Integrated Analysis of Energy and Water Supply in Islands. Case Study of S. Vicente, Cape Verde

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Abstract

The electricity production in the island of S. Vicente is based on fossil fuel and wind power and, although there are significant wind resources, they are not fully used because of its intermittent nature. In a previous work, we proposed solutions to tackle this issue. Since this island does not have fresh water available, excess wind power can be provided to desalination units to produce desalinated water to supply the population. Other solution studied previously was the use of desalinated water in a pumped hydro system to store the remaining excess wind power. In this article, the scenarios modelled previously are updated with more recent data on energy and water consumption and the respective annual costs are estimated. The results show that with the current installed wind power and desalination capacity, and with the installation of a pumped hydro system, it is possible to have, by 2020, 36% of electricity production from renewable energy sources, with costs 7% lower than those forecasted for that year. If the installation of more wind power and desalination capacity is considered, renewable energy sources production can reach 72% (51% wind power, 21% pumped hydro), with about 19% decrease of costs in relation to those predicted for 2020.

Keywords: Energy and water supply; renewable energy; islands; intermittent integration; desalination; pumped hydro

1. Introduction

For small islands that are not interconnected with the mainland, the penetration of intermittent energy sources, e.g., wind power, in the electricity supply system is limited, even when there is a large renewable energy potential. This is due to technical constraints of the conventional generating units (namely their minimum loading level) and the dynamic penetration limit that is usually applied for grid stability. [1] In these cases, in order to minimize the curtailed wind power, the installed wind power is limited.

The electricity supply system of S. Vicente, Cape Verde, is based on fossil fuel and wind power (cf. Section 3.1) and, although this island has important wind resources (cf. Section 3.1), they are not fully used because of its intermittent nature. In addition, this island does not have any source of fresh water, being forced to desalinate seawater to produce water suitable for human consumption (cf. Section 3.2). This puts more pressure to the electricity supply system, since desalination requires a significant amount of energy. This can be an opportunity to implement renewable energy driven desalination.

To date, a number of studies have been carried out on the feasibility of integrating renewable energy sources (RES) in islands, and all of them rely on energy storage and/or demand side management strategies. Duić et al. [2] proposed a wind powered pumped hydro system (PHS) for the island of Corvo in The Azores. This study showed that only by adding storage to energy and water resource systems is it possible to significantly increase the penetration of locally available renewable energy resources, and thus increase the security of supply and decrease the import dependence. Krajačić et al. [3] concluded that with an energy storage system based on hydrogen, the island of Mljet in Croatia could become 100% renewable island concerning electricity and simulated transport needs and also could export additional power to the mainland power grid. The prospect of creating a combined wind-hydro energy production station for Aegean Sea islands in Greece has been analyzed by Kaldellis and

Kavadias [4]. Bakos [5] discussed the operation of a hybrid wind/hydro power system aimed at producing low cost electricity for the island of Ikaria in Greece.

A number of analyses have been also carried out on the feasibility of using RES in desalination plants. Spyrou and Anagnostopoulos [6] investigated the optimum design and operation strategy of a stand-alone hybrid desalination scheme, capable of fulfilling the fresh water demand of an island. The scheme consisted of a reverse osmosis desalination unit powered by wind and solar electricity production systems and by a pumped storage unit. Fadigas and Dias [7] proposed an alternative configuration to conventional reverse osmosis desalination systems by incorporating the use of both gravitational potential energy and wind energy.

All of the cited studies have examined either the energy or the water supply system. The studies in references [2-5] focus on the energy supply systems and the studies in references [6, 7] concentrate on the water supply systems, although they deal with the energy demand of such systems. Novosel et al. [8] stated that an important concept for a wide scale implementation of desalination units is the integration of energy and water resources. Siddiqi et al. [9] conclude that joint consideration of both water and energy domains can identify new options for increasing overall resource use efficiencies. Østergaard et al. [10] investigated a Jordanian energy scenario with different desalination technologies; they use desalination to decrease excess electricity production and conclude that water storage has some implication for the system's ability to integrate wind power.

This article discusses ways to increase the penetration of RES in the island of S. Vicente, Cape Verde, by coupling the energy and water supply systems. The scenarios established propose two ways of storing excess wind power in this island. One way is to provide the excess wind power to the desalination units and the other is to use this excess in a pumped hydro system, which is possible in S. Vicente, since it has the suitable topography.

The use of excess wind power in the desalination units can be considered a demand side management strategy since the water cannot be turned back to electricity with a reasonable efficiency. However water can be stored. In our previous work [11], these solutions have already been proposed and modelled. The results showed that it is possible to have more than 30% of yearly power production from RES (33% wind power and 3% PHS) and 50% of the water supplied to the population from wind power. It was concluded that there was the need to calculate the cost of the scenarios developed, in order to assess their economic viability and compare the solutions proposed to the current systems [11]. It was also previously demonstrated that to decrease the wind power curtailed, the capacity of the desalination units need to increase; however, it is very important to ensure that the load of the desalination units is high enough to guarantee the financial viability of the system [11].

The main objective of this study is to find a solution that minimizes the costs, while keeping the penetration of wind power the highest possible. The scenarios modelled previously are updated with more recent data on energy and water consumption of the island, and the electricity and water production costs are estimated. This study intends also to understand how the electricity and water production costs vary with the wind power curtailed and with the load of the desalination units in order to find an optimum configuration.

2. Methodology

As in our previous work [11], the simulation tool used is the H2RES model, which simulates the integration of renewable sources and hydrogen in the energy systems of islands or other isolated locations. It is based on hourly time series analysis of demand (water, electricity, hydrogen, heat); storage (pumped hydro, batteries, hydrogen, heat) and resources (wind speed, solar radiation, precipitation) [3]. More information on the H2RES model can be found in reference [3] and, more specifically, on the desalination module in reference [11].

The wind power produced is used firstly to cover the load, according to the dynamic (hourly) penetration limit allowed. The wind power that surpasses this limit (excess) is used in the desalination units. The desalination units use this wind power to fill the reservoir used to supply water to the population (lower reservoir). After that, if there is still wind power available it is stored as pumped water into an upper reservoir. The energy that is stored can be retrieved later, and supplied to the system as electricity. The remaining energy needs are covered by fossil fuel-based systems.

Østergaard [12] investigated how energy systems can be designed to achieve the optimal integration of fluctuating energy sources. Such systems can be designed from an economic perspective or from a technical-operational perspective, which render different results. The optimisation criteria used in this study is the minimization of the costs, while keeping the wind power integration in the water and energy supply systems the highest possible.

Since the H2RES model does not allow performing optimization, it is necessary to run all potential configurations and verify their technical feasibility (i.e., if they are able to supply the required electricity and water demand at all hours) and identify the one with lower total annual costs. The optimization performed in this study is an investment and operational optimization. On one hand each iteration has a specific potential configuration (capacity of the equipments installed), and, on the other hand, certain operational conditions could be changed in order to avoid the overflow of the reservoirs, namely the maximum amount of wind powered desalinated water in each hour.

The total annual costs are estimated using the simplified levelised cost of energy method. The term levelised cost of energy emphasizes the fact that this cost is determined over a certain time (technical lifetime of a specific technology). In practise, the objective is to find the price of energy that sets the sum of all future discounted cash flows to zero [12]. Each production cost includes the investment cost of the components used to produce the specific output (electricity and water).

2.1 Electricity production cost

The electricity production cost of each scenario is estimated as follows:

$$EPC = \frac{IC_e\, CRF + OMC_e + FC}{E} \quad (€/kWh) \tag{1}$$

where IC_e is the total investment cost of the system. This value includes the investment costs of all necessary equipment in the energy supply system. The investment costs of equipments already installed on the island, but within lifetime, are considered. *CRF* is the capital recovery factor (annuity factor) that is used to annualize the investment cost and depends on the lifetime of the equipments (n) and on the discount rate considered (i) as follows:

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

In Eq. (1), OMC_e is the total yearly operation and maintenance cost of the system that usually is, according to the technology, a given percentage of the investment cost, *FC* is the yearly fossil fuel costs, and *E* is the total yearly electricity production. The total annual costs are divided by this value to assess the electricity production cost in €/kWh.

The technologies considered are the ones already installed in S. Vicente: fossil fuel-based generators, wind turbines and a system for energy storage that is pumped hydro.

2.2 Water production cost

The water production cost is calculated as follows:

$$WPC = \frac{IC_w \, CRF + OMC_w + EC}{W} \quad (€/\mathrm{m}^3) \tag{3}$$

where IC_w is the total investment cost of the water supply system. It also considers the investment cost of existing equipment on the island. In Eq. (3), OMC_w is the total yearly operation and maintenance cost of the system that usually is a given percentage of the investment cost, EC is the yearly electricity costs, and W is the total yearly water produced.

The technology considered for the production of water is the only one that is used in S. Vicente, i.e., desalination of seawater using reverse osmosis. The electricity costs consider the electricity production costs calculated with the method described above. In this way, the electricity production cost has obviously a strong influence on the water production costs.

2.3 Total costs

The total annual costs (TC) can be divided in electricity production costs and water production costs, and depend on the total yearly electricity and water produced. It can be calculated as follows:

$$TC = EPC \, E + WPC \, W \quad (€) \tag{4}$$

3. Case Study

S. Vicente is a 227 km^2 island of the Arquipelago of Cape Verde, located about 450 km of the West African coast. It is the second most crowed island of the country, it had ~76,000 inhabitants in 2010, mostly concentrated in Mindelo, its main city [13]. Figure 1 shows a map of S. Vicente [14]. This island is not interconnected with any other island.

Power in Cape Verde is supplied by the multi-utility ELECTRA, which is also responsible for the water supply in some of the islands, like in S. Vicente. Cape Verde has achieved a relatively high electrification rate. According to the National Census of 2010, 81% of the total population has access to electricity [13]. This value is above the average for African countries (43%), and also above the average for developing countries (76.1%), but below the average for transition economies and OECD countries that reach 99.8% [15]. However, the increase in the electrification rate over the years in Cape Verde was not accompanied by a proportional increase in the electricity production, with the power installed decreasing. Between 2002 and 2006, the power installed decreased about 4%, while connections rose by 40% and production by 10%. Hence, blackouts became more frequent and longer in duration due to a tight demand-supply balance [16].

In Cape Verde energy production is largely dependent on fossil fuel-based plants, which in turn rely on expensive fuel imports. Fuel costs represent more than 70% of the power production costs [16].

A single power price is applied across all islands despite differences in costs – a geographical cross-subsidization justified on the grounds of social equity. Cape Verde’s power prices are among the highest in Africa due to its dependency on the importation of expensive fuel. [16]. According to ELECTRA, the electricity price in Cape Verde in 2012 was 0.283 €/kWh [17].

The local authorities are planning to replace diesel-fired generating plants by fuel oil-fired plants, which would immediately halve the fuel costs. The government also plans to invest in renewable energy to reduce oil dependency [16].

Cape Verde has by far the most expensive water tariffs in Africa, and among the most expensive in the world [16]; specifically, 3.313 €/m^3 in 2012 [17]. This value is more than double the average water tariffs in the OECD major cities [18]. These high prices reflect the scarcity of the water resources that has forced the country to rely on desalination for approximately 85% of the production. Moreover, the cost of the energy-intensive desalination process is particularly high due to its dependence on power generation, whose high costs in turn reflect reliance on small-scale diesel generators and expensive imported oil [16].

3.1 Electricity supply system of S. Vicente

The electrification rate of S. Vicente reached 90% in 2010 [13], a value above the national average. The technologies used for the production of electricity on the island are based on fossil fuel-fired plants and wind turbines. Figure 2 shows the power generation in S. Vicente by source in 2010. There are two conventional thermal fossil fuel-based plants, the Matiota and the Lazareto plants. In 2010, the Matiota plant had four fuel oil and diesel generators, with an installed capacity of 10,900 kW. The Lazareto plant had two fuel oil generators, with an installed capacity of 7,440 kW. There is also a wind park in Selada Flamengo with three Nordtank wind turbines of 300 kW each. The electricity production in 2010 was about 65 GWh, with a peak power of 10.9 MW [19]. The electricity demand is relatively stable throughout the year, as there are not large climate variations, as can be seen in Figure 3, which represents the hourly electricity load of S. Vicente in a summer day and in a winter day in 2010.

Early in 2011, the company Cabeólica installed seven Vestas V52 wind turbines of 850 kW each, and in September 2011 four of these wind turbines started operation and supplying electricity to the central grid. The remaining three wind turbines were not in operation. Hence, the installed wind power in the island was about 6.85 MW, although only with 4.3 MW in operation.

In 2012, the installed fossil fuel-based generators were the same as in 2010, and the electricity production was about 66 GWh with a peak power of 11.7 MW. Table 1 shows the power installed in S. Vicente in 2012.

According to the Renewable Energy Plan of Cape Verde [20], Group III and IV (Deutz generators) were decommissioned in the end of 2012 (after about 30 years of operation), and groups V and VI (MAK generators) will also be decommissioned in 2015 (after about 20 years of operation), taking out a total of 10.9 MW capacity from S Vicente.

The island has important wind resources. The hourly wind speed values used in this study were collected from the meteorological station of S. Pedro in 2005 [21]. Although the meteorological station is very close to the wind parks (Figure 1), a wind speed adjustment was applied using monthly correction factors defined to match wind power production in 2005. In this year, the average wind speed was about 8 m/s.

3.2 Water supply system of S. Vicente

All fresh water supplied to the population in S. Vicente is desalinated water [17, 19]. The desalination units are installed in the Matiota plant and, in 2010, the desalination capacity was about 7,300 m^3/day. The total water production in 2010 was 1,252,665 m^3. In August 2010, the oldest desalination unit, MED 2400, was deactivated [19]. Figure 4 shows the daily water production in S. Vicente in 2010.

In 2012, all the desalination units used reverse osmosis technology, three with a production of 1,000 m^3/day and two with a production of 1,200 m^3/day. According to the ELECTRA 2012 report, about 5 kWh/m^3 of water produced was necessary to desalinate and pump the water supplied to the population, that reached 1,250,804 m^3 [17].

The water reservoirs available in S. Vicente are distributed throughout the island, close to the population clusters. The total capacity of these reservoirs is about 14,680 m^3.

3.3 Future electricity and water demand

In our previous work [11], the evolution of the electricity and water demand considered was the one estimated in the National Energy Plan for Cape Verde [22]. This plan considered the forecast of the evolution of the Gross Domestic Product and of the resident population in order to estimate the growth in the consumption of electricity in the different islands of Cape Verde.

The forecast for the electricity production in S. Vicente considered in this article was compared with the actual data from the ELECTRA reports, and it was noticed that this forecast is greater than the actual production. Against this background, the data for the yearly production of electricity was updated and, in this study, actual data for 2010, 2011 and 2012 are considered. For the remaining years, the growth considered is the one estimated in the slow scenario of the National Energy Plan. The forecast of the water production was determined in the same way as the electricity production. Table 2 shows the electricity and water production in 2010 [19] and the forecast for 2015 and 2020 [22] along with the peak power production for each year.

The forecasted peak production was used to determine the installed fossil fuel-based generators in each year (for all scenarios), according to the security criteria currently used by ELECTRA. These criteria include the consideration of the unavailability of the biggest thermal unit (N-1 situation), the failure of all intermittent renewable energy sources, and a 3% reduction of the production in relation to the power installed, corresponding to a temperature factor. This factor is introduced to account for the reduction in nominal production capacity of the power generating units due to the increase of the ambient temperature. In this way, the peak demand coverage index (*PDC*) can be calculated as follows:

$$PDC = \frac{P_{available} - Peak}{Peak} \tag{5}$$

where $P_{avaliable}$ is the available power after considering all the three security criteria and *Peak* is the peak demand forecasted for the period in analysis [20].

For 2015, and after considering the decommissioning of the two smaller groups of the Matiota power station, there is a need to install more fossil fuel power in order to keep this index positive. The Renewable Energy Plan of Cape Verde [20] foresees the installation of two fossil fuel-based generators, one of 3.5 MW and another of 5.5 MW in the Lazareto power station, and hence this solution was considered in this study. The power of the fossil fuel-based plants considered for this year is 23.04 MW.

For 2020, the remaining groups of the Matiota power station will be decommissioned and the need to install more fossil fuel power in order to keep the peak demand coverage index positive occurs again, hence the installation of one more generator of 3.5 MW and another of 5.5 MW is considered. The total installed fossil fuel power considered for this year is 25.44 MW.

3.4 Economic data

The discount rate used to annualize the investment costs of the system is 10% [3], which is the value usually used in the region for the analyses of the financial viability of this type of projects.

Table 3 shows the costs and lifetime of the installed equipment. The fixed operation and maintenance (O&M) costs are different according to the technology and are a given percentage of the total investment cost that should be paid each year during the lifetime.

The investment and O&M costs of the wind parks and of the fossil fuel-fired units are based on the costs for projects foreseen for Cape Verde stated in the Renewable Energy Plan of Cape Verde published in 2011 [20].

The fuel cost per kWh of electricity produced by the fossil fuel technologies is estimated for the years from 2007 to 2012 based on the information on the fuel specific consumption (g/kWh) of the existing fossil fuel-fired units, percentage of use of each fuel to produce electricity [17, 19], and the current prices of each fuel (€/kg) in Cape Verde, according to the National Economic Regulatory Agency [25]. In 2010, fuel costs reached 0.129 €/kWh. Based on these values, the estimations for 2015 and 2020 are made by linear regression, which lead to 0.195 €/kWh in 2015 and 0.268 €/kWh in 2020. It is important to refer that the volatile nature of the fuel costs requests for a sensitivity analysis that will be made in the future.

3.5 Scenarios considered

Five different scenarios are considered in this study, all having 2010 as the base year. The first scenario is the Business As Usual (BAU), as it only considers the projects that are already foreseen for the island, and it was established in order to allow the comparison between the results of the proposed solutions and the current energy and water supply systems, including electricity and water production costs and total yearly costs.

The second scenario considers the supply of wind power to the desalination plants already installed on the island. Although S. Vicente has several reservoirs spread through the island, this scenario considers that there is only one reservoir in the island with the capacity of all of them, about 14,680 m^3, where the water that comes out of the desalination plant is stored before being supplied to the population. When the excess wind power is not enough to desalinate all the water needed the fossil fuel-based generators are used to supply the remaining required electricity.

The third scenario was established by finding which installed wind power and desalination capacity minimizes the total annual costs of the electricity and water supply systems for 2020, while keeping the wind power penetration the highest possible.

The fourth scenario considers the storage of the excess wind power production through pumping of the desalinated water. This scenario contemplates the construction of two water reservoirs, one at low altitude and another at 500 m of altitude. The wind park would supply electricity to a desalination plant and to a pumping station that pumps desalinated water from the lower reservoir into the upper reservoir. When it is necessary to supply water and electricity to the population, the water retrieved from the upper to the lower reservoir, passing through the hydro turbine, as shown schematically in Figure 5. The cycle efficiency of the pumped hydro storage is about 69%.

The fifth scenario was established by finding which installed wind power, desalination capacity, hydro power and pump power minimizes the total annual costs of the electricity and water supply systems for 2020, while keeping the wind power penetration the highest possible.

These five scenarios were modelled limiting to 30% the hourly intermittent energy penetration, which means that only 30% of the load of one hour can be covered by wind power [1, 26].

For Scenarios 1, 3 and 5, alternative scenarios were made taking into consideration an hourly intermittent energy penetration of 100% (Scenarios 1a, 3a and 5a), in order to compare the results with the remaining scenarios. It is important to notice that these scenarios present great risk of power instability on the grid, hence, it is necessary to consider that the wind turbines installed possess some degree of frequency and voltage control. There is no need to simulate Scenario 2 and 4 with an hourly intermittent energy penetration of 100% because, with this limit, the wind power curtailed is not enough to supply the desalination units and the pumps. For the other three scenarios, it is interesting to examine the consequences of an increase in the installed wind power.

In Scenarios 1, 1a, 2 and 4 the current installed wind power and desalination capacity in S. Vicente is considered. In Scenarios 3, 3a, 5 and 5a, the installed wind power and desalination capacity are those that minimized the total costs, while keeping the RES penetration the highest possible. Table 4 summarizes all scenarios considered in this study.

4. Results

4.1 Scenario 1 - BAU

This scenario considers the installed wind power and the fossil fuel-based generators currently in S. Vicente. For 2015 and 2020, the installed wind power is similar to that in 2012, with all the installed wind turbines in operation, but the fossil fuel power is increased in order to keep the peak demand coverage index positive, as described in section 3.3. Table 5 summarizes the results obtained for this scenario. It is clear that with the new wind generators installed in 2011, the percentage of wind power generation increases significantly; specifically, from 5% in 2010 to 22% in 2015, and 21% in 2020. The wind power will have a strong presence in the power generation of S. Vicente in the upcoming years, but the fossil fuel will remain very important, promoting a considerable increase in the electricity production cost, and, consequently, in the water production cost.

The results also reveal that there will be a significant wind power curtailed; specifically, in 2015 it will reach 44% of all potential wind power, and in 2020 about 37%. Scenario 2 is built to use this wasted wind power.

4.2 Scenario 2 - wind powered desalination

Scenario 2 considers the construction of a medium voltage (MV) power line from the wind parks (located in Selada Flamengo) to the desalination units (located in the Matiota power station). This would enable the supply of wind power directly to the desalination units. The distance between these two locations is about 12 km, and the cost per km of the construction of a MV power line was considered to be 20,000 €/km [27]. This cost was annualized considering the discount rate and the lifetime of 20 years and was added to the total yearly costs of the water supply system. Besides the power line, this scenario considers equipments already installed in the island: 6.85 MW of wind power and 5,400 m^3/day of desalination capacity.

Table 6 summarizes the results obtained for this scenario. In 2020, the electricity production costs are about 3% lower than those in the BAU Scenario. This is because there is more wind power used, lowering the electricity needed from fossil fuel. The wind power curtailed decreases from 44% to 31% in 2015 and from 37% to 25% in 2020.

The water production costs, which include the investment in the new power line mentioned above, are slightly lower, and the electricity used to desalinate water is mostly wind power. This percentage of wind powered desalination can increase if the capacity of the reservoir increases. This, however, would involve the construction of additional reservoirs, which was not considered in this scenario.

4.3 Scenario 3 - wind powered desalination with minimum total costs in 2020

The optimal configuration found has 6.85 MW of installed wind power and 5,400 m^3/day of desalination capacity, which is currently installed on the island.

During the optimization process it was possible to conclude that the addition of more desalination capacity only increased the costs. Even if the desalination capacity increases dramatically, the wind power curtailed does not decrease much. This is because of the limited capacity of the reservoirs in which the desalinated water is stored, and the relatively low water consumption. If the reservoirs are full, the desalination stops and wind power is curtailed.

For the current desalination capacity installed, it is not possible to have 100% wind powered desalination. Only if the installed desalination capacity doubles would be possible to achieve such goal, and even then, a reservoir of about 300,000 m^3 would be needed, which corresponds to about 60 days of water demand in 2020. These values are disproportionate to the water consumption of this island. This is the first difficulty of coupling the energy and water supply systems. The construction of new reservoirs was not accounted for in this scenario, as it is considered that the existing ones are suitable for the current water consumption of the island.

This optimal configuration leads to 25% of total electricity production from wind power, 56% of wind powered desalination, about 25% of wind power curtailed and a load of the desalination units of 88%. The total annual costs are about 3% lower than those in the BAU Scenario for 2020.

From an economic point of view, it is possible to conclude that it is better to keep the load of the desalination units higher than to minimize the wind power curtailed by adding more desalination units.

4.4 Scenario 4 - wind powered desalination and pumped hydro

The previous scenario still resulted in a certain amount of wind power curtailed. In order to use this curtailed wind power, a pumped hydro storage is included in Scenario 4. Apart from the pumped storage, the existing equipments on the island are also considered (wind power and desalination capacity). The upper reservoir has a capacity of 50,000 m^3, and the lower one a capacity of 35,000 m^3 (about one week of average water demand in 2020).

According to Kaldellis and Kavadias [4], the most theoretically disturbed energy management scenario is based on the hypothesis that there is a complete disharmony between electricity demand and wind power harnessing. Hence, the rated power of the hydro station is determined in order to cover the peak production, which is about 12.5 MW. The pump station should have capacity to absorb the rated wind power minus the minimum consumption of the grid. Hence, the pump power should be around 4 MW.

With these hydro and pump power, the production of RES reached 43% in 2015, but the load of the hydro turbines was very low. Hence, their rated power was decreased step by step, always checking if the percentage of RES did not decrease. The same was done with the power of the pumps. In this way, 2.5 MW for hydro power and 3.5 MW for pump power were reached.

It was noticed that the capacity of the upper reservoir does not influence the results, since all that is pumped is immediately retrieved back through the hydro turbine. Hence the capacity of this reservoir was kept as low as possible (10,000 m^3) to decrease costs. Figure 6 shows the power demand (load, desalination and PHS charging) for one day in January 2020 in this scenario, and Figure 7 shows the power production (wind, fossil fuel and PHS) for the same day.

Table 7 shows the results obtained for Scenario 4. The total annual costs are lower than those for Scenario 2 because there is more wind power used, lowering the electricity needed from fossil fuel. The wind power curtailed decreases from 31% to 0.6% in 2015, and from 25% to 1% in 2020, which means that almost all wind power potential is used. In comparison with the BAU Scenario, the costs decrease about 9% in 2015 and 7% in 2020. In 2015 about 32% of the electricity used to supply demand is RES (23% wind power and 9% PHS). In 2020 this value decreases to 28% (22% wind power and 6% PHS).

4.5 Scenario 5 - wind powered desalination and pumped hydro with minimum total costs

In order to establish Scenario 5, and having Scenario 4 as a starting point, several values for the wind, hydro, pump power and desalination capacity were evaluated with the H2RES model.

The configuration that minimized the total yearly costs was 17.9 MW of installed wind power, 7,400 m^3/day of desalination capacity, 6.5 MW of hydro power and 8.5 MW of pump power. This resulted in a load of the desalination units of 65%, a load of the hydro turbine of 47% and a load of the pumps of 52%. The RES production reached 72% and the wind power curtailed was about 17%. As for the electricity used to supply demand, about 57% is RES (23% wind power and 33% PHS).

Again it was noticed that the capacity of the upper reservoir has a small influence in the results, since all water that is pumped is immediately retrieved back through the hydro turbine. Hence, the capacity of this reservoir was kept as low as possible, in this case 35,000 m^3, to decrease costs.

Table 8 shows the results obtained for Scenario 5. The higher penetration of wind power with the wind powered desalination and the pumped hydro storage results in a reduction of the total yearly costs of about 19% in relation to the BAU Scenario.

Considering an emission factor of 0.66 kgCO_2/kWh for the fuel oil power plants [20], this configuration avoids the emission of 22,423 tCO_2 in comparison with the BAU Scenario, which represents about 49% of the total CO_2 emissions foreseen for 2020.

4.6 100% hourly intermittent energy penetration scenarios

As referred to earlier, Scenarios 1, 3 and 5 were modelled one more time, but now allowing the hourly intermittent energy penetration rate to reach 100% (see Table 4). For this, it is necessary to consider that the wind turbines installed possess some degree of frequency and voltage control, with a correspondent cost rise of 15% [28].

The BAU Scenario with this condition (Scenario 1a, Table 4) decreases dramatically the wind power curtailed; specifically, 2.3% in 2015 and 0.5% in 2020. The percentage of wind power in the production of energy reaches 39% in 2015 and 34% in 2020, which means that the current installed wind power is not sufficient to cover the load at all hours of the year.

To establish Scenario 3a, the method described earlier to set up Scenario 3 was repeated for 2020. The configuration that minimizes the annual costs is 17.05 MW of wind power and 5,400 m^3/day of desalination capacity, which results in 66% of total electricity produced from wind power, 50% of wind powered desalination, 22% of wind power curtailed, and a load of the desalination units of 88%. From an economic point of view, it is better to keep the load of the desalination units higher than to minimize the wind power curtailed by adding more desalination units. Table 9 shows the costs obtained for Scenario 3a. In this scenario the electricity production costs are 25% lower than those in Scenario 3, the water production costs are 16% lower and the total costs decrease 24%. In this case, although these wind turbines are more expensive, the extra amount of wind power produced compensates the higher costs.

Moreover, increasing significantly the desalination capacity does not reduce much the wind power curtailed due, again, to the capacity of the reservoirs and the low water demand.

To establish Scenario 5a, the method described earlier to establish Scenario 5 was repeated for 2020. The configuration that minimized the total yearly costs was 17.9 MW of installed wind power, 6,400 m^3/day of desalination capacity, 1 MW of hydro power, and 1.5 MW of pump power. This resulted in a load of the desalination units of 75% and a load of the hydro turbine and of the pumps of 15%. The RES production reached 70% (68% wind power and 2% PHS), the wind power curtailed was about 22%, and the wind powered desalination was 61%. This configuration resulted in total annual costs about 9% lower than those of Scenario 5, but with a very slightly lower RES production. It seems that Scenario 5a does not take advantage of the pumped hydro system as much as Scenario 5 and this is expected since there is less need for storage when it is possible to deliver 100% of wind power directly into the grid.

4.7 Comparison between scenarios

Figure 8 shows the power production in 2020 for five different scenarios. It is clear that Scenario 3 (only desalination) does not differ much from the BAU Scenario, although the costs are lower. In Scenario 5 (desalination and pumped hydro) there is a significant increase in the penetration of RES.

Comparing the scenarios that only consider desalination but have different intermittent limits, a 100% intermittent limit allows a significantly higher penetration of wind power. However, for the scenarios that consider desalination and pumped hydro, the penetration of RES is almost the same.

Figure 9 shows the desalinated water production in 2020 for four different scenarios. The desalination and pumped hydro scenarios allowed for a higher percentage of water desalinated from wind power than the scenarios with only desalination, for both intermittent limits.

5. Conclusions

The main objective of this work was to find a solution that minimized the total annualized costs of the energy and water supply systems, while keeping the wind power penetration the highest possible in the island of S. Vicente, Cape Verde. The study intended to understand how the electricity and water production costs vary with the wind power curtailed and with the load of the desalination units in order to find an optimum configuration. The results indicate that it is better to keep the load of the desalination units higher than to minimize the wind power curtailed by adding more desalination units. Obviously, the solutions proposed to increase the penetration of wind power are greatly affected by the capacity of the water reservoirs.

The results also reveal that, with the current installed wind power and desalination capacity on S. Vicente, it is possible to have, by 2020, more than 25% of wind power production, together with more than 56% of the water supplied to the population produced from wind power, with slightly lower costs than the ones foreseen for this year. With a pumped hydro system, the RES production can reach 36% (31% wind power and 5% PHS), with 56% of wind powered desalinated water and with about 7% decrease of costs in relation to the ones foreseen for 2020. If the installation of more wind power and desalination capacity is considered, renewable energy sources production can reach 72% (51% wind power and 21% PHS), with

92% of wind powered desalinated water, with about 19% decrease of costs in relation to those predicted for 2020. This configuration avoids about 49% of CO_2 emissions forecasted for 2020.

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Table 1. Installed capacity in S. Vicente in 2012 [17].

Location	Name	Installed capacity (kW)
Matiota power plant	Group III (Deutz)	2,100
	Group IV (Deutz)	2,200
	Group V (MAK)	3,300
	Group VI (MAK)	3,300
Lazareto power plant	Group VII (Caterpillar)	3,720
	Group VIII (Caterpillar)	3,720
Selada Flamengo wind park	3 NTK 300	3 x 300
Cabeólica wind park	7 Vestas V52	7 x 850

Table 2. Electricity and water production in 2010 [19] and the forecast for 2015 and 2020 22].

	2010	2015	2020
Electricity production (MWh)	65,029	74,922	88,518
Peak production (MW)	10.9	13.8	16.3
Water production (m^3)	1,252,665	1,469,404	1,736,061

Table 3. Costs and lifetime of the installed equipment [20, 23, 24].

Technology		Investment cost	Fixed O&M cost (%)	Variable O&M cost (€/MWh)	Lifetime (years)
Wind turbines		2,000 €/kW	3	-	20
Fossil fuel-based units		1,200 €/kW	1.5	-	20
Desalination [23]		1,000 €/(m^3/day)	10	-	20
Pumped hydro storage [24]	Hydro	500 €/kW	1.5	1.5	40
	Pump	500 €/kW			
	Storage	7.5 €/kWh			

Table 4. Scenarios considered.

Scenario	Description	Hourly wind power penetration
1	BAU	30%
2	wind powered desalination	
3	wind powered desalination with minimum costs	
4	wind powered desalination and PHS	
5	wind powered desalination and PHS with minimum costs	
1a	BAU	100%
3a	wind powered desalination with minimum costs	
5a	wind powered desalination and PHS with minimum costs	

Table 5. Results obtained for Scenario 1.

Year	2010		2015		2020	
Power generation (MWh)						
Wind power	3,455	5%	16,706	22%	18,966	21%
Fossil fuel	61,760	95%	58,215	78%	69,552	79%
Total	65,215	100%	74,922	100%	88,518	100%
Wind power curtailed (MWh)	-	-	13,158	44%	10,898	37%
Production costs						
EPC (€/kWh)	0.161		0.212		0.276	
WPC (€/m^3)	1.772		1.893		2.086	
Total costs (€)	12,747,010		18,577,899		27,952,711	

Table 6. Results obtained for Scenario 2.

Year	2015		2020	
Power generation (MWh)				
Wind power	20,545	27%	22,475	25%
Fossil fuel	54,722	73%	66,434	75%
Total	75,267	100%	88,909	100%
Wind power curtailed (MWh)	9,319	31%	7,389	25%
Water production (m^3)				
Wind power	1,019,002	69%	973,076	56%
Fossil fuel	458,586	31%	769,381	44%
Total	1,477,588	100%	1,742,458	100%
Production costs				
EPC (€/kWh)	0.202		0.266	
WPC (€/m^3)	1.825		2.019	
Total costs (€)	17,918,962		27,155,385	

Table 7. Results obtained for Scenario 4.

Year	2015		2020	
Power generation (MWh)				
Wind power	29,679	35%	29,573	31%
PHS	6,144	7%	4,876	5%
Fossil fuel	48,347	57%	61,526	64%
Total	84,169	100%	95,974	100%
Wind power curtailed (MWh)	184	0.6%	291	1%
Water production (m^3)				
Wind power	1,068,465	72%	980,233	56%
Fossil fuel	408,841	28%	761,942	44%
Total	1,477,306	100%	1,742,176	100%
Production costs				
EPC (€/kWh)	0.171		0.237	
WPC (€/m^3)	1.669		1.875	
Total costs (€)	16,858,219		26,001,803	

Table 8. Results obtained for Scenario 5.

Power generation (MWh)		
Wind power	65,348	51%
PHS	26,632	21%
Fossil fuel	35,578	28%
Total	127,558	100%
Wind power curtailed	13,555	17%
Water production (m^3)		
Wind power	1,613,387	92%
Fossil fuel	140,503	8%
Total	1,753,890	100%
Production costs		
EPC (€/kWh)	0.154	
WPC (€/m^3)	1.703	
Total costs (€)	22,626,074	

Table 9. Results obtained for Scenario 3a.

	2020
Electricity production cost (€/kWh)	0.200
Water production cost (€/m^3)	1.689
Total yearly costs (€)	20,144,822

Figure Captions

Figure 1. Map of S. Vicente.

Figure 2. Power production in S. Vicente in 2010.

Figure 3. Hourly electricity load of S. Vicente in a summer day and in a winter day in 2010.

Figure 4. Daily water production in S. Vicente in 2010.

Figure 5. Schematic diagram of Scenario 4

Figure 6. Demand in 2020 for Scenario 4.

Figure 7. Production in 2020 for Scenario 4.

Figure 8. Power production in S. Vicente in 2020 for different scenarios.

Figure 9. Production of desalinated water in S. Vicente in 2020 for different scenarios.


Matiota
Mindelo
Lazareto
Monte Verde
S. Pedro
Selada Flamengo
Data SIO, NOAA, U.S. Navy, NGA, GEBCO

Figure 1.

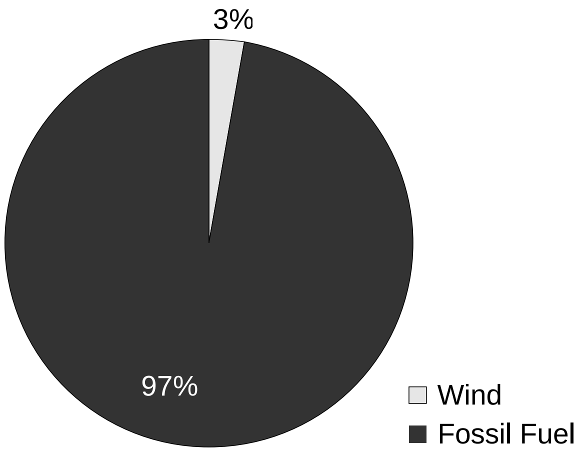

Figure 2.

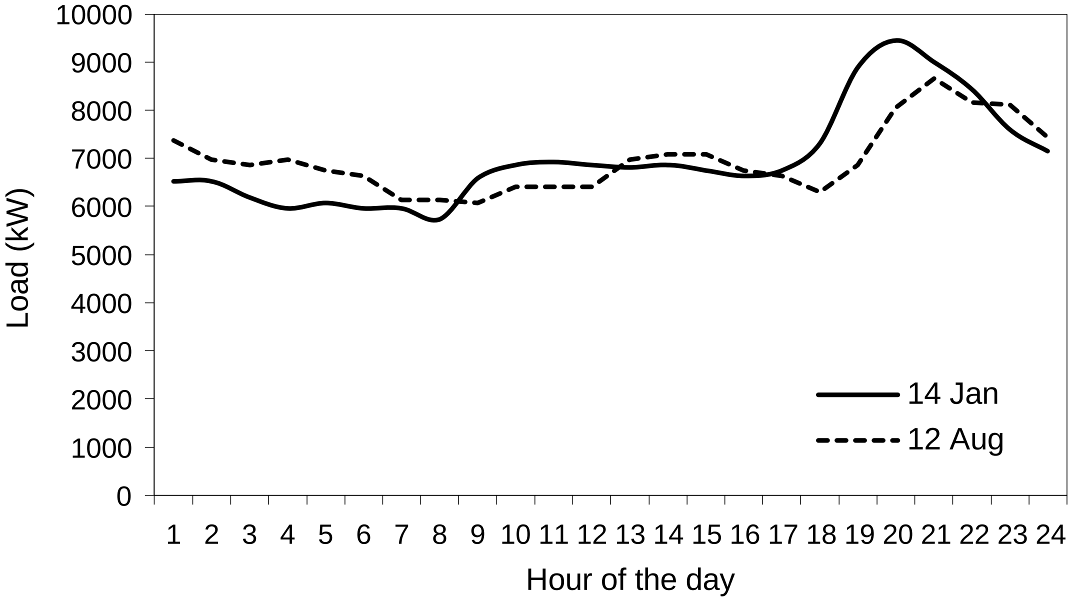
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Load (kW)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour of the day
14 Jan
12 Aug

Figure 3.

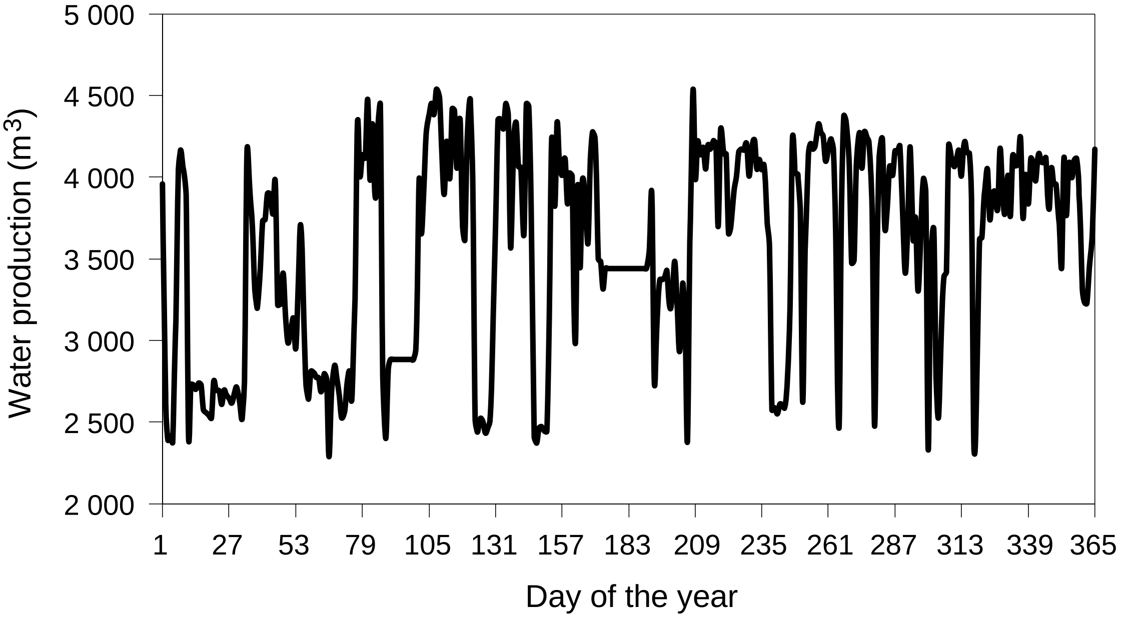
5 000
4 500
4 000
3 500
3 000
2 500
2 000
Water production (m3)
1
27
53
79
105
131
157
183
209
235
261
287
313
339
365
Day of the year

Figure 4.

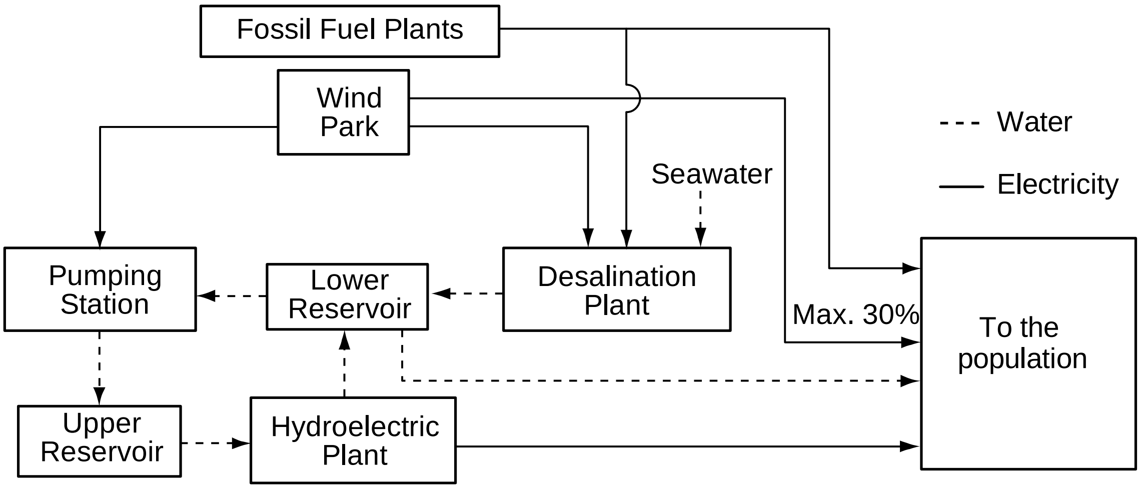
Fossil Fuel Plants
Wind Park
Seawater
Water
Electricity
Pumping Station
Lower Reservoir
Desalination Plant
Max. 30%
To the population
Upper Reservoir
Hydroelectric Plant

Figure 5.

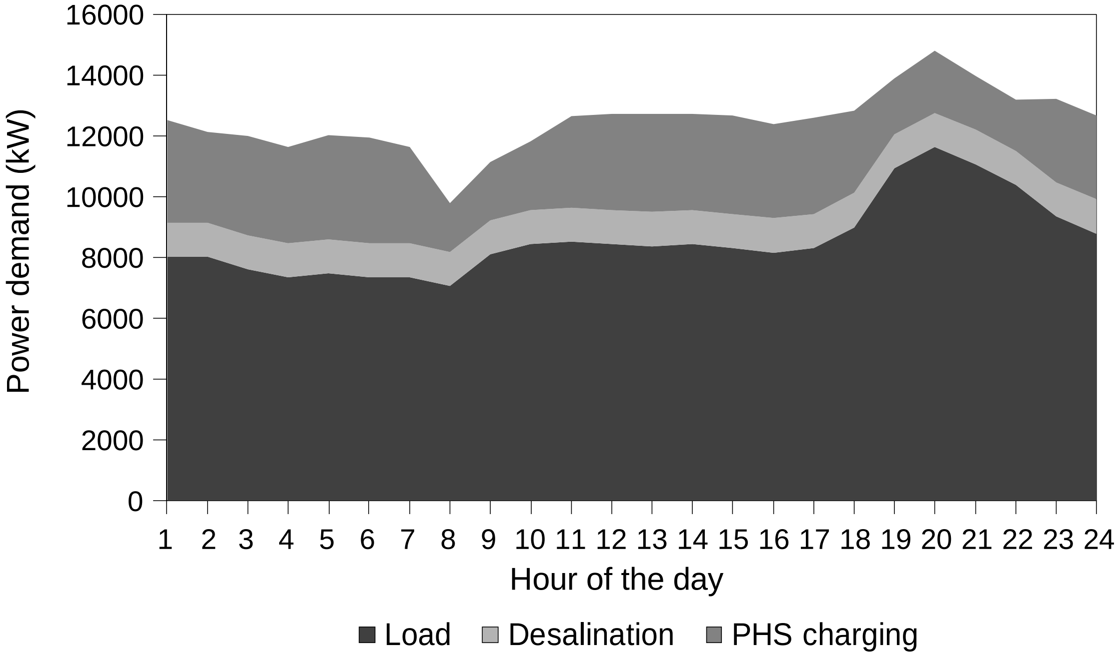
16000
14000
12000
10000
8000
6000
4000
2000
0
Power demand (kW)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
Hour of the day
Load
Desalination
PHS charging

Figure 6.

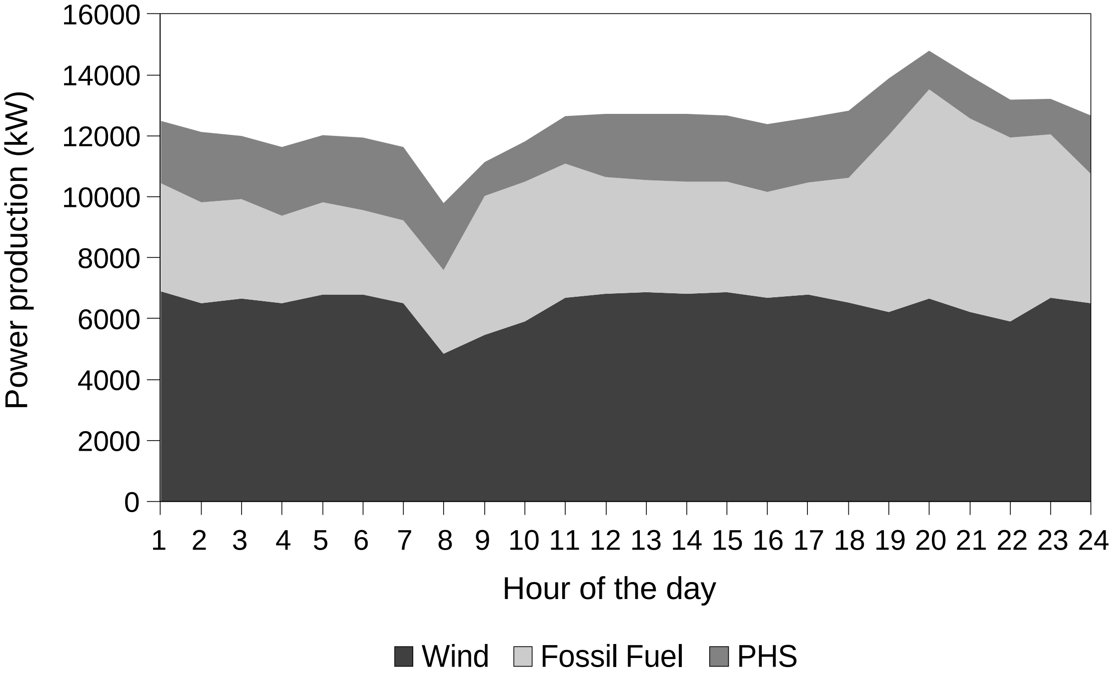
Power production (kW)
16000
14000
12000
10000
8000
6000
4000
2000
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
Hour of the day
Wind
Fossil Fuel
PHS

Figure 7.

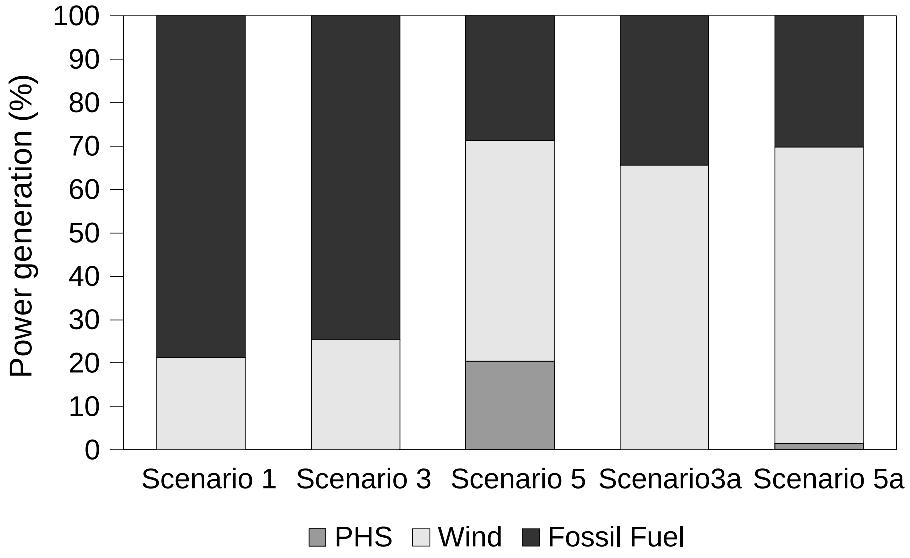
Power generation (%)
100
90
80
70
60
50
40
30
20
10
0
Scenario 1
Scenario 3
Scenario 5
Scenario3a
Scenario 5a
PHS
Wind
Fossil Fuel

Figure 8.

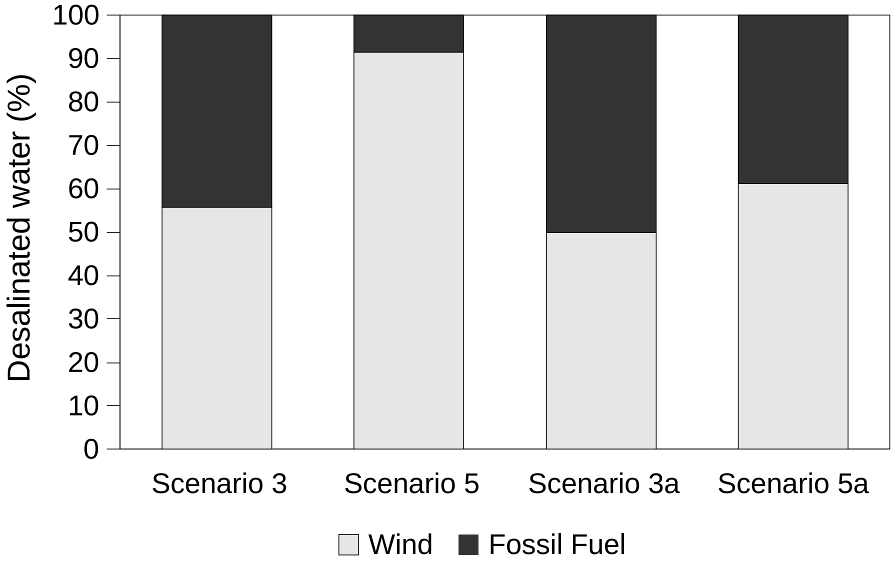
Desalinated water (%)
100
90
80
70
60
50
40
30
20
10
0
Scenario 3
Scenario 5
Scenario 3a
Scenario 5a
Wind
Fossil Fuel

Figure 9.