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Assessing the use of photovoltaic energy at a seawater reverse osmosis desalination plant: a case study of Porto Santo Desalination Plant (Madeira – Portugal)

Elías Jesús Medina Domínguez*, Rayco Parra Batista, Jesús Manuel de León Izquier

Renewable Energies Department, Canary Islands Institute of Technology (ITC), C/Playa de Pozo Izquierdo s/n, Santa Lucía de Tirajana (Gran Canaria) 35119, Spain, emails: Tel. +34 928 727 560; email: ejmedina@itccanarias.org (E.J.M. Domínguez), Tel. +34 928 727 609; email: rparra@itccanarias.org (R.P. Batista), Tel. +34 928 727 618; email: jdeleon@itccanarias.org (J.M. de León Izquier)

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ABSTRACT

Renewable energies can benefit the water sector, reducing the cost and the environmental impact of water production. This paper presents a technical and economic assessment of a photovoltaic generation project to supply energy to a grid-connected seawater reverse osmosis (SWRO) desalination plant and of an associated battery energy storage system (BESS) using lithium-ion batteries. It examines the case study of the SWRO desalination plant on Porto Santo Island (Madeira, Portugal). The assessment is supplemented by a sensitivity analysis of several variables. The findings indicate that photovoltaic generation in desalination plants results in a lower levelized cost of energy (LCoE) and reduces the consumption of fossil fuel energy from the electrical grid. This can lead to lower desalinated water costs and greenhouse gas emissions. A feasible rated power range was identified for the photovoltaic plant in this case study, taking the internal rate of return, net present value, payback and LCoE into consideration. The results also point to a higher LCoE when a lithium-ion BESS is used.

Keywords: Photovoltaic powered desalination; Seawater reverse osmosis; Photovoltaic generation; Cost; Lithium-ion battery energy storage system; Grid-connected

1. Introduction

Renewable energy sources (RES) and solar photovoltaic (PV) energy in particular have been used to power desalination plants for many years [1–4]. In most cases, the coupling of RES to desalination plants has been limited to stand-alone projects in remote areas and on islands [5–8].

Given the intermittent, fluctuating nature of renewable energy sources, battery energy storage systems (BESS) have been used in these projects to increase the integration of non-dispatchable energy and achieve a more constant operation of the reverse osmosis (RO) membranes. In this sense, impacts of the fluctuating energy or intermittent operation, such as reduction of the membrane permeability, mechanical damage of the membranes or higher energy consumption, can be reduced or avoided [9–12]. Lead-acid batteries have been the most common energy storage technology because they are a mature technology and require a low initial investment [8,13]. However, stand-alone desalination plants powered by PV energy without BESS have also been studied [14–16].

Renewable energies such as PV energy have been further developed in recent years as a result of national government policies, international agreements like the Paris

* Corresponding author.

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Agreement [17] and European Union policies [18,19]. This has led to technological improvements and a progressive reduction in costs [20–22].

Ongoing reductions in the cost of PV energy are set to make the large-scale coupling of PV plants to grid-connected RO desalination plants more technically and economically viable [23–25]. As a result, there has been a proliferation of research into these types of projects in recent years. Several studies have demonstrated the potential economic feasibility of these systems [26–29], while other researchers have concluded that they are not feasible [30–33]. These different findings owe largely to the strong influence of local factors, such as the price of electricity from the grid, fuel subsidies and government financial incentives for the installation of PV plants. Nevertheless, several large-scale desalination plants are being developed at the time of writing [34,35].

With regard to BESS, systems based on lithium-ion batteries are sufficiently developed to provide stationary energy storage, delivering high energy intensity and a high number of charge/discharge cycles. Lithium-ion BESS can store surplus energy from the PV plant for later consumption [36,37]. Moreover, the cost of lithium-ion BESS for grid-connected systems has decreased in recent years [38,39]. This makes lithium-ion BESS a potential energy storage option in projects coupling a PV plant to a RO desalination plant [40].

Despite these features, the economic feasibility of using a lithium-ion BESS is still significantly influenced by cost [41]. Any feasibility analysis must consider not only the cost of a lithium-ion BESS but also local economic aspects such as those mentioned above.

This paper analyses the feasibility and sizing of a PV plant and lithium-ion BESS coupled to a grid-connected seawater reverse osmosis (SWRO) desalination plant. The analysis is based on current energy costs and technology, assuming that the PV plant and lithium-ion BESS operate without selling energy to the electrical grid. Unlike previous studies, it also seeks to explain how the size of the PV plant and lithium-ion BESS affects the technical and economic parameters analysed. As part of the study, a sensitivity analysis was performed to assess the influence on the study parameters of electricity prices on the grid, initial investment in the PV plant and reduced photovoltaic generation due to degradation of the photovoltaic modules.

The paper focuses on the SWRO desalination plant on Porto Santo Island in the autonomous region of Madeira (Portugal) as an example of a medium-scale SWRO desalination plant. An analysis of the energy results is then presented, followed by an economic assessment. PV energy generation, BESS energy flow and total energy balance were obtained using HOMER Pro® software [42], with energy data collected hourly. The economic assessment covers a period of 25 y and considers parameters such as net present value (NPV), internal rate of return (IRR), payback and levelized cost of energy (LCoE). A detailed description of the methodology and sensitivity analysis used in the study is provided in section 2. Section 3 presents the results and discussion, while the main conclusions drawn from the analysis are summarized in section 4.

2. Methodology

The assessing of the feasibility and sizing is based on a technical and economic analysis. As stated above, Porto Santo SWRO desalination plant is used as a case study and a brief description of this plant is provided in section 2.1. The data used in the analysis can be found in section 6.

The technical and economic analysis is carried out for two types of system configuration: (a) a PV plant coupled to the SWRO desalination plant (hereafter referred to as a PV-RO system) and (b) a PV plant and lithium-ion BESS coupled to the SWRO desalination plant (hereafter referred to as a PV-BESS-RO system). These two system types are shown in Fig. 1.

The analysis takes several rated power values for the PV plant ($P_{\text{rated PV}}$) into consideration, ranging from 300 to 1,050 kW with 50 kW intervals. Several different capacity values for the BESS are also examined. The BESS rated capacity ($C_{\text{rated BESS}}$) values studied here are 100, 200, 300 and 400 kWh. A 400 kWh capacity represents around 3% of the

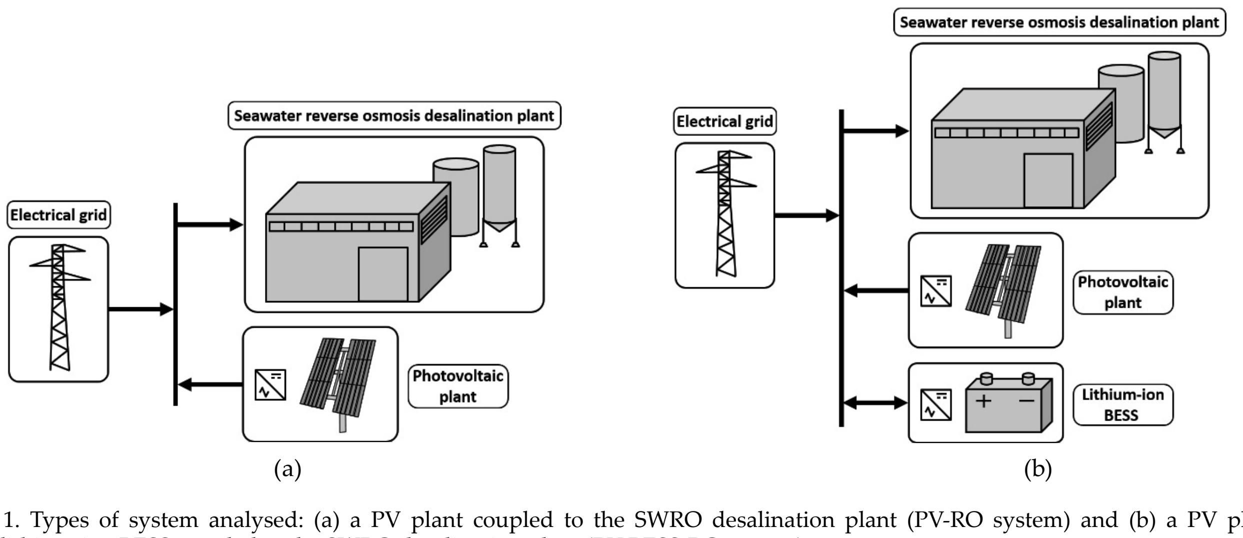

Fig. 1. Types of system analysed: (a) a PV plant coupled to the SWRO desalination plant (PV-RO system) and (b) a PV plant and lithium-ion BESS coupled to the SWRO desalination plant (PV-BESS-RO system).

SWRO desalination plant's daily energy consumption. The plant's annual energy consumption is around 4,834 MWh, as stated above. The study assumes the same annual energy demand hourly profile for the SWRO desalination plant for each year of the study period. This simplifies the analysis and enables a focus on the energy contribution of both the PV plant and the BESS. It is also assumed that no energy is injected into the electrical grid from either the PV plant or the BESS. The study also considers the required sizing of the PV plant and lithium-ion BESS to supply energy to the SWRO desalination plant. It is only possible to charge the BESS with surplus energy from the PV plant, so this energy produced by the PV plant is not consumed by the SWRO desalination plant. Therefore, the operation of the BESS allows the SWRO desalination plant's energy demands to be met with surplus energy from the PV plant.

The technical and economic analysis in this study focuses first on the hourly energy balance for a year, before conducting an economic assessment for a project lifetime of 25 y.

The hourly energy balance for a year is calculated on the basis of a load following strategy using HOMER Pro® v3.12.4 software. This strategy serves the load at the lowest total cost for each time interval and it may be viewed as the basis for an economic dispatch [43,44]. This strategy could be represented by Eqs. (1) and (2):

$$\text{Min}\sum_{s=1}^{n}\left(E_s \cdot C_s\right) \tag{1}$$

$$\sum_{s=1}^{n} E_s = E_{\text{load}} \tag{2}$$

where E_s: energy generated by the source s. s = 1, 2, …, n; C_s: production cost of the source s per energy unit; E_{load}: energy demand to be met.

The energy sources considered here are the electrical grid and the PV plant. The analysis of the PV-BESS-RO system considers the BESS as an additional energy source. In this regard, BESS discharge follows Eqs. (1) and (2). The minimum state of charge (SoC) permitted in the BESS is 20%.

The energy produced by the PV plant is obtained by calculating the power generated ($P_{\text{gen PV}}$) at each time interval using Eq. (3) [42,45]:

$$P_{\text{gen PV}} = P_{\text{rated PV}} \cdot f_{\text{PV}}\left(\frac{G_T}{G_{T,\text{STC}}}\right)\left[1+\alpha_p\left(T_c - T_{c,\text{STC}}\right)\right] \tag{3}$$

where $P_{\text{rated PV}}$: rated power of the PV plant (kW); f_{PV}: PV derating factor (%) which takes into account factors that would cause the output of the PV array to deviate from that expected under ideal conditions, such as soiling of the panels, wiring losses, shading or snow cover; G_T: solar irradiance incident on the PV array (kW/m²); $G_{T,\text{STC}}$: incident irradiance at standard test conditions (1,000 W/m²); α_p: temperature coefficient power (%/°C); T_c: PV cell temperature (°C); $T_{c,\text{STC}}$: PV cell temperature under standard test conditions (25°C). These parameters are all constant with the exception of G_T and T_c, which are calculated for each time interval using solar global horizontal irradiance data and ambient temperature data. The calculation can be viewed in [42,45,46].

E_{load} is the energy demand of Porto Santo SWRO desalination plant. The annual energy demand profile is assumed to be constant throughout the project's lifetime, as stated above.

The hourly results from the hourly energy balance are used in the economic assessment and to obtain other technical results for a project lifetime of 25 y.

NPV, IRR, payback and LCoE are calculated in the economic assessment. Annual cash flows throughout the project lifetime are calculated for the two types of system with the aim of obtaining these parameters.

Revenue in the annual cash flows refers to the savings made due to reduced consumption of energy from the electrical grid. This reduction is achieved by supplying energy via the PV plant and BESS.

Other factors considered to obtain the annual cash flows are:

- Initial investment (I_0) in PV plant and BESS;
- Operational and maintenance expenditure for PV plant and BESS;
- Amortization;
- Corporation tax;
- Insurance costs;
- Annual increase in electricity prices on the electrical grid;
- Annual increase in consumer price index (CPI);
- Annual reduction in energy generated by PV plant due to PV module degradation;
- Replacement of PV plant inverters in year 10;
- Replacement of BESS in year 12 due to capacity degradation.

The NPV and IRR are obtained using the well-known Eqs. (4) and (5) [43].

$$\text{NPV} = \sum_{t=1}^{n}\frac{\left(R_t - C_t\right)}{\left(1+i\right)} - I_0 \tag{4}$$

$$\text{IRR: } \sum_{t=1}^{n}\frac{\left(R_t - C_t\right)}{\left(1+i\right)^t} = I_0 \tag{5}$$

where (R_t – C_t): cash flow in year t; R_t: revenue in year t; C_t: cost of system in year t; i: discount rate; I_0: initial investment.

An i value of 7% is used to represent an interest rate in a reasonably profitable project. I_0 is the initial investment in the PV plant in the analysis of the PV-RO system. Likewise, I_0 is the sum of the initial investments in the PV plant and BESS in the analysis of the PV-BESS-RO system. The I_0 values used in the analysis for both the PV plant and BESS are shown in Tables 1 and 2 respectively and were calculated using the data in Tables 5 and 7 in section 6.

The amortization period is 12 y and is taken into consideration in the corresponding annual cash flows. The annual

Table 1
Initial investment in PV plant

$P_{\text{rated PV}}$ (kW)	I_0 (€)	$P_{\text{rated PV}}$ (kW)	I_0 (€)
300	377,500	700	853,500
350	437,000	750	913,000
400	496,500	800	972,500
450	556,000	850	1,032,000
500	615,500	900	1,091,500
550	675,000	950	1,151,000
600	734,500	1,000	1,210,500
650	794,000	1,050	1,270,000

Table 2
Initial investment in BESS

$C_{\text{rated BESS}}$ (kWh)	I_0 (€)
100	100,000
200	200,000
300	300,000
400	400,000

increase in electricity prices on the electrical grid is 5%. The annual reduction in energy generated by the PV plant due to PV module degradation is 0.3%.

LCoE is also calculated, as stated above. LCoE can be defined as the sum of the costs over a system's lifetime divided by the system's energy production [47–50] and is given by general Eq. (6):

$$\text{LCoE} = \frac{\sum_{t=1}^{n} \frac{C_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^t}} \tag{6}$$

where C_t: cost of system in year t; E_t: energy generated in year t; i: discount rate.

C_t is the cost of the energy consumed from the electrical grid and the cost relating to the PV plant in year t for the PV-RO system. BESS cost is added in the analysis of the PV-BESS-RO system. Costs relating to the PV plant or BESS include the corresponding I_0 in year 1. Likewise, E_t is the energy consumed by the SWRO desalination plant in year t for this case study.

The other parameters presented in the results are:

- Energy generated by the PV plant;
- Energy consumed by the SWRO desalination plant that is supplied by the PV plant and BESS (if applicable);
- Renewable energy ratio, which indicates the SWRO desalination plant's energy demand that is met by the PV plant and BESS (if applicable) as a proportion of its total energy demand.

A sensitivity analysis is also carried out with the aim of observing the impact of variations in electricity prices from the grid, the I_0 of the PV plant and PV module degradation. The impact of these parameters on the NPV, IRR and LCoE is analysed for the PV-RO system. The values considered in the sensitivity analysis are:

- Annual increase in electricity prices from the electrical grid: 6%, 7%, 8%, 9% and 10%;
- I_0 of the PV plant: 110%, 120%, 130%, 140% and 150%, based on the values shown in Table 1;
- Annual reduction in the energy generated by the PV plant due to PV module degradation: 0.5%, 0.7%, 0.9%, and 1.1%.

2.1. Porto Santo SWRO desalination plant

This subsection provides a brief description of the Porto Santo SWRO desalination plant case study.

Porto Santo Island is a Portuguese island in the Madeira archipelago in the North Atlantic Ocean. Porto Santo Island has a SWRO desalination plant to provide the population with fresh water, among other applications.

Porto Santo SWRO desalination plant comprises two production lines based on RO. Production line 1 (PL1) has a maximum capacity of 3,800 m^3/d and production line 2 (PL2) has a maximum capacity of 3,000 m^3/d. The SWRO desalination plant is assumed to operate 24 h/d.

Seawater is obtained via four intake tunnels drilled under the beach and pumped to seawater reservoirs. These seawater reservoirs supply water to the production lines.

The main characteristics of the two production lines are:

- Two 45 kW feed pumps.
- Pre-treatment system consisting of an anti-fouling injection system and filtration units. An anti-fouling injection system is used to increase the solubility of the dissolved salts. The two filtration units are equipped with a 5 µm cartridge filter to prevent larger particles from entering the RO racks.
- 450 kW (PL1)/315 kW (PL2) high pressure pump (HPP) with an operational pressure of 55–65 bar.
- RO rack comprising pressure vessels each housing four 8-inch spiral wound RO membranes in a two-tier arrangement without intermediate pressure increase.
- Energy recovery device (ERD) based on three rotary pressure exchangers.
- 18.5 kW (PL1)/30 kW (PL2) booster pump.

Post-treatment consists of remineralization using five calcite contactors and the addition of sodium hypochlorite for disinfection purposes.

The desalination plant is equipped with four 45 kW pumps to supply the distribution system with fresh water.

All electrical motors are powered by variable frequency drives. The SWRO desalination plant's annual energy consumption is approximately 4,834 MWh and the base-load is 552 kW throughout the year. More details about the plant's energy consumption can be found in section 6.

3. Results and discussion

This section presents the results of the study for the two types of systems analysed.

In order to obtain a reference point and establish a comparison, the LCoE was calculated for a case where the electrical grid is the only energy supply for the study period. That is, all the energy consumed by the SWRO desalination plant comes from the electrical grid for the duration of the study period. The LCoE value obtained is 0.1504 €/kWh.

All result values can be consulted in the appendix.

3.1. PV-RO system

The energy consumed by the SWRO desalination plant is supplied by the electrical grid and the PV plant. The energy produced by the PV plant and consumed by the SWRO desalination plant increases as $P_{\text{rated PV}}$ rises. As a result, the amount of energy consumed from the electrical grid decreases. This can be seen in Fig. 2, which shows the values for the first year of operation. In this regard, the renewable energy ratio is increased.

However, the SWRO desalination plant does not use or consume all the available energy generated by the PV plant. This is illustrated in Fig. 3, which shows the available energy generation capacity of the PV plant and the energy consumed by the SWRO desalination plant that was supplied by the PV plant for the first year of operation. Most of the PV plant's energy generation capacity is used by the SWRO desalination plant across the whole $P_{\text{rated PV}}$ range studied but there is a surplus of energy produced, which increases as $P_{\text{rated PV}}$ rises. The energy surplus values for the plant's first year of operation are shown in Fig. 4. Energy surplus is energy not generated and it is caused both by non-operation of the SWRO desalination plant during maintenance periods and by the PV plant's available energy generation capacity exceeding the SWRO desalination plant's consumption. The latter increases exponentially as $P_{\text{rated PV}}$ values rise, resulting in an exponential increase in energy surplus.

Fig. 5 presents the NPV, IRR and LCoE results for the $P_{\text{rated PV}}$ range studied.

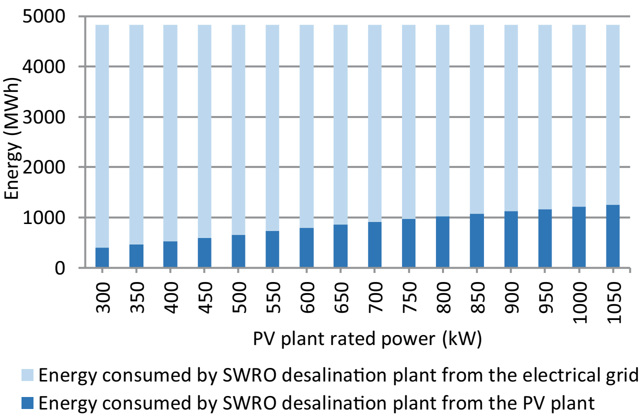

Fig. 2. Energy supplied to SWRO desalination plant by PV-RO system in first year of operation.

The NPV can be seen to increase as $P_{\text{rated PV}}$ rises. However, the NPV does not continue to increase at the higher $P_{\text{rated PV}}$ values studied. This is due to an increase in the PV plant energy surplus and a higher I_0. Higher profits are obtained for the $P_{\text{rated PV}}$ range of 850 and 950 kW. NPV values exceed 590,000 €. In this case study, a 900 kW PV plant produces the highest NPV.

Higher IRR values are obtained for the $P_{\text{rated PV}}$ range of 450 and 650 kW and they exceed 11.90%. The highest IRR value is 11.97% and is found in the 550 kW PV plant.

The LCoE values for the total energy consumed by the SWRO desalination plant for the $P_{\text{rated PV}}$ range studied are all lower than the corresponding values in a case where all energy consumed comes from the electrical grid. By way of example, the LCoE values are 0.137 and 0.141 €/kWh for the $P_{\text{rated PV}}$ values that maximize NPV and IRR (a 900 kW PV plant and a 550 kW PV plant respectively). These LCoE values are lower than 0.1504 €/kWh, which is the LCoE value of the energy consumed by the SWRO desalination plant from the electrical grid. Moreover, higher $P_{\text{rated PV}}$ values tend to result in lower LCoE values. This is because the more energy is generated by the PV plant, the less energy is consumed from the electrical grid, reducing the annual cost of the energy consumed by the SWRO desalination plant. This reduction in LCoE ceases at higher $P_{\text{rated PV}}$ values for the same reasons explained for the NPV above.

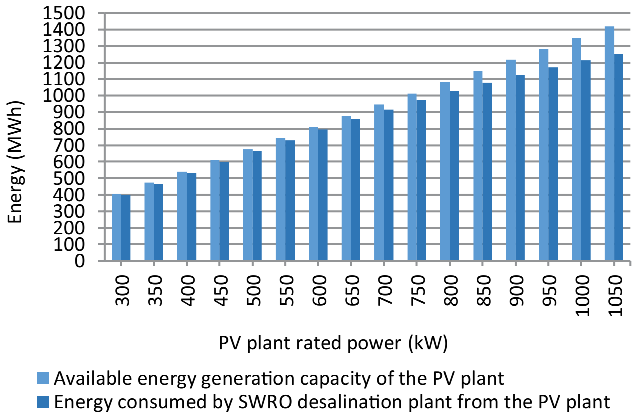

Fig. 3. Energy generated by PV plant and energy consumed by SWRO desalination plant from PV plant in first year of operation for PV-RO system.

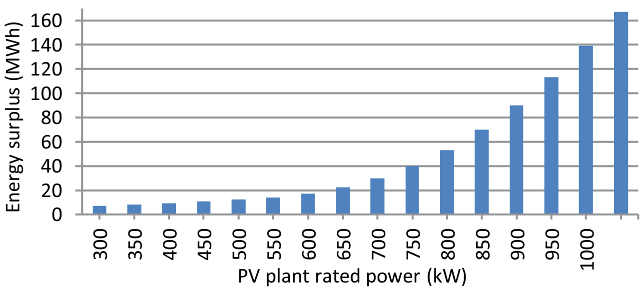

Fig. 4. Energy surplus produced by PV-RO system in first year of operation.

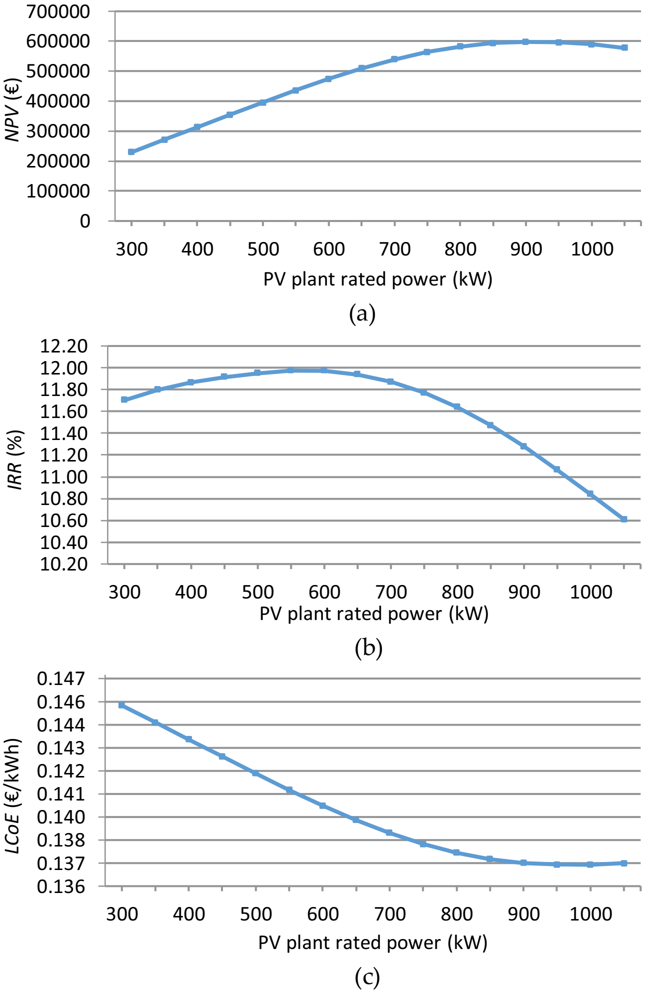

Fig. 5. NPV, IRR and LCoE values for PV-RO system.

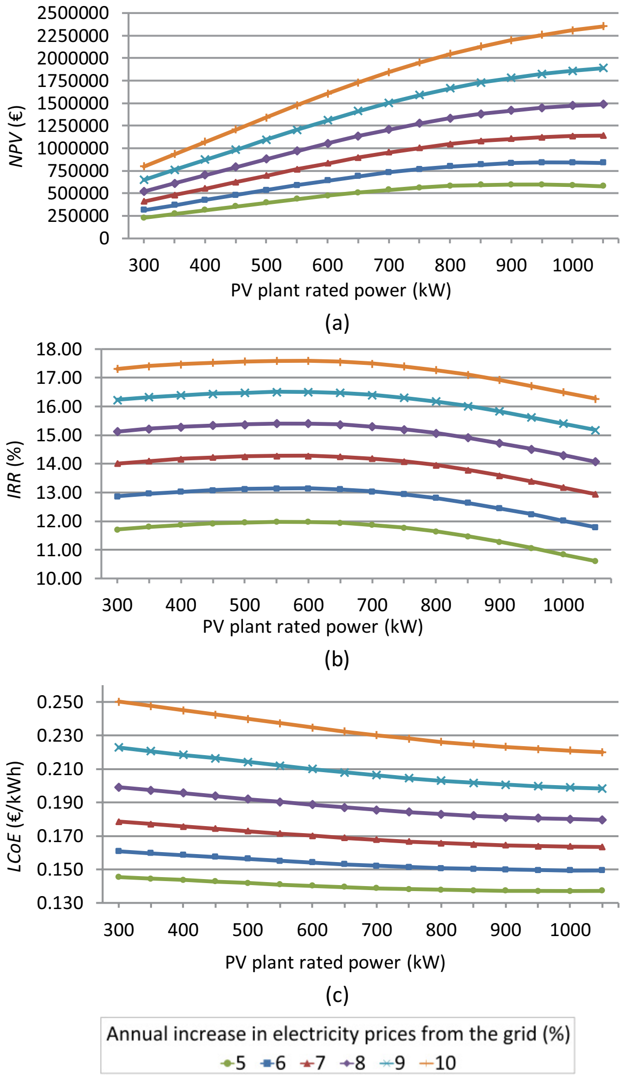

Fig. 6. NPV, IRR and LCoE values of PV-RO system for different annual increases in electricity prices from the grid.

Payback tends to increase as $P_{\text{rated PV}}$ rises due to the causes of variation in NPV and IRR set out above. Payback values are between 14 and 16 y.

The sensitivity analysis reveals the impact on the NPV, IRR and LCoE of annual increases in the price of electricity from the grid, the I_0 of the PV plant and the annual reduction in the energy generated by the PV plant due to PV module degradation.

Higher electricity prices from the grid lead to higher NPV and IRR values for the full $P_{\text{rated PV}}$ range studied. Revenues in annual cash flows refer to the savings made, as stated above. Therefore, the higher the electricity prices, the greater the savings made. This results in higher NPV and IRR values, as shown in Fig. 6a and b. The cost of energy from the electrical grid is considered when calculating the C_t values following Eq. (6). An increase in the price of electricity from the grid leads to higher LCoE values, as shown in Fig. 6c.

The NPV and IRR results depend directly on the I_0 of the PV plant, in accordance with Eqs. (4) and (5). Fig. 7a and b illustrate how an increase in the I_0 of the PV plant reduces NPV and IRR values. Since the I_0 of the PV plant is taken into consideration to obtain the C_t for the first year of the study period, higher I_0 values for the PV plant result in higher LCoE values. This is shown in Fig. 7c.

A reduction in the energy generated by the PV plant due to PV module degradation causes more energy to be consumed from the electrical grid. As energy consumption from the electrical grid increases, the total cost of the consumed energy rises and revenues in the cash flows drop. As a result, NPV and IRR values decrease and LCoE values increase, as shown in Fig. 8.

3.2. PV-BESS-RO system

The results for the energy supplied to the SWRO desalination plant by the PV plant and lithium-ion BESS are shown in Fig. 9. The supplied energy values are practically identical for all $C_{\text{rated BESS}}$ values studied with lower $P_{\text{rated PV}}$ values. Slight differences can be identified with higher $P_{\text{rated PV}}$ values. The performance of the BESS is poor due to an insufficient energy surplus produced by the PV plant

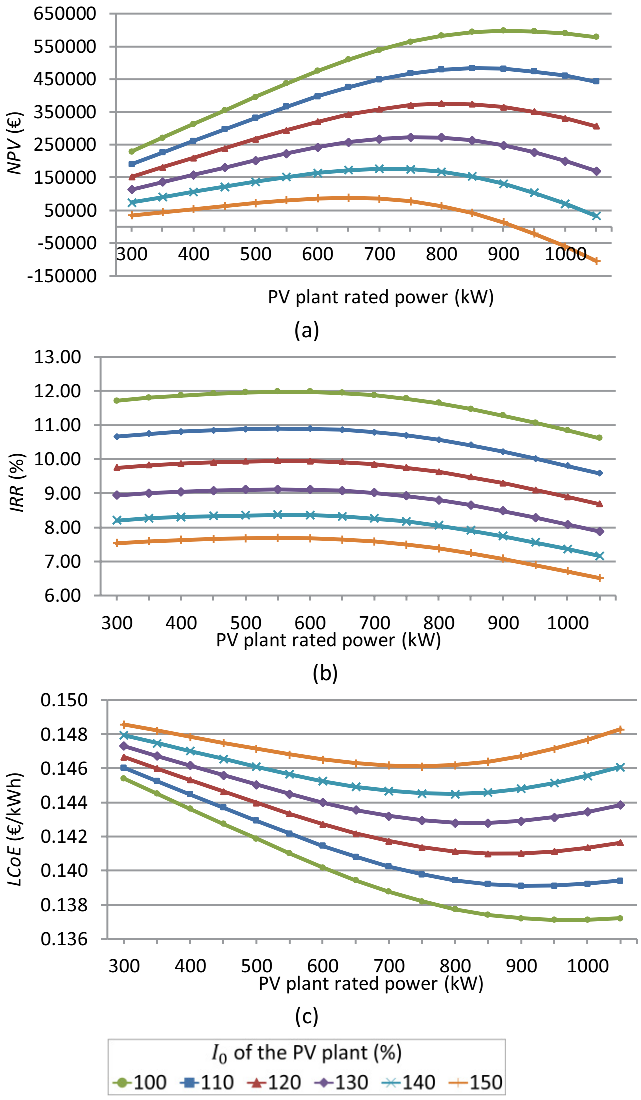

Fig. 7. NPV, IRR and LCoE values of PV-RO system for different I_0 values for the PV plant.

to charge the system, especially at lower $P_{\text{rated PV}}$ values. Optimal performance of the BESS requires a daily charge and discharge cycle, which is not achieved on many days of the year.

Therefore, the use of a BESS leads to a very slight increase in the renewable energy ratio compared with the renewable energy ratio values for the PV-RO system.

Fig. 10 shows the NPV, IRR and LCoE values for the $C_{\text{rated BESS}}$ values and $P_{\text{rated PV}}$ range studied. The results for the PV-RO system are also shown to demonstrate the impact of incorporating a lithium-ion BESS.

The NPV and IRR values for the PV-BESS-RO system are lower than the values for the PV-RO system as the revenues in annual cash flows are low to compensate for the higher I_0 of the PV-BESS-RO system.

Since revenues refer to the savings made, as stated above, their values depend on factors such as the performance of the BESS and the price of electricity from the grid. When the performance of the BESS is improved, more of

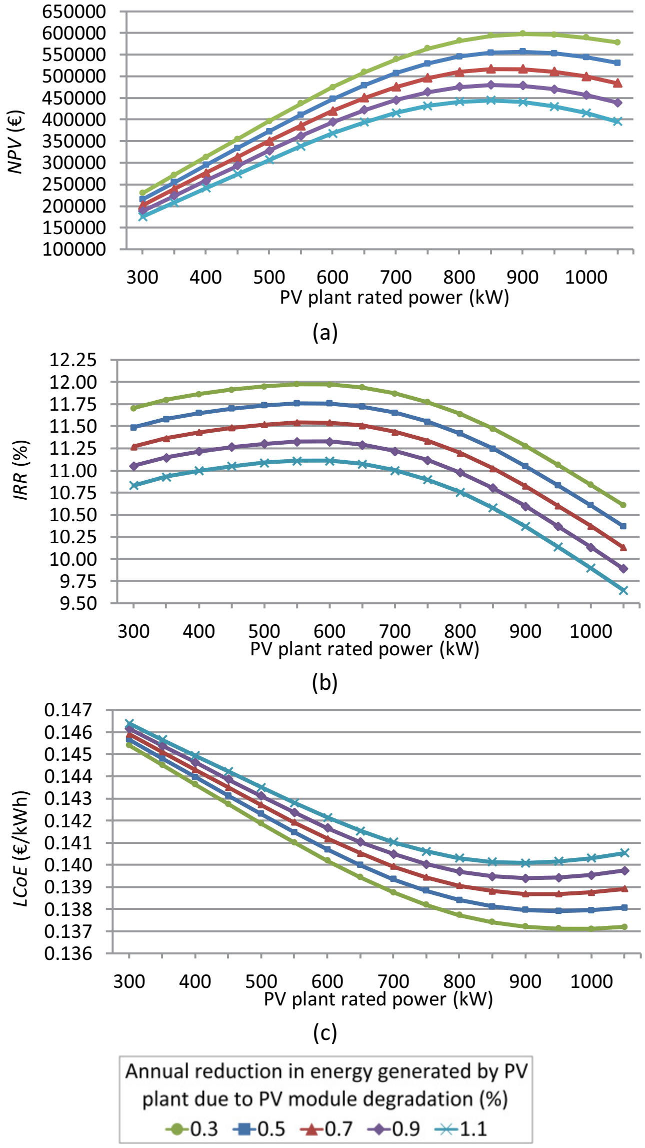

Fig. 8. NPV, IRR and LCoE values of PV-RO system for different annual reductions in energy generated by PV plant due to PV module degradation.

the energy consumed is generated by the PV plant and less energy is consumed from the electrical grid. However, the results show that BESS performance is poor, as stated above. Therefore, few savings are obtained by using the BESS. Moreover, the price of electricity from the grid is relatively low, resulting in lower revenues through savings.

As an example, the difference in NPV between a PV-RO system with a 900 kW PV plant and a PV-BESS-RO system with both a 900 kW PV plant and a 100 kWh BESS stands at around –94,025 €. The reduction in the IRR is –1.734% in systems with a 550 kW PV plant.

Moreover, the higher the $C_{\text{rated BESS}}$, the greater the reduction in both NPV and IRR values. Since a higher $C_{\text{rated BESS}}$ requires a higher I_0, NPV and IRR values decrease as $C_{\text{rated BESS}}$ values rise. The NPV can even fall into negative values and IRR values are lower than i.

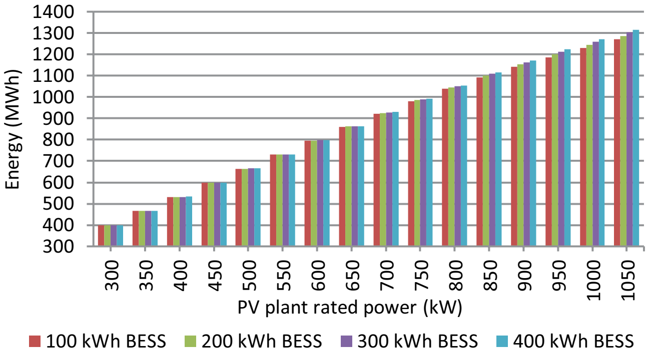

Fig. 9. Energy consumed by SWRO desalination plant from PV plant and lithium-ion BESS in first year of operation.

LCoE values also increase with higher $C_{\text{rated BESS}}$ values due to the increase in I_0 and insufficient revenues in the cash flows, as shown in Fig. 10c. Some of the LCoE values calculated for $C_{\text{rated BESS}}$ values of 300 and 400 kWh are even higher than in cases where the electrical grid is the only energy source during the study period.

Payback obtains higher values than in the PV-RO system. Higher $C_{\text{rated BESS}}$ values lead to an increase in payback values. In some cases, I_0 is not recovered and this is particularly true for higher $C_{\text{rated BESS}}$ values.

4. Conclusions

This paper analyses the coupling of a PV plant and lithium-ion BESS to a grid-connected SWRO desalination plant using the Porto Santo SWRO desalination plant as a case study. Several different rated power values for the PV plant and lithium-ion BESS capacities are studied. Annual and daily energy consumption at the desalination plant are 4,834 and 13.243 MWh respectively. The only energy used to charge the BESS is the energy surplus from the PV plant and energy injection into the electrical grid is avoided.

The coupling of a PV plant to a SWRO desalination plant can lead to positive NPV or IRR values above the discount rate considered, as well as lower paybacks and LCoE values.

NPV rises as the rated power of the PV plant is increased up to the highest rated power values studied. NPV is gradually reduced from higher rated power values due to the unused energy surplus from the PV plant and the higher initial investment cost. Certain rated power ranges of the PV plant maximize NPV, producing higher revenues by reducing energy consumption from the electrical grid. This rated power range is between 850 and 950 kW, with a corresponding NPV exceeding 590,000 € in the case study. Maximum NPV is obtained by a 900 kW PV plant.

IRR values increase with a different rated power range of the PV plant, which is between 450 and 650 kW. Here, IRR values exceed 11.90%. The highest IRR value can be seen in a 550 kW PV plant.

Payback values may be low: the payback values for both rated power ranges stated above are 15 and 14 y respectively for this case study. These values are lower than the expected operational lifetime of a PV plant, which is around 25 y.

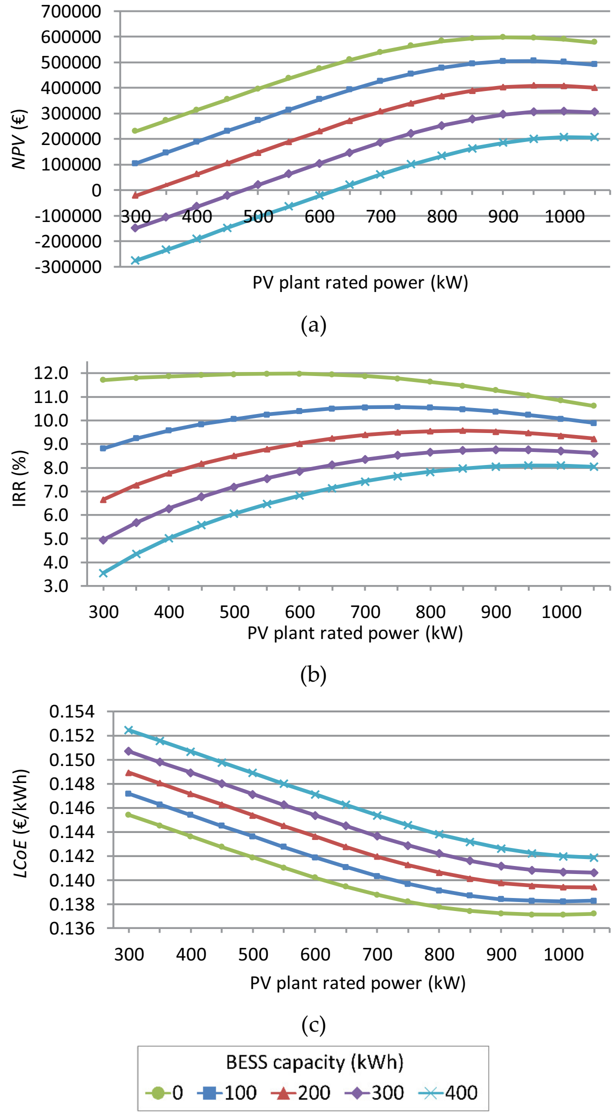

Fig. 10. NPV, IRR and LCoE values of PV-BESS-RO system.

A PV plant could reduce the LCoE of the energy consumed by the grid-connected SWRO desalination plant. LCoE values for a PV plant are low compared with LCoE values when all energy consumed is supplied by the electrical grid. A reduction in LCoE values is observed when PV plant rated power is increased up to the highest rated power values studied. This reduction in LCoE ceases for the highest rated power values due to the unused energy surplus of the PV plant and the higher initial investment, as in the case of the NPV.

The ratio of energy supplied by the PV plant to the SWRO desalination plant can be gradually increased by increasing the PV plant rated power.

A sensitivity analysis was carried out for the PV plant coupled to the SWRO desalination plant to examine the influence on the NPV, IRR and LCoE of annual increases in electricity prices from the grid, initial investment in the PV plant and annual reductions in the energy generated by the PV plant due to PV module degradation. An increase in electricity prices from the grid leads to higher NPV and IRR values, suggesting that higher electricity prices make the coupling of the PV plant to the SWRO desalination plant a more profitable investment. NPV and IRR values decrease with higher values of initial investment in the PV plant and annual reductions in the energy generated by the PV plant due to PV module degradation. Nevertheless, the NPV and IRR values calculated for the case study indicate that the PV plant remains viable. It is also observed that the PV plant rated power that produces the highest NPV and IRR values does not change for all studied values of electricity prices, initial investment in PV plant and reduction in energy generated by the PV plant.

The results for a PV plant coupled to a grid-connected SWRO desalination plant indicate that such a project may be technically and economically feasible. Moreover, a reduction in the energy consumed from the electrical grid could reduce greenhouse gas emissions associated with conventional electrical power generation.

The case study shows that a PV plant and lithium-ion BESS coupled to the SWRO desalination plant result in lower NPV and IRR values and higher LCoE values than a system based on a PV plant alone. Moreover, even lower NPV and IRR values and higher LCoE values are obtained for higher lithium-ion BESS capacity values. These NPV and IRR values are caused by the higher initial investment in the PV-BESS-RO system, poor performance of the BESS and relatively low electricity prices on the grid. These economic parameters in the case study indicate that the use of a lithium-ion BESS is not suitable.

Poor BESS performance is caused by insufficient energy surplus generated by the PV plant, which is the only source used to charge the BESS. In this regard, the sizing of the PV plant, the sizing of the BESS and the energy demand profile of a SWRO desalination plant must be considered in combination to maximize the performance of the BESS. BESS performance would be adequate with a daily charge and discharge cycle.

Electricity prices on the grid and initial investment in the BESS have a direct impact on the NPV, IRR and LCoE results. Higher electricity prices on the grid, lower lithium-ion BESS costs and anticipated future evolutions in these costs could make the coupling of a lithium-ion BESS and PV plant to a grid-connected SWRO desalination plant viable.

In this analysis, the BESS was charged using only PV energy and energy sales to the electrical grid were not taken into consideration. Moreover, the energy demand of the SWRO desalination plant studied here is a real energy demand profile, which meant that energy management could not be considered. Future research could analyse a scenario where the BESS is charged by energy from the electrical grid as well as PV energy to improve BESS performance. Likewise, management of the desalination plant's energy demand and energy sales to the electrical grid to achieve higher utilization of PV energy could be studied.

This paper has examined NPV and IRR. The highest NPV and IRR values are achieved at different PV plant rated power values. IRR must be taken into account in cases where the cost of financing the project and cost-effectiveness are considered. NPV is more closely related to revenues obtained by reducing energy consumption from the electrical grid using a new renewable energy source. Therefore, a project selected on the basis of NPV criteria could produce a higher renewable energy ratio than a project selected according to IRR criteria.

5. Acknowledgments

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6. Reference data

6.1. General data

Table 3
General data

Project lifetime (y)	25
Discount rate (%)	7
Amortization (y)	12
Annual increase in consumer price index (CPI) (%)	2
Corporation tax (%)	3
Insurance costs (€/W)	0.016
Annual increase in electricity prices on the grid (%)	5

6.2. PV plant

The PV plant is a generic fixed-mounted PV plant comprising crystalline silicon PV modules with 16% efficiency. The tilt angle of the PV modules is based on the latitude. The costs corresponding to the PV plant area are not taken into consideration as a roof-mounted PV plant on the desalination plant facilities is assumed.

Table 4
Technical data for PV plant

$P_{\text{rated PV}}$ (kW)	300–1,050, in intervals of 50
α_p (%/°C)	–0.44
f_{PV} (%)	80
$T_{c,\text{STC}}$ (°C)	25
$G_{T,\text{STC}}$ (kW/m^2)	1,000

Table 5
Component costs of PV plant to determine I_0

PV module cost (€/W) [51]	0.65
Solar inverter cost (€/W) [51]	0.19
Cost of other elements (€/W)	0.25
Engineering costs (€/W)	0.1
Fixed costs (project management costs) (€)	20,500

Table 6
Additional data for PV plant

Operational and maintenance costs of PV plant (€/W)	0.012
Annual reduction in energy generated by PV plant due to PV module degradation (%)	0.3
Replacement of PV plant inverter in year 10 (€/W)	0.19

6.3. Battery energy storage system

The BESS is based on a generic lithium-ion battery.

Table 7
Data for BESS

Rated capacity (kWh)	100	150	200	250	300	350	400
Charge power (kW)	100.2	150.3	200.4	250.5	300.6	350.7	400.8
Discharge power (kW)	300	450	600	750	900	1,050	1,200

I_0 (€/Wh) (lithium-ion battery, power electronic converters, control system, ancillary systems, engineering, transportation and commissioning) [37]	1
Minimum SoC (%)	20
Degradation of BESS capacity (%/y) (Based on the typical C-rate in PV applications)	3
Replacement cost of BESS in year 12 (€/Wh) (Replacement year based on the typical C-rate in PV applications)	0.4
Power converter efficiency (%) [42]	95

6.4. Electricity prices from grid

Table 8
Electricity prices from grid for customers at medium voltage level in the autonomous region of Madeira in 2019 [52]

	Schedule		Periods I and IV	Periods II and III
Hourly period	Winter time	Summer time	Price (€/kWh)	Price (€/kWh)
Peak demand	18:00–22:00	10:30–13:00 20:30–22:00	0.1235	0.1206
Intermediate	09:00–18:00 22:00–23:00	09:00–10:30 13:00–20:30 22:00–23:00	0.1048	0.1045
Normal off-peak demand	06:00–09:00 23:00–02:00	06:00–09:00 23:00–02:00	0.0727	0.0741
Super off-peak demand	02:00–06:00	02:00–06:00	0.0613	0.0690

	Period	Schedule
January	I	Winter
February	I	Winter
March 1st to March 30th	I	Winter
March 31st	I	Summer
April	II	Summer
May	II	Summer
June	II	Summer
July	III	Summer
August	III	Summer
September	III	Summer
October 1st to October 26th	IV	Summer
October 27th to October 31st	IV	Winter
November	IV	Winter
December	IV	Winter

6.5. Energy demand of Porto Santo SWRO desalination plant

The hourly data on Porto Santo SWRO desalination plant's energy demand used in the study were composed from real daily data.

The same annual energy demand profile was assumed throughout the project lifetime. The total annual energy demand was also the same for every year of the project lifetime.

Total annual energy demand is approximately 4,833.82 MWh, which corresponds to 13,243 kWh/d. The baseload is 552 kW throughout the year. Monthly energy demand and average power demand are shown in Figs. 11 and 12.

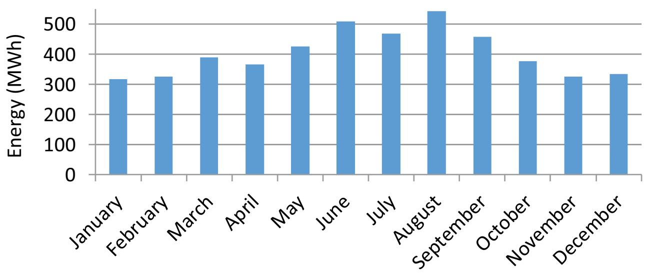

Fig. 11. Monthly energy demand of Porto Santo SWRO desalination plant used in the study analysis.

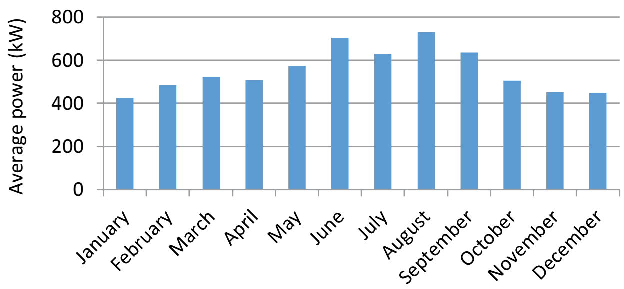

Fig. 12. Monthly average power demand of Porto Santo SWRO desalination plant used in the study analysis.

6.6. Solar irradiance and ambient temperature

Hourly data on solar global horizontal irradiance and ambient temperature for a year were obtained using Meteonorm v7.3.4 software [53], based on data from a weather station near Porto Santo SWRO desalination plant on Porto Santo Island.

Fig. 13 shows the daily mean horizontal irradiation and hourly mean ambient temperature calculated from the data.

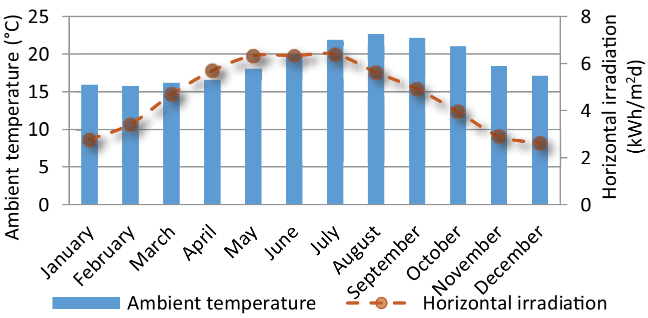

Fig. 13. Daily mean horizontal irradiation and hourly mean ambient temperature obtained using Meteonorm software.

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Appendix. Result values

A1. Result values for PV-RO system

$P_{rated\ PV}$ (kW)	NPV (€)	IRR (%)	Payback (y)	LCoE (€/kWh)	Energy generated by PV plant (year 1) (kWh)	Energy consumed by SWRO desalination plant from PV plant (year 1) (kWh)	Renewable energy ratio (year 1) (%)
300	229,342.07	11.705	14	0.145	405,333	398,458	8.24
350	271,300.12	11.797	14	0.145	472,888	464,854	9.62
400	313,030.05	11.864	14	0.144	540,444	531,125	10.99
450	354,639.43	11.915	14	0.143	607,999	597,324	12.36
500	395,789.07	11.951	14	0.142	675,555	663,277	13.72
550	436,305.19	11.974	14	0.141	743,110	728,892	15.08
600	474,669.68	11.973	14	0.140	810,666	793,387	16.41
650	509,296.76	11.939	14	0.139	878,221	855,972	17.71
700	539,107.46	11.870	14	0.139	945,776	916,104	18.95
750	563,824.33	11.771	14	0.138	1,013,332	973,652	20.14
800	582,127.38	11.638	14	0.138	1,080,887	1,027,952	21.27
850	593,475.59	11.472	15	0.137	1,148,443	1,078,721	22.32
900	597,802.80	11.277	15	0.137	1,215,998	1,125,967	23.29
950	596,028.27	11.063	15	0.137	1,283,554	1,170,140	24.21
1,000	589,546.59	10.840	16	0.137	1,351,109	1,211,933	25.07
1,050	578,310.32	10.609	16	0.137	1,418,665	1,251,339	25.89

A2. Result values for PV-BESS-RO system

The values for the energy generated by the PV plant in the first year are similar to those for the PV-RO system.

$C_{\text{rated BESS}}$ 100 kWh							$C_{\text{rated BESS}}$ 200 kWh						
$P_{\text{rated PV}}$ (kW)	NPV (€)	IRR (%)	Payback (y)	LCoE (€/kWh)	Energy consumed by SWRO desalination plant from PV plant and BESS (year 1) (kWh)	Renewable energy ratio (year 1) (%)	$P_{\text{rated PV}}$ (kW)	NPV (€)	IRR (%)	Payback (y)	LCoE (€/kWh)	Energy consumed by SWRO desalination plant from PV plant and BESS (year 1) (kWh)	Renewable energy ratio (year 1) (%)
300	104,005.73	8.813	20	0.147	398,813	8.25	300	−22,477.13	6.656	–	0.149	399,168	8.26
350	146,140.61	9.240	19	0.146	465,223	9.62	350	19,816.50	7.270	24	0.148	465,578	9.63
400	188,227.71	9.575	18	0.145	531,600	11.00	400	62,101.72	7.763	22	0.147	531,988	11.01
450	230,115.49	9.843	17	0.144	597,877	12.37	450	104,225.51	8.167	21	0.146	598,321	12.38
500	271,786.67	10.062	17	0.144	664,031	13.74	500	146,207.49	8.504	20	0.145	664,583	13.75
550	312,957.71	10.240	17	0.143	729,946	15.10	550	187,819.02	8.788	20	0.144	730,635	15.12
600	353,799.10	10.389	16	0.142	795,606	16.46	600	229,216.76	9.030	19	0.144	796,497	16.48
650	391,979.99	10.495	16	0.141	859,881	17.79	650	270,080.17	9.236	19	0.143	861,991	17.83
700	425,580.32	10.553	16	0.140	921,829	19.07	700	307,136.05	9.390	18	0.142	925,535	19.15
750	454,638.91	10.570	16	0.140	981,454	20.30	750	339,276.37	9.492	18	0.141	986,615	20.41
800	477,480.78	10.543	16	0.139	1,037,952	21.47	800	366,780.47	9.553	18	0.141	1,045,316	21.63
850	494,188.32	10.479	16	0.139	1,091,334	22.58	850	387,854.51	9.567	18	0.140	1,100,791	22.77
900	503,777.91	10.377	16	0.138	1,141,174	23.61	900	401,889.19	9.539	18	0.140	1,152,784	23.85
950	504,824.45	10.233	17	0.138	1,186,748	24.55	950	407,780.05	9.466	18	0.140	1,200,738	24.84
1,000	500,600.12	10.072	17	0.138	1,229,671	25.44	1,000	406,697.19	9.362	18	0.139	1,245,213	25.76
1,050	490,887.43	9.893	17	0.138	1,269,849	26.27	1,050	399,844.58	9.234	19	0.139	1,286,793	26.62

(Continued)

A2. Continued

$C_{rated\ BESS}$ 300 kWh							$C_{rated\ BESS}$ 400 kWh						
$P_{rated\ PV}$ (kW)	NPV (€)	IRR (%)	Payback (y)	LCoE (€/kWh)	Energy consumed by SWRO desalination plant from PV plant and BESS (year 1) (kWh)	Renewable energy ratio (year 1) (%)	$P_{rated\ PV}$ (kW)	NPV (€)	IRR (%)	Payback (y)	LCoE (€/kWh)	Energy consumed by SWRO desalination plant from PV plant and BESS (year 1) (kWh)	Renewable energy ratio (year 1) (%)
300	−149,426.42	4.953	–	0.151	399,523	8.27	300	−276,555.05	3.553	–	0.152	399,879	8.27
350	−106,994.90	5.682	–	0.150	465,933	9.64	350	−234,058.58	4.357	–	0.152	466,288	9.65
400	−64,564.71	6.277	–	0.149	532,343	11.01	400	−191,546.00	5.021	–	0.151	532,698	11.02
450	−22,156.74	6.772	–	0.148	598,753	12.39	450	−149,040.03	5.580	–	0.150	599,108	12.39
500	19,968.23	7.190	24	0.147	665,027	13.76	500	−106,605.82	6.057	–	0.149	665,471	13.77
550	62,004.23	7.548	23	0.146	731,238	15.13	550	−64,379.70	6.468	–	0.148	731,723	15.14
600	103,654.91	7.855	22	0.145	797,181	16.49	600	−22,353.11	6.827	–	0.147	797,802	16.50
650	145,246.63	8.125	21	0.144	862,981	17.85	650	19,492.56	7.142	24	0.146	863,686	17.87
700	185,362.86	8.354	21	0.144	927,958	19.20	700	61,123.60	7.421	23	0.145	929,344	19.23
750	220,833.99	8.526	20	0.143	990,606	20.49	750	99,803.93	7.652	23	0.145	993,480	20.55
800	251,278.15	8.650	20	0.142	1,050,695	21.74	800	133,224.03	7.829	22	0.144	1,054,982	21.83
850	276,878.24	8.733	20	0.142	1,108,329	22.93	850	162,063.62	7.963	22	0.143	1,114,137	23.05
900	295,368.56	8.767	20	0.141	1,162,476	24.05	900	184,927.58	8.052	21	0.143	1,170,375	24.21
950	305,819.77	8.755	20	0.141	1,212,651	25.09	950	199,862.56	8.092	21	0.142	1,222,715	25.30
1,000	308,564.77	8.703	20	0.141	1,259,010	26.05	1,000	207,274.64	8.091	21	0.142	1,271,343	26.30
1,050	304,413.45	8.619	20	0.141	1,301,917	26.93	1,050	206,263.89	8.048	21	0.142	1,315,799	27.22