer period, as this are the months responsible for the lowest RES penetrations achieved.

The sensitivity analysis performed to the fuel cost revealed that this parameter does have a significant impact on the system costs. With the fuel price considered, all scenarios become attractive in terms of costs, as great reductions in terms of costs are achievable at very high RES penetrations. This is highly relevant since the future oil price can very well dictate at what extent the RES installed capacity should be present, i.e. installed power and ES capacity to achieve medium RES penetrations due to still low oil prices or a more aggressive RES power system, aiming for higher RES penetrations with ambitious economic savings in terms of fuel usage in the PP.

The sensitivity analysis performed to the maximum hourly RES share also revealed that this parameter has significant impacts in system costs and allowing for higher RES penetrations obtained. The system most positively affected is scenario 2, which is explained by the savings in the batteries systems, as these are no longer required to perform such a high number of cycles, as more RES power can be directly injected into the power grid, without having the need to cycle though the batteries.

Still regarding the batteries system, the sensitivity analysis performed to the useful lifetime of the batteries system in terms of cycles again suggests how important the costs of this ES technology is to the final system costs. When considering a battery capable of performing the double of cycles than the reference assumed condition, the differential LCOE is reduced by more than 1 cent-€.

5.2 100% RES penetration

Due to the seasonality phenomena, i.e. the difference between electricity consumed in the summer respective to the winter months, the RES system is not flexible and cannot produce electricity when it is most need it. Figure 6 summarizes the RES production pattern with the electricity demand along the year for a RES system with 8.3 MW of wind and PV power.

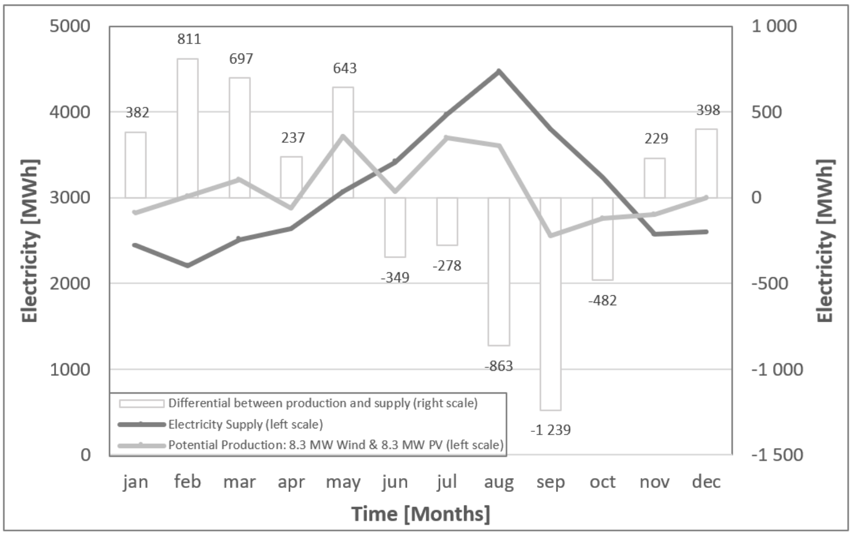

Figure 6 – RES production and supply monthly patterns

There is a mismatch between production and supply. In the summer period, roughly from June to October, there is a RES power deficit production of about 3.2 GWh and in the rest of the year (November until May) there is an excess of RES power production of about 3.4 GWh. To achieve the 100% RES mark, this 3.4 GWh of excess power would have to be transported to the summer period. This would require a battery of 3.4 GWh, which is not possible with current Lithium-ion technology and would require a storage of about 5,000,000 cubic meters of water at 250 m head (or 3 million cubic meters at 400 m head), which again is not possible given the island topography.

The maximum hourly share of RES power that can be injected into the grid also has a great impact in the results (as shown in the sensitivity analysis). There is a clear tradeoff between the increasing of the RES installed power (at the expense of the curtailment) or the costs and technical difficulties involved in a very large storage system. Figure 7 illustrates this (for a battery with a roundtrip efficiency of 90%).

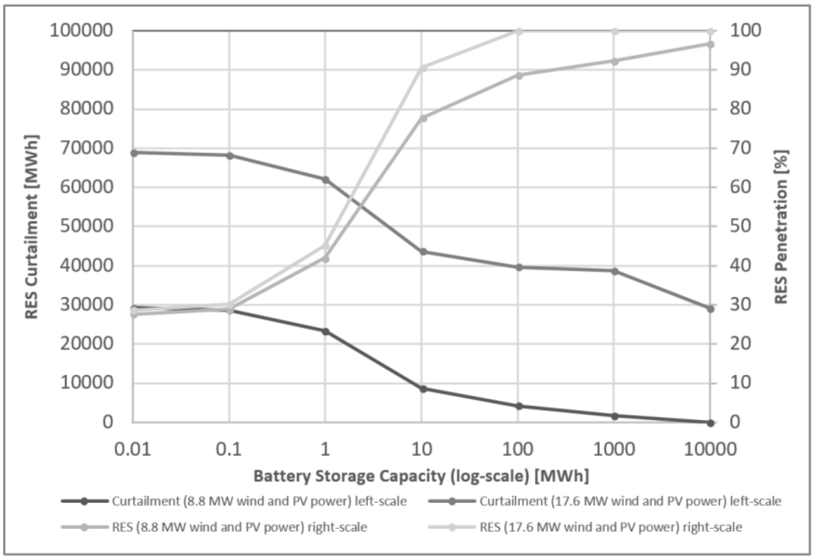

Figure 7 – Relation between storage capacity, RES curtailment and RES penetration for a given RES installed power

For Porto Santo island, the range in storage capacity that allows for a greater increase in the RES penetration, and maintaining a realistic financial and technical environment, is of 1-10 MWh range. Depending on the RES installed power, a battery with this range can increase the RES penetration up to 50pp and decreasing the curtailment by over 20 GWh. For 100% RES penetration situations, a battery in the 100-1000 MWh range (or more) would have to be considered instead. ES technologies currently known to achieve this are for instances the PHS and the compressed air energy storage (CAES) [38]. In fact, scenario 3a returned a RES penetration of 98.5%, with 23.1 MW of wind power, 6.6 MW of PV power and 101.5 MWh of storage (98.5 MWh in the PHS and 3 MWh in the batteries).

6. Conclusions

It can be concluded that some form of energy storage technology along with further installations in wind and PV power could turn out to be very profitable, increasing 20-50pp the RES penetration from current levels at decent costs. For a 100% RES penetration situation, results suggest that a system with: i) comprising a PHS; ii) no minimum hourly PP load; iii) a higher fuel cost; iv) a technology progression that allows for more RES power to be directly injected into the power grid than the present considered 30%; all of this would be theoretically sufficient to have a situation of 100% RES penetration.

It was also found that there is a great synergetic relation that can be explored between the power and water sectors. By using the water production, i.e. the desalination plant, as a demand-side strategy, there is great potential to use excess RES power to produce water, and hence increasing the RES penetration, provided that the desalination plant can use only RES power without restriction, since it is possible that some technical improvements are still needed so that the desalination plant can rely only on RES power to produce water.

Most of the curves tested suggest a lower differential LCOE relatively to the BaU proposal, being scenario 3 the most desired in terms of RES penetration to system costs. Also, the 50-60% RES penetration mark seems to correspond to the range where the minimum production in the PP limits the RES penetration, as configurations start to show some inflexibility when they hit this range of penetration while maintaining the PP minimum load. All the scenarios that were considered with this PP minimum load have investment costs lower than 10 million Euros up to a 50% RES penetration mark. Finally, wind power is preferred relatively to PV power in terms of further installations for this island, as there are two main reasons for this: i) higher capacity factor for wind (2,523 hours of production at nominal power for wind against 1,340 hours for PV power for the present situation); ii) higher production flexibility for wind power, as this technology can produce energy on average 24 hours per day without great deviations from hour to hour, contrary from PV power which produces roughly only half the hours of the day and in a bell shape, peaking production at noon, and more PV installed power will only enhance this difference in the production pattern, which would not be profitable to the power system.

Nomenclature

$\Delta LCOE$	Differential levelized cost of electricity, €/kW
I	Total investment costs in the RES production system, €
CRF	Capital recovery factor
$O\&M$	Yearly operation and maintenance costs, €
PP_{costs}	Cost variations in fuel use and CO_2 emission licenses from the power plant operation, €
E_{sup}	Total electricity supplied by the power system, kWh
i	discount rate
n	lifetime of equipment, years

Acronyms

BAU	Business as usual
ES	Electricity storage
PHS	Pumped hydro system
PP	Power plant
PV	Photovoltaic
RES	Renewable energy sources

References

[1] European Commission. Climate Action. Available at: https://ec.europa.eu/clima/policies/international/negotiations/paris_en> [accessed 25.02.2018].

[2] National Aeronautics and Space Administration. Press Release. Available at: <https://www.nasa.gov/press-release/nasa-noaa-data-show-2016-warmest-year-on-record-globally> [accessed 25.02.2018].

[3] Levy M, Percentage of total population living in coastal areas. Palisades, NY, USA: Center for International Earth Science Information Network at Columbia University (CIESIN).

[4] Stagl J, Mayr E, Koch H, Hattermann FF, Huang S. (2014) Effects of Climate Change on the Hydrological Cycle in Central and Eastern Europe. In: Rannow S, Neubert M (Eds), Managing Protected Areas in Central and Eastern Europe Under Climate Change. Advances in Global Change Research, vol 58. Springer, Dordrecht.

[5] Segurado R, Madeira JFA, Costa M, Duic N, Carvalho MG. Optimization of a wind powered desalination and pumped hydro storage system. Applied Energy 2016;177:487-499.

[6] Stenzel P, Schreiber A, Marx J, Wulf C, Schreieder M, Stephan L. Renewable energies for Graciosa Island, Azores – Life Cycle Assessment of electricity generation. Proceedings of the 11th International Renewable Energy Storage Conference, IRES 2017, 14-16 March 2017, Düsseldorf, Germany.

[7] Chen F, Duić N, Alves LM, Carvalho MG, Renewislands - Renewable Energy Solutions for Islands. Renewable and Sustainable Energy Reviews 2007;11:1888-1902.

[8] Empresa de Eletricidade da Madeira. 2015 Annual Report. Available at: <https://www.eem.pt/media/266828/en_eem_annualreport_2015.pdf> [accessed 25.02.2018].

[9] Empresa de Eletricidade da Madeira 2016 Annual Report. Available at: <https://www.eem.pt/media/323601/rc2016_uk.pdf> [accessed 25.02.2018].

[10] Agência Regional da Energia e Ambiente da Região Autónoma da Madeira. Sustainable Energy Action Plan Porto Santo Island Report. Available at: <http://aream.pt/files/2016/05/ISEAP_Porto_Santo_EN.pdf> [accessed 25.02.2018].

[11] McKinsey. Enduring Ideas: The GE–McKinsey nine-box matrix – Availabe at: https://www.mckinsey.com/business-functions/strategy-and-corporate-finance/our-insights/enduring-ideas-the-ge-and-mckinsey-nine-box-matrix> [accessed 11.03.2018]

[12] Østergaard PA, Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations. Applied Energy 2015;154:921-933.

[13] Águas e Resíduos da Madeira, SA. Dessalinizadora Porto Santo Report. Available at:<http://www.aguasdamadeira.pt/Portals/0/Documentos/Instala%C3%A7%C3%B5es/Dessalinizadora.pdf> [accessed 25.02.2018].

[14] Empresa de Eletricidade da Madeira. 2016 Caracterização da Rede de Transporte e Distribuição em AT e MT Report. Available at: <https://www.eem.pt/media/159012/sepm_2014.pdf> [accessed 25.02.2018].

[15] Empresa de Eletricidade da Madeira. Porto Santo Sustentável Report. Available at: <http://greenbusinessweek.fil.pt/wp-content/uploads/2016/02/Porto-Santo-Sustentavel-_EMM.pdf> [accessed 25.02.2018].

[16] Águas e Resíduos da Madeira, S.A.. “Relatório e Contas 2016”, 2016.

[17] Papathanassiou, Stavros & G. Boulaxis, Nikos. (2006). Power limitations and energy yield evaluation for wind farms operating in island systems. Renewable Energy. 31. 457-479. 10.1016/j.renene.2005.04.002.

[18] Weisser, Daniel & S. Garcia, Raquel. (2005). Instantaneous wind energy penetration in isolated electricity grids: Concepts and review. Renewable Energy. 30. 1299-1308. 10.1016/j.renene.2004.10.002.

[19] Águas e Resíduos da Madeira, S.A.. “Relatório e Contas 2014”, 2014.

[20] Águas e Resíduos da Madeira, S.A.. “Relatório e Contas 2015”, 2015.

[21] Direção Geral de Energia e Geologia. “Estatísticas e Preços, Eletricidade, Consumo por Concelho, por Setor de Atividade”, 2014.

[22] Direção Geral de Energia e Geologia. “Estatísticas e Preços, Eletricidade, Consumo por Concelho, por Setor de Atividade”, 2015.

[23] Direção Geral de Energia e Geologia. “Estatísticas e Preços, Eletricidade, Consumo por Concelho, por Setor de Atividade”, 2016.

[24] Evans, Annette & Strezov, Vladimir & Evans, Tim. (2012). Assessment of utility energy storage options for increased renewable energy penetration. Renewable and Sustainable Energy Reviews. 16. 4141–4147. 10.1016/j.rser.2012.03.048.

[25] Staffell, Iain & Rustomji, Mazda. (2016). Maximising the value of electricity storage. Journal of Energy Storage. 10.1016/j.est.2016.08.010.

[26] Luis Gato, Instituto Superior Técnico, Lisboa, “Hydroelectric Energy”, 2016.

[27] Aneke, Mathew & Wang, Meihong. (2016). Energy storage technologies and real life applications – A state of the art review. Applied Energy. 179. 350-377. 10.1016/j.apenergy.2016.06.097.

[28] Kougias, Ioannis & Szabó, S. (2017). Pumped hydroelectric storage utilization assessment: Forerunner of renewable energy integration or Trojan horse?. Energy. 140. 10.1016/j.energy.2017.08.106.

[29] U.S. Department of Energy. “Revolution Now The Future Arrives for Five Clean Energy Technologies – 2016 Update”, 2016.

[30] European Commission. “Energy Technology Reference Indicator projections for 2010-2050”, 2014.

[31] Bloomberg New Energy Finance. “Lithium-ion Battery Costs and Market”, 2017.

[32] Connolly, D & Lund, Henrik & Mathiesen, Brian & Pican, Emmanuel & Leahy, Martin. (2012). The technical and economic implications of integrating fluctuating renewable energy using energy storage. Renewable Energy. 43. 10.1016/j.renene.2011.11.003.

[33] Eletricidade dos Açores. “Relatório e Contas 2016”, 2016.

[34] International Energy Agency. “Renewable Energy: RD&D Priorities”, 2006.

[35] International Energy Agency. “International Energy Outlook 2016”, 2016.

[36] Evans, Annette & Strezov, Vladimir & Evans, Tim. (2012). Assessment of utility energy storage options for increased renewable energy penetration. Renewable and Sustainable Energy Reviews. 16. 4141–4147. 10.1016/j.rser.2012.03.048.

[37] Grant Thornton International. “Renewable energy discount rate survey results – 2017”, 2017.

[38] European Commission. “Overview of storage technologies “, 2016.