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Sustainability economic study of the islands of the Azores archipelago using photovoltaic panels, wind energy and storage system

Inês Melo[1], João Paulo Neto Torres[1,2*], Carlos Alberto Ferreira Fernandes[1,2]
and Ricardo A. Marques Lameirinhas[1*]

Abstract

Currently, the nine islands of the Autonomous Region of the Azores have fossil fuel-fired power stations as the main source of electric power. Each island has an independent electrical system classified as an isolated micro-system, given its size and location. The aim of this paper is to analyse the best set of technologies to have nine sustainable hybrid systems. For this purpose, some factors will be considered, such as actual data production of the island, economic scenarios, growth perspectives of consumption and reliability of supply. The results of these studies will allow us to conclude on the applicability of these systems and to quantify the consequent socio-economic, environmental and fossil energy-saving benefits. A system is projected to the archipelago, in order to reduce the energy production due to non-renewable energies, budgeted on 783.28 million euros, which intend to instal wind farms and photovoltaic parks (using polycrystalline and cadmium telluride technologies).

Keywords: Energy consumption, Isolated micro-network, Network stability, Renewable energies, Photovoltaic conversion, Eolic conversion

Introduction

The Azores archipelago is geographically located in a region where three lithospheric plates are connected: the American, the Eurasian and the African. This Portuguese archipelago has 9 islands divided into three main groups, according to their location, as illustrated in Fig. 1: The eastern group composed by Santa Maria and São Miguel islands, the central group formed by Terceira, Graciosa, São Jorge, Faial and Pico and the western group constituted by Flores and Corvo. A great deal of geomorphological aspects has to be considered, because these islands had origin on several types of volcanic eruptions. In general, the landscape is characterised by a vigorous and busy orography, with the maximum altitude of the islands quite variable, ranging between 402 m in Graciosa and 2351 m in Pico mountain, which is the highest point in Portugal (Report of the State of Spatial Planning of the Autonomous Region of the Azores 2003). Regarding the climate, the region is in the transition zone between subtropical hot and humid air masses, the subpolar air fresh and drier air masses. Thus, it is considered as a temperate wet, mesothermal temperate climate, given the low thermal amplitude, persistent wind, high rainfall and relative humidity (Report of the State of Spatial Planning of the Autonomous Region of the Azores 2003).

The main goal of this article is to find a solution of a hybrid energy system, gathering wind and photovoltaic energy, and an energy storage system that can reduce the energy production based on non-renewable sources (Melo and Torres 2019). The focus is maximising the contribution of renewable sources and minimising the cost of generating fossil electricity in the nine micro-grids

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*Correspondence: joaotorres@tecnico.ulisboa.pt; ricardo.lameirinhas@tecnico.ulisboa.pt
[1] Department of Electrical and Computer Engineering, Instituto Superior Técnico, 1049-001 Lisbon, Portugal
Full list of author information is available at the end of the article

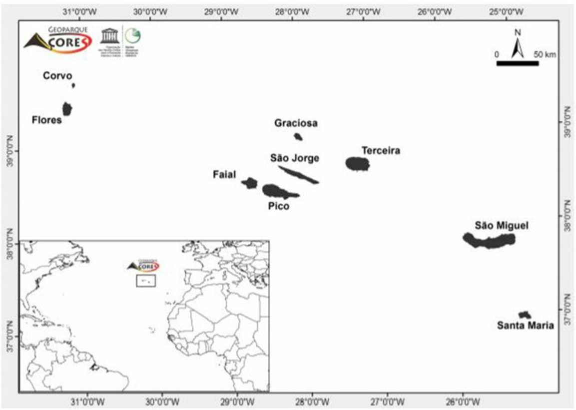


Fig. 1 Geographical location of Azores archipelago

of the archipelago, using different and recent technologies (Melo and Torres 2019; Durão et al. 2020; Kaldellis et al. 2009; Stenzel et al. 2017; Franzitta and Rizzo 2010). In this case, the energy storage system is used to store energy during periods of high electricity production and return it to consumption, mainly during periods of low solar irradiance or wind speed (Durão et al. 2020; Kaldellis et al. 2009; Stenzel et al. 2017; Franzitta and Rizzo 2010; Culotta et al. 2015; Curto et al. 2020; Alves et al. 2019; Gils et al. 2017).

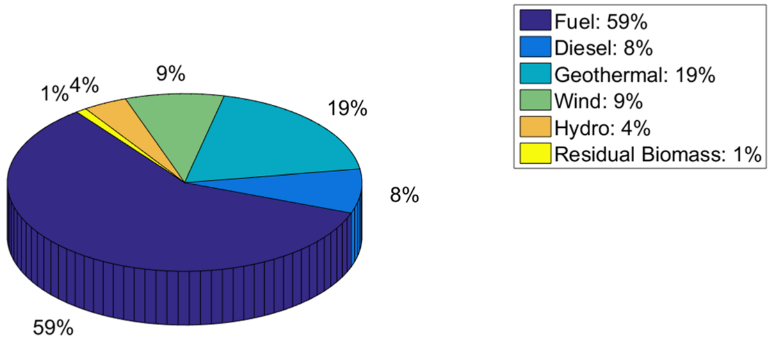
Nowadays, the actual energy systems on the islands depend mainly on the use of fossil fuels, which is not the most environment friendly energy source, beyond of it has a serious disadvantage of having to be transported to the islands, leading to high costs and an enormous environmental footprint associated to an endless list of negative impacts (Melo and Torres et al. 2019; Durão et al. 2020; Curto et al. 2020; Alves et al. 2019; Gils et al. 2017). In this context, renewable energies have a great opportunity to appear and to substitute the actual system, leading to the reduction of some of these problems (Durão et al. 2020; Franzitta and Rizzo 2010; Alves et al. 2019; Gils et al. 2017). However, the integration of floating renewables, especially in small and weak island networks, as the Azores ones, is a tremendous engineering challenge (Melo and Torres 2019; Durão et al. 2020; Alves et al. 2019). Energy storage is a technical solution for decoupling electricity supply and demand, providing flexibility without compromise the overall system (Alves et al. 2019). By combining renewable energy and storage systems into hybrid energy approaches, it is possible to replace fossil electricity generation by approximately 100%. In conclusion, the use of renewable sources as an alternative to fossil electricity generation on islands is becoming more and more attractive from the economic and ecological point of view (Melo and Torres 2019; Durão et al. 2020; Stenzel et al. 2017).

This article presents a point of view of how solar and wind resources can be integrated on Azores islands power systems, in order to mitigate the necessity to use non-renewable sources, since they are more reliable, and its outcomes are more predictable. Similar studies, which consider the implementation of new renewable sources systems for isolated regions, are already in the literature, not only for the Azores archipelago, but also for other islands (Kaldellis et al. 2009; Stenzel et al. 2017; Franzitta and Rizzo 2010; Culotta et al. 2015; Curto et al. 2020; Alves et al. 2019; Gils et al. 2017). However, this study takes into account more recent data, both energy-wise and population-wise, as well as state-of-art technology, considering, for example, the implementation of Building Integrated Photovoltaics (BIPV) technology and new rankings and studies' conclusions about the comparison among different panels and turbines, for this specific and challenging engineering problem. The aim of this article is not to exploit the interconnection of islands sub-systems, similarly to what is already done in (Alves et al. 2019), but it is to study the possibility of creating nine systems. The interconnection among islands could be possible only in close islands, since energy transport for long distances leads to high system losses and huge implementation costs. Before thinking of connecting the islands, it is necessary to study the possibility of implementing standalone systems with recent technology, since we are talking about insulated and isolated regions. This is not only the first step to reduce the non-renewable dependence, but also the one that allows more reduction, since non-renewable sources are substituted directly by renewable sources.

Background

During 2016 the total energy consumption in Azores was 801 GWh, in which only one-third of it was generated from renewable energy sources, the remaining being produced in fuel oil and diesel powerplants (EDA 2016). From the data presented in Fig. 2, it seems that the largest share of electricity production in the region comes from fossil fuels. At the level of renewable energy production in the region, it is possible to verify that the geothermal plants are responsible for the largest share of production, due to the availability of the resource, the stable production of these plants and their ability to guarantee power to the system (EDA 2016). Moreover, 9% of total production comes from wind production, with a high degree of intermittency. Finally, hydropower has a seasonal behaviour, responsible for 4% of the total produced energy (EDA 2016).

To do the sizing of the project for each island, it is necessary to analyse the general characteristics of each isolated micro-network. Therefore, it is necessary to synthesise several information and data from



Source	Production GWh	Production Total %
Fossil	**536**	**67**
Fuel	470	59
Diesel	66	8
Renewable	**265**	**33**
Geothermal	152	19
Wind	73	9
Hydro	31	4
Mini/Micro	1	0
Residual Biomass	9	1
TOTAL	**801**	**100**

Fig. 2 Produced energy in Azores archipelago (sourced and adapted from Stenzel et al. (2017))

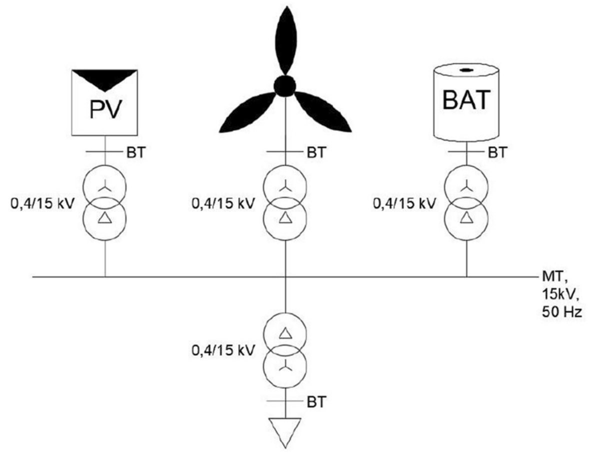


Fig. 3 General scheme of the hybrid system to be installed in the archipelago (sourced from Sónia and Artur (2018))

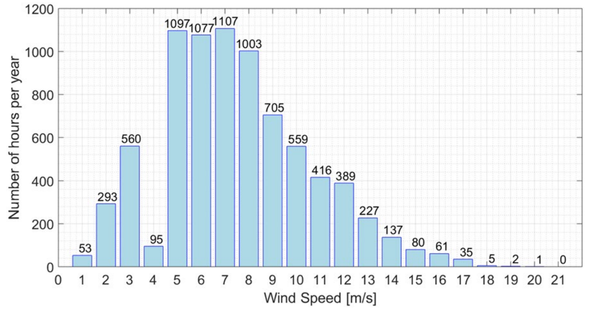


Fig. 4 One-year wind speed histogram (sourced from Meteoblue (2019))

each system, namely the evolution of emission values for the network, which were obtained for the years of 2006, 2013, 2018 and 2019 (Kaldellis et al. 2009). The total emission data rather than consumption data were selected, because the emission data already consider network losses. All resources currently installed in the islands and the characteristics of each network will be evaluated in order to observe the current power of renewable sources, so that it is possible to manage the necessary sizing for each island (EDA 2016).

To design the wind and photovoltaic system, some information such as irradiance, temperature and wind speed is needed, which was collected taking into account the locations for each renewable source. Moreover, it is intended to instal a hybrid power system with a power storage system, so given the distance between the sources, it becomes necessary to instal voltage booster substations. Thus, to implement this project, a single-line scheme as the one illustrated in Fig. 3 is considered.

Data for wind turbine sizing

The average hourly wind speed data were obtained for a year. Due to the wind characteristics uncertainty, a certain location is assumed to collect this data and use it to size the project for all the nine islands. Even that on the north Atlantic islands the wind speed variation is high, this assumption is valid since it was verified that a more central location of the archipelago could be used to describe a prediction for all the nine islands, having identical wind profiles. Thus, a more central position of the archipelago, on Graciosa island, was chosen and its values are presented in the histogram of Fig. 4. There, the values are catalogued per speed and it is possible to observe the number of hours associated to each value. Based on this figure, it is possible to predict the amount of energy produced by a wind farm.

Data for sizing photovoltaic panels

In the same way that the wind speed influences the sizing of the wind turbines, the irradiance analysis has to be done in order to size the photovoltaic sub-system. Thus, the monthly irradiance in each island was obtained (European Commission 2019). To design a photovoltaic system, both irradiance and temperature should be considered. However, in this specific system and location, only the irradiance will influence the sizing of photovoltaic panels, because the ambient temperature is mesothermal, which is the same to say that it never reaches values above 45 °C, allowing the temperature of the photovoltaic module not exceed the operating temperature range.

Implementation methodology

Technologies for photovoltaic energy production

Polycrystalline photovoltaic panels

Crystalline silicon technology is feasible for this kind of project, despite the fact that monocrystalline panels have a higher efficiency, the cost is higher in comparison with polycrystalline panels. Both technologies guarantee the project's viability and long-term yield, but for the Azores climate type, where there is a favourable sun exposure, the best option is the polycrystalline panels as they provide an advantageous price–quality ratio.

The chosen panels are from SolarWatt, which were considered, according to the 2019 list of solar panels prepared by Bloomberg New Energy Finance PV Module Tiering System, the most guaranteed panels in the world, leading a ranking called "World's Greatest Warranty" (Bloomberg new energy finance photovoltaic module tiering system 2019). For this specific case of study, it is quite important to choose components with confirmed and convince experimental results, in order to establish a minimum operating guarantee, which is in this case given by the aforementioned ranking list. From SolarWatt panels, the Vision 60P model is chosen, with their electrical characteristics detailed in Table 23 of Appendix 1, because the most commonly panels used in this kind of project have a maximum peak power of 280 W (Solarwatt 2019). Since the photovoltaic park will consist of a group of polycrystalline panels, series connections of 5 panels will be considered, in order to fulfil the power range of the existing charge controllers and maximum power point trackers (MPPT), which specifications are detailed in Table 25 of Appendix 2, and of the existing inverters, that have their main specifications described in Table 26 of Appendix 2. Each group of 5 panels connected on series will have a charge controller, a MPPT and a inverter and, in order to increase the produced power parallel more and more groups (of 5 panels connected on series) are going to be connected in parallel, each of them with an inverter and charge controller with a MPPT.

Photovoltaic cells cadmium telluride

To increase the power generation on the island, other photovoltaic solutions are analysed in order to add to the previous one. The solution to be presented is based on cadmium telluride (CdTe) solar cells.

Cadmium telluride is a direct bandgap semiconductor, very well suited to the solar spectrum, because it has a high bandgap of approximately 1.45 eV, which leads to really efficient solar cells (Jean et al. 2015). Furthermore, these cells have the lowest greenhouse gas emissions per kWh of electricity produced (De Wild-Scholten 2013). Cadmium telluride solar panels are commercially available as colourless and frameless modules. Their transparency range usually varies from 10 to 50% and the higher their transparency is, the lower output power they produce. As BIPV technology, it is possible to apply them on glass and window. They can replace these glasses or windows, or it is possible to build it from scratch. On both cases, single and double glasses are usually designed, which has also the benefit of improving the thermal and noise isolation (Durão et al. 2020; Polysolar 2019).

This technology is a good solution to incorporate in a system capable to produce energy for limited locations and places, such as island, because to generate the same amount of energy, this solution will occupy significantly less area than solutions-based photovoltaic panels characterised to produce less energy, i.e., in this last scenario the system will have to have much more panels to turn available the same amount of energy. House windows will be replaced by these single or double-glass panels.

Despite the fact that CdTe is a toxic chemical element, this study will analyse the use of this kind of panels in house windows. Thus, based on some approximations, the energy produced in the island will be determined, assuming that each house windows can be replaced by a single or double-glass CdTe panel. To size this project, it is assumed, as an average and worst-case scenario, that each house has a total of 8 windows or doors where the replacement process can be done. Based on this assumption, each house will have 16 CdTe panels. Another consideration is the fact that is assumed 4 inhabitants per house. The island's population is obtained from the last official data from the Portuguese's census, and its value is detailed below, whenever it is necessary to size systems (Provisional Annual Estimates of Resident Population 2011).

The characteristics of the chosen CdTe solar panel are presented in Table 24, accessible in Appendix 1. In this case, to fulfil the power range of the charge controller and the MPPT, specified in Table 25 of Appendix 2, and of the inverter, detailed in Table 26 of Appendix 2, each house sub-system will be composed by 4 groups, connected in parallel, of 4 panels associated in series. Thus, each house will have only one charge controller with MPPT and an inverter. Moreover, it will also have an ABB single-phase distribution transformer (specially designed for aerial distribution residential cargo power) with a power of 5 kVA. This component allows that the energy produced by these panels may be directly connected to the distribution network of each island and consequently, it is possible to feed other houses or public facilities with energy that is exceeded in a certain house.

Technologies for wind energy production

At the market there are two different types of wind turbines: horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT) (Durão et al. 2020; Culotta et al. 2015). HAWT are characterised to be able to produce a large amount of energy however, their start-up speed is usually higher than the VAWT ones (Durão et al. 2020; Culotta et al. 2015). VAWT are more environment friendly and aesthetic turbines, being recognised by their huge potential to be integrated on buildings, since they have a lower noise power level (Durão et al. 2020; Culotta et al. 2015). Moreover, as usually in residential areas the wind blows weaker, i.e., the wind speed is not as higher as it should be to be able to be converted into mechanical energy, this kind of turbines are made in order to have a lower start-up speed (Durão et al. 2020; Culotta et al. 2015). As a result of it, their capability to convert energy is smaller than the HAWT ones and, consequently their nominal power is lower (Durão et al. 2020; Culotta et al. 2015). Since the main goal of this project is to be able to produce the maximum amount of renewable energy, in order to fulfil the island consumption, mitigating the use of non-renewable energy, it is clear that it is necessary to choose HAWT turbines and place them in isolated and windy areas.

To sell its turbines typically, manufactures present the component power characteristic curve, or at least the more important points, such as the turbine starting, nominal and cutting speed and the power associated to each of these points. Usually, the wind speed related to these points is around 3 m/s, 14 m/s and 25 m/s, respectively.

The wind conditions that exist on Azores region allow us to place wind turbines in order to produce energy. When sun is covered, both in night and in not clear sky days, energy should continue to be produced. A hybrid system as this, allow us to store energy mainly when both solar and wind sources are co-working and the consumption is less than the production. This stored energy will be precious when the production level will be lower than the consumption one. The turbines generation when solar source is off, can diminish the need of stored energy, extending the use of renewable energy and decrease the necessity of fossil fuels.

To determine the number of turbines in order to reach a certain energy generation, the values from Fig. 4 are used. First, based on these values, the average energy produced per turbine is calculated and after that, the number of turbines can be determined. However, it is also needed to choose the turbine, in order to size the project according to its specifications, mainly its output nominal power. On all islands except Flores and Corvo, that produce the least, the sizing will be done with wind turbines with a nominal power of 2 MW. The sizing for Corvo and Flores will be done with 150 kW turbines. The performance of the system was analysed for a generic turbine with the aforementioned characteristics, since there are several similar turbines capable to follow these specifications.

Storage–battery centre

Installing a battery centre on each island is very important, not only because it makes possible to store energy near the source or load and consequently, reduce the system losses, but also because it allows to correct the power factor in the network.

Reactive energy is an integral part of utility bills and constitutes a significant financial burden. Reactive power consumption can, however, be excluded from the bill by installing a power factor correction system. Power factor correction is done by replacing the reactive power consumption of the grid through battery generation. Reducing reactive energy promotes proper functioning of facility energy, maximising the installed energy harvest. It should also be noted that the investment in this system can be recovered through the saved money related to the reactive energy compensation.

To measure how many batteries or battery banks should be installed in each island, it was assumed that each island would have an installed battery power equal to the island's peak energy reached in January 2019, which is the worst case due to the low production profile (winter, less irradiance) and the higher consumption level (low temperatures, more devices connected to the grid) (Melo and Torres 2019; Durão et al. 2020; Alves et al. 2019; Gils et al. 2017; EDA 2019). Thus, knowing the efficiencies of the inverter and the capacity of each battery bank, it is possible to determine the number of banks required for each island, using expressions 1 and 2. Differently of the inverter used on the photovoltaic panel groups, other inverter is used, and its electrical specifications are presented in Table 27 of Appendix 3.

$$E_{\text{bat}} = \frac{E_{\text{tip}}}{\eta_{\text{inv}}} \tag{1}$$

$$n_{\text{bat}} = \frac{E_{\text{bat}}}{E_{\text{bank}}} \tag{2}$$

Thus, battery banks should be installed in parallel in order not to exceed the operating voltage of this inverter. For this purpose, it was stipulated that an inverter is connected to 40 battery banks. Each AC/DC inverter is also connected to an ABB medium power transformer for distribution with a power of 3000 kVA.

Regarding the batteries types currently in the market, the most used are the lithium ion and nickel metal hydride (NiMH), since they are the most mature and traditional ones capable to be applied on systems that require high energy density in a short time.

Lithium-ion batteries are evolving rapidly as the electric car industry drives its development. Nowadays they are the most popular choice for solar energy storage due to warranty, design, and price. Other solutions are not only expensive, but also have a lower rate of energy management efficiency, making lithium-ion batteries the most reliable choice.

Thus, a lithium-ion battery bank from LG was chosen, named Chem R800, whose specifications are presented in Table 28 of Appendix 3.

Sizing for each island of the archipelago

The main goal of the sizing of the photovoltaic sub-system will be to produce approximately half of the production that is currently still provided by the island's thermoelectric plants. Wind energy generation will be sized to produce the remaining energy (50%) of fossil production. Wind and photovoltaic energy must be as balanced as possible, because they complement each other in different seasons, it being the starting point. However, considering the available area, it should not be completely possible for every island. The implementation takes into account the available island area to place the components. The bill of material is presented in Appendix 4, considering the fundamental components and devices to implement this project and in Appendix 5 are illustrated the island areas where it should be possible to place them. The use of BIPV solar technology, considering the CdTe panels, allows us to produce energy using residential areas and, consequently, mitigate the problem of the available area. This problem is bigger in highly populated or in smaller islands, because there is less available area and it is where the BIPV solution has more impact. Thus, the 50–50% would not be possible to reach in some cases, without the compromise the reduction of the non-renewable energies' footprint.

Santa Maria

According to the most recent data for this island, annual energy production in 2018 is known to have been around 20.64 GWh (EDA 2019). By checking data for January 2019, it is concluded that approximately 76% of energy production is still provided by fossil energy sources (EDA 2019). It is still necessary to ensure the "green" production of 15.69 GWh and, consequently, the sizing will be based on this value.

Photovoltaic production

To size the photovoltaic system, the software tool from the Photovoltaic Geographic Information System (PVGIS) was used, allowing to simulate photovoltaic, not only in Santa Maria, but in all the Azores islands, considering past, but real, measured values (European Commission 2019). The choice of this tool is due to the possibility of determining the potential of our standalone system, using solar radiation, temperature and meteorological conditions data, which were recorded recently for each global coordinate, allowing us not only to extract and use average data, but also to choose among annual, monthly or daily weights (European Commission 2019). The irradiance on each island is considered in order to describe the final system and its output power. Besides that, a solution is imposed for the optimum tilt and azimuth angles, when analysing the polycrystalline panels park and an angle of 90° is forced for the CdTe house solution.

Polycrystalline photovoltaic panels In order to approach the production goal of 15.69 GWh, it was decided to study the implementation of an 8.4 MW photovoltaic park, which is described in Table 1.

Photovoltaic cells cadmium telluride As heretofore introduced, it is needed to estimate each island population in order to verify how many houses and consequently, the number of CdTe panels installed on the island houses and the total average energy produced by them. According to the Provisional Annual Estimates of Resident Population, updated on June 15 of 2018 by the Portuguese statistical institute (Instituto Nacional de Estatística—INE), Santa Maria island has 5652 inhabitants. Given the approximations for the sizing of this technology, referred above, it is concluded that the island has approximately 1413 houses. For this case, the overall system is characterised by the

Table 1 Santa Maria system design data with polycrystalline photovoltaic panels

Number of polycrystalline panels	30,000
Tilt angle	30°
Azimuth angle	6°
Total losses	− 12.8%
Maximum power installed	8.4 MW
Annual irradiance	1700 kWh/m^2
Annual photovoltaic production	12,400 MWh

Table 2 Data for cadmium telluride photovoltaic system sizing

Number of CdTe panels	22,608
Tilt angle	90º
Maximum power installed	1266.05 kW
Annual photovoltaic production	1090 MWh

specifications presented in Table 2, resulting in a maximum installed power of 1266.05 kW.

Wind production

In Fig. 5 it is possible to observe the annual production of the 2 wind turbines, where it is possible to conclude that August is the worst month and November the best one in terms of energy production.

General production

In Fig. 6 it is possible to observe the total consumption of the island in blue over the 12 months of 2018 and the total production of the various renewable energy sources in red, considering the actual and the designed systems. The renewable energy production per month is the sum of the wind production presented in Fig. 6 and the photovoltaic generation extracted from the PVGIS software tool, for each month.

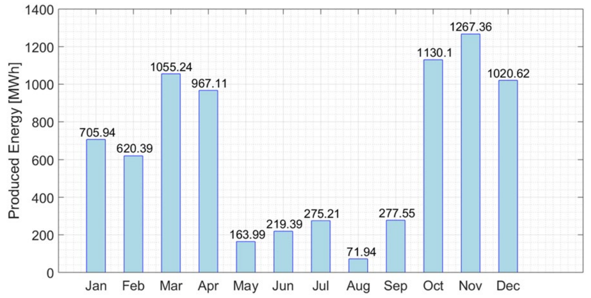


Fig. 5 Annual wind energy production on Santa Maria island

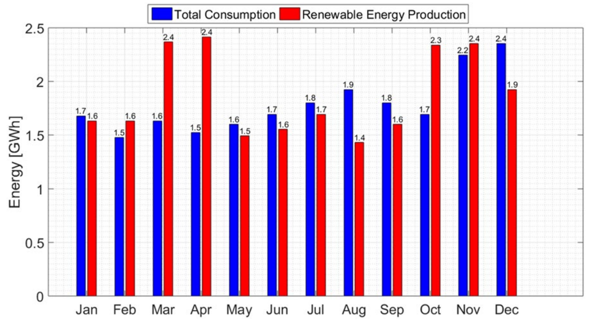


Fig. 6 Estimated total renewable energy emission and monthly consumption for 2018 in Santa Maria

Moreover, it is verifiable that on the months of January, May, June, July, August, September and December the total consumption is higher than the production due to renewable sources. Thus, the storage system should balance it, under forfeit of having to produce it by fossil sources.

Storage

According to the records for the month of January 2019, the highest power peak of Santa Maria system was 3351 kW (EDA 2019). Thus, according to expressions 1 and 2, it is concluded that this island needs 78 Chem R800 battery banks.

São Miguel

According to the most recent data, the annual energy production for 2018 is around 436.90 GWh (EDA 2019). Taking into account this information, it is still necessary to ensure a production of 210 GWh from the available renewable sources, so the sizing will be based on this value.

Photovoltaic production

Polycrystalline photovoltaic panels In order to reach the production intention to generate of 210 GWh from new renewable energy sources, it was thought to study the implementation of a 25 MW photovoltaic park, which is described in Table 3.

Photovoltaic cells cadmium telluride According to the Provisional Annual Estimates of Resident Population, updated on June 15 of 2018 by the Portuguese statistical institute (Instituto Nacional de Estatística—INE), São Miguel has 138,213 inhabitants, which gives an estimative of 34,553 houses. Using the aforementioned tool, the system is described in Table 4, where it is possible to visualise that it is predicted a system characterised by an installed maximum power of 30,959.49 kW.

Table 3 São Miguel system design data with polycrystalline photovoltaic panels

Number of polycrystalline panels	100,000
Tilt angle	30º
Azimuth angle	3º
Total losses	− 13.1%
Maximum power installed	25 MW
Annual irradiance	1580 kWh/m^2
Annual photovoltaic production	34,200 MWh

Table 4 Data for cadmium telluride photovoltaic system sizing for São Miguel

Number of CdTe panels	552,848
Tilt angle	90º
Maximum power installed	30,959.49 kW
Annual photovoltaic production	25,500 MWh

Wind production

The project for this island considers 45 turbines, each of them characterised by a nominal power 2 MW. Thus, taking into consideration the average hourly speed for a year, it is possible to estimate the amount of energy produced in this wind farm, for each month, as illustrated in Fig. 7.

General production

When analysing the behaviour of both generation systems when working together to reach the same goal, the sum of the generated energy is presented in Fig. 8. There, it is possible to analyse that the renewable sources cannot fulfil the energy demand on the island on the months of May, June, July, August and September. Thus, as referred before, the storage system should compensate it, in order not to use non-renewable sources.

Storage

According to the records for the month of January 2019, the maximum recorded power peak of São Miguel was 67,763 kW (EDA 2019). Thus, considering expressions 1 and 2, it is determined that this island will need at least a total of 1573 battery banks, taking into consideration the R800 LG battery banks.

Terceira

According to the most recent data, its annual energy production in 2018 was 190.76 GWh (EDA 2019). Checking the data for January 2019, it is shown that approximately 59% of energy production is still provided by fossil energy sources. It is still necessary to ensure the production of 113 GWh by renewable energy, so the sizing made will be based on this value.

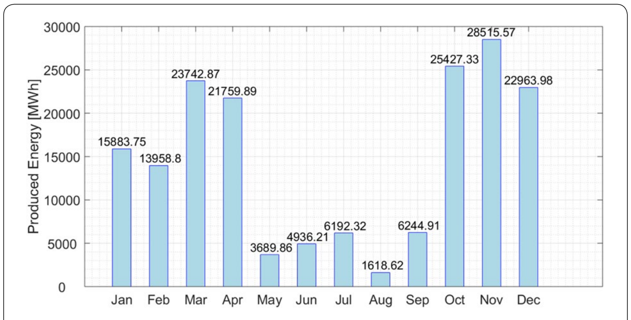


Fig. 7 Annual wind energy production on São Miguel island

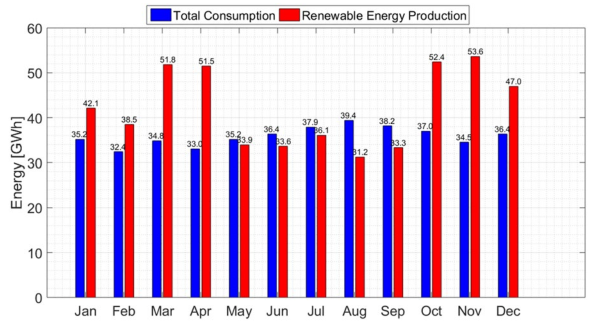


Fig. 8 Estimated total renewable energy emission and monthly consumption for 2018 in São Miguel

Photovoltaic production

Polycrystalline photovoltaic panels The project for this island will allow to produce 113 GWh from renewable sources. A 56-MW photovoltaic park is intended to be implemented in order to make this objective possible. The photovoltaic park is described in Table 5.

Photovoltaic cells cadmium telluride According to the Provisional Annual Estimates of Resident Population, updated on June 15 of 2018 by the Portuguese statistical institute (Instituto Nacional de Estatística—INE), Terceira has 56,141 inhabitants, making possible to estimate a total of 14,035 houses. Using the PVGIS tool, a system as the one described in Table 6 is designed in order to have an installed maximum power of 12 575.36 kW.

Wind production

A wind farm composed by 14 turbines of 2 MW (nominal power) is projected. Considering the wind speed data, that were used to develop Fig. 4, it is possible to predict

Table 5 Terceira system design data with polycrystalline photovoltaic panels

Number of polycrystalline panels	200,000
Tilt angle	30º
Azimuth angle	4º
Total losses	− 12.8%
Maximum power installed	56 MW
Annual irradiance	1590 kWh/m^2
Annual photovoltaic production	77,600 MWh

Table 6 Data for cadmium telluride photovoltaic system sizing for Terceira

Number of CdTe panels	224,560
Tilt angle	90º
Maximum power installed	12,575.36 kW
Annual photovoltaic production	9250 MWh

the electrical generation value due the wind, as illustrated in Fig. 9 for each month.

General production

Combining both generation systems, it is possible to analyse the amount of energy produced per month and compare this value with the consumption demand. In Fig. 10 these values are presented, and based on it, it is possible to observe that the renewable sources cannot meet the energy goal for the island on the months of January, May, June, July, August and September. Thus, as referred before, the storage system should compensate it, in order not to use non-renewable sources.

Storage

According to the records in the month of January 2019, it is verified that the maximum power peak of Terceira was 29,724 kW (EDA 2019). Thus, taking into account expressions 1 and 2, it is necessary at least a total of 690 battery banks.

Graciosa

According to the most recent data, it is known that the annual energy production of 2018 was 13,439.81 MWh (EDA 2019). When checking data for January 2019, it is concluded that 100% of energy production is still provided by fossil energy sources. However, in August 2019 the Graciólica Project was inaugurated, which will allow 65% of the energy consumed by the island to be ensure by a hybrid energy system. Thus, the sizing for Graciosa will be based on 35% not yet assured by renewable energy, which represents a total of 4703.94 MWh. As this project has already implemented a wind farm, the sizing will only be done using photovoltaic energy. Furthermore, this island has already battery banks, that can guarantee 2.60 MWh of saved energy. This battery bank was designed to cover the tip of the island, which is 2.27 MW, verified on January 2019 (EDA 2019). As the recorded tip value does not change, the storage system is already available, and it is not necessary to project another or a complement one.

Table 7 Graciosa system design data with polycrystalline photovoltaic panels

Number of polycrystalline panels	12,000
Tilt angle	32º
Azimuth angle	5º
Total losses	− 12.6%
Maximum power installed	3.36 MW
Annual irradiance	1610 kWh/m^2
Annual photovoltaic production	4720 MWh

Photovoltaic production

Polycrystalline photovoltaic panels To accomplish the goal to generate more 4.7 GWh by renewable energies, it is used only photovoltaic generation, because a brand-new wind farm started working in 2019. To reach that, a 3.36 MW photovoltaic park is studied as described in Table 7.

Photovoltaic cells cadmium telluride According to the Provisional Annual Estimates of Resident Population, updated on June 15 of 2018 by the Portuguese statistical institute (Instituto Nacional de Estatística - INE), a total of 4339 inhabitants are living in Graciosa, making possible to estimate a total of 1084 houses. Based on the PVGIS output information for this project, a system as the one described in Table 8 should be installed in order to reach a maximum power installed of 971.27 kW.

General production

Including the energy produced for the projected photovoltaic park and the new wind farm, created by the Graciólica Project, it is possible to conclude from Fig. 11, that renewable energies will produce sufficient energy to fulfil the island demand, except on the months of January, February, August, October, November and December. Nonetheless, the improvement when comparing with the actual system is quite notable. As previously referred, to tend to the neglect of non-renewable energies, the storage system should store the energy surplus.

São Jorge

According to the most recent data, it is verified that the annual energy production of 2018 was around 28,901.97 MWh (Solarwatt 2019). When checking data for the month of January 2019, it is reported that approximately 89% of energy production is still provided by fossil energy

Table 8 Data for cadmium telluride photovoltaic system sizing for Graciosa

Number of CdTe panels	17,344
Tilt angle	90º
Maximum power installed	971.27 kW
Annual photovoltaic production	808 MWh

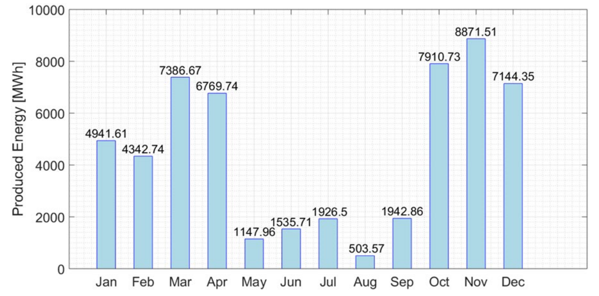


Fig. 9 Annual wind energy production on Terceira island

sources (EDA 2019). Then, a 25,722.75 MWh project will be done, using renewable energies.

Photovoltaic production

Polycrystalline photovoltaic panels In order to approach the objective to produce approximately 2.57 GWh of energy from renewable sources, first it is projected a photovoltaic park of 11.76 MW nominal power, as specified in Table 9, from the analysis done on the PVGIS software tool.

Photovoltaic cells cadmium telluride According to the Provisional Annual Estimates of Resident Population, updated on June 15 of 2018 by the Portuguese statistical institute (Instituto Nacional de Estatística—INE), there are 8556 people living in São Jorge, on approximately 2139 houses. Based on the PVGIS output information for this project, the implementation of this system will allow to generate around 1.9 GW, as the installed maximum power, as presented on Table 10.

Wind production

To achieve the proposed goal, a wind farm formed by 3 turbines, each one with a nominal power of 2 MW was designed. Considering the wind speed data, it is predictable the amount of energy generated by the wind farm per month, as it is illustrated in Fig. 12.

General production

Combining both wind and solar systems, it is possible to determine the amount of energy produced per month and compare this value with the consumption demand. These values are presented in Fig. 13, where it is possible to conclude that on the months of January, May, June July, August and September the energy goal is not totally verified. Thus, as referred before, the storage system should compensate it, in order not to use non-renewable sources.

Table 9 São Jorge system design data with polycrystalline photovoltaic panels

Number of polycrystalline panels	42,000
Tilt angle	30º
Azimuth angle	12º
Total losses	– 12.8%
Maximum power installed	11.76 MW
Annual irradiance	1520 kWh/m^2
Annual photovoltaic production	15,500 MWh

Table 10 Data for cadmium telluride photovoltaic system sizing for São Jorge

Number of CdTe panels	34,224
Tilt angle	90º
Maximum power installed	1916.54 kW
Annual photovoltaic production	1490 MWh

Storage

According to the records for the month of January 2019, the highest recorded power peak of São Jorge was 4715 kW (EDA 2019). Thus, considering expressions 1 and 2, it is concluded that this island will need, at least, a total of 109 battery banks.

Pico

According to the most recent data, annual energy production in 2018 is known to have been 44,871.52 MWh (EDA 2019). By checking data for January 2019, it is concluded that approximately 85% of energy production is still provided by fossil energy sources (EDA 2019). It is still necessary to ensure the production of 38,140.79 MWh for renewable energy, so the size will be based on this value.

Photovoltaic production

Polycrystalline photovoltaic panels It is needed to generate approximately 3.8 GWh of energy from renewable sources and so that a photovoltaic park of 14 MW nominal power is projected, as in Table 11, from the analysis done on the PVGIS software tool.

Photovoltaic cells cadmium telluride According to the Provisional Annual Estimates of Resident Population, updated on June 15 of 2018 by the Portuguese statistical institute (Instituto Nacional de Estatística—INE), there are 13,883 inhabitants in Pico and consequently, the approximation of 3470 houses is used. Using PVGIS tool, it is possible to obtain a system that will produce a maximum power of approximately 3.1 GW, as shown on Table 12.

Table 11 Pico system design data with polycrystalline photovoltaic panels

Number of polycrystalline panels	50,000
Tilt angle	30º
Azimuth angle	− 3º
Total losses	− 12.8%
Maximum power installed	14 MW
Annual irradiance	1600 kWh/m^2
Annual photovoltaic production	19,500 MWh

Table 12 Data for cadmium telluride photovoltaic system sizing for Pico

Number of CdTe panels	55,520
Tilt angle	90º
Maximum power installed	3109.12 kW
Annual photovoltaic production	2260 MWh

Wind production

This wind farm is composed by 5 turbines of 2 MW, which are able to produce the amount of energy predicted and presented in Fig. 14, considering the wind speed data analysed before.

General production

Combining both renewable energy sources, it is possible to calculate the energy production per month and compare it with the consumption demand. These values are presented in Fig. 15, where it is possible to conclude that in the months of January, February, May, June July, August and September the energy objective is not totally verified. Thus, as referred before, the storage system should compensate it, in order not to use non-renewable sources.

Storage

According to the records for January 2019, this island power peak was 7299 kW (EDA 2019). Thus, taking into account the expressions 1 and 2, it is determined that this island needs, at least, 169 battery banks.

Faial

According to the most recent data, it is known that the annual energy production in 2018 was 46,315.50 MWh (EDA 2019). Checking the data for January 2019, it was observed that approximately 83% of energy production is still provided by non-renewable sources (EDA 2019). The "green" production of 38,441.87 MWh is still needed to be assured, so the sizing will be based on this value.

Photovoltaic production

Polycrystalline photovoltaic panels It is needed to generate approximately 3.84 GWh of energy from renewable sources and so that a photovoltaic park of 14 MW nominal power is projected, as specified in Table 13, from the analysis done on the PVGIS software tool.

Photovoltaic cells cadmium telluride According to the Provisional Annual Estimates of Resident Population, updated on June 15 of 2018 by the Portuguese statistical institute (Instituto Nacional de Estatística—INE), there are 14,824 residents in Faial and consequently, it gives us an approximation of 3706 houses. Using PVGIS tool, it is possible to obtain a system that will produce a maximum power of approximately 3.32 GW, as presented on Table 14.

Wind production

As this island is energetically identical to Pico, both solar and wind systems are also very similar. As verified before, the solar system is quite similar to the Pico's one and the wind system will be too. Thus, this wind farm will be composed by 5 turbines of 2 MW, which can produce the energy values illustrated in Fig. 16, considering the wind speed data analysed before.

General production

Considering the energy production from renewable energies that was projected for this island, it is time to analyse if systems power output can reach the demand necessity. These values, capable of being compared, are detailed in Fig. 17, where it is possible to conclude that in the months of January, February, May, June July, August and September this kind of sources cannot produce enough energy to satisfy the energy consumption. Thus, as referred before, the storage system should balance it, in order not to use non-renewable sources.

Storage

According to the records in the document for January 2019, the maximum power peak registered was 7648 kW (EDA 2019). Thus, considering expressions 1 and 2, it is verified that this island will need a storage system composed by, at least, 177 battery banks.

Flores

According to the most recent data, annual energy production in the 2018 reaches the value of approximately 11,381.60 MWh (EDA 2019). Checking the data for the month of January 2019, it is concluded that approximately 39% of energy production is still provided by fossil

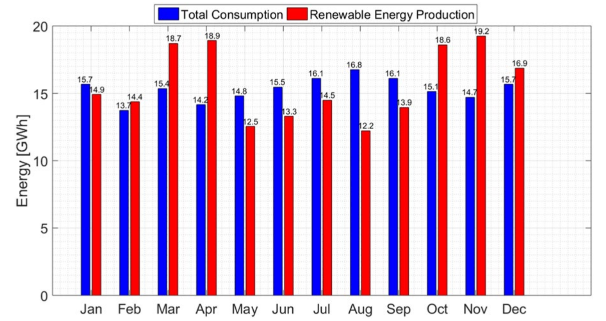


Fig. 10 Estimated total renewable energy emission and monthly consumption for 2018 in Terceira

energy sources (EDA 2019). The production of 443.99 MWh from renewable energy is still to be assured, so the sizing will be based on this value.

Photovoltaic production

Polycrystalline photovoltaic panels It is needed to generate approximately 0.44 GWh of energy from renewable sources and so that a photovoltaic park of 2.8 MW nominal power is projected, as specified in Table 15, from the analysis done on the PVGIS software tool.

Photovoltaic cells cadmium telluride According to the Provisional Annual Estimates of Resident Population, updated on June 15 of 2018 by the Portuguese statistical institute (Instituto Nacional de Estatística—INE), there are 3699 residents in Flores, resulting onto an approximation of 924 houses. Using PVGIS tool, it is possible to obtain a system that will produce a maximum power of approximately 827.9 kW., as presented on Table 16.

Wind production

The projected wind farm will be composed by 3 turbines of 150 kW, characterising a production estimation illustrated in Fig. 18, taking into consideration the wind speed data used before.

General production

Considering the energy production from renewable energies that was projected for this island, it is time to analyse if systems power output can reach the demand necessity. These values, capable to be compared, are detailed in Fig. 19, where it is possible to conclude that on the months of May, June July, August and September this "green" sources cannot produce enough energy to satisfy the energy consumption. Thus, as referred before, the storage system should balance it, in order not to use non-renewable sources.

Table 13 Faial system design data with polycrystalline photovoltaic panels

Number of polycrystalline panels	50,000
Tilt angle	31º
Azimuth angle	3º
Total losses	− 12.8%
Maximum power installed	14,000 kW
Annual irradiance	1600 kWh/m^2
Annual photovoltaic production	19,500 MWh

Table 14 Data for cadmium telluride photovoltaic system sizing for Faial

Number of CdTe panels	59,296
Tilt angle	90º
Maximum power installed	3320.58 kW
Annual photovoltaic production	2710 MWh

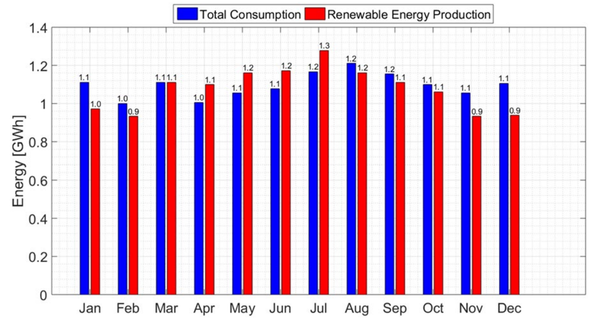


Fig. 11 Estimated total renewable energy emission and monthly consumption for 2018 in Graciosa

Storage

According to the records for the month of January 2019, the maximum peak of Flores was 7648 kW (EDA 2019). Thus, using expressions 1 and 2, it is possible to conclude that this island needs 43 battery banks.

Corvo

According to the most recent data, annual energy production in 2018 is known to have been 1562.75 MWh (EDA 2019). When checking data for January 2019, it is concluded that this island has no renewable energy sources yet (EDA 2019). The energy production is still assured by fossil energy sources. Thus, sizing will be based on the total value of current annual production.

Photovoltaic production

Polycrystalline photovoltaic panels It is needed to generate approximately 1.56 GWh of energy from renewable sources and so that a photovoltaic park of 840 kW nomi-

Table 15 Flores system design data with polycrystalline photovoltaic panels

Number of polycrystalline panels	10,000
Tilt angle	31º
Azimuth angle	1º
Total losses	− 12.8%
Maximum power installed	2 800 kW
Annual irradiance	1560 kWh/m^2
Annual photovoltaic production	3810 MWh

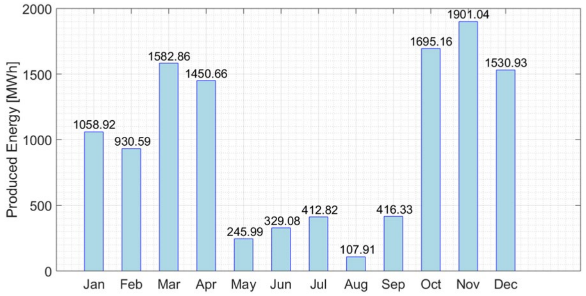


Fig. 12 Annual wind energy production on São Jorge island

nal power is projected, as specified in Table 17, from the analysis done on the PVGIS software tool.

Photovoltaic cells cadmium telluride According to the Provisional Annual Estimates of Resident Population, updated on June 15 of 2018 by the Portuguese statistical institute (Instituto Nacional de Estatística—INE), there are 459 inhabitants in Corvo, resulting in an approximation of 114 houses. Using PVGIS tool, it is possible to obtain a system that will produce a maximum power of approximately 102.14 kW, as illustrated on Table 18.

Wind production

The projected wind farm will be composed by 2 turbines of 150 kW, characterising a production estimation illustrated in Fig. 20, taking into consideration the wind speed data used before.

General production

Considering the energy production from renewable energies that was projected for this island, it is time to analyse if systems power output can reach the demand necessity. These values, capable of being compared, are detailed in Fig. 21, where it is possible to conclude that only on January the renewable energy sources cannot produce enough energy to satisfy the energy consumption. Thus, as referred before, the storage system should balance it, in order not to use non-renewable sources.

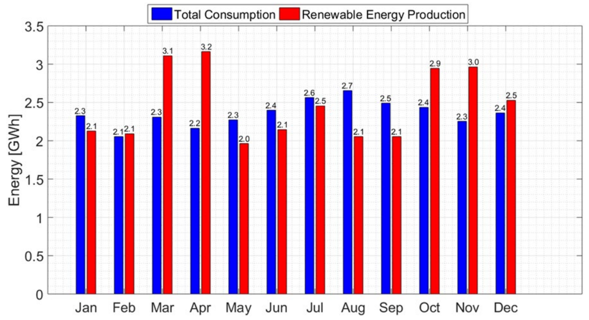


Fig. 13 Estimated total renewable energy emission and monthly consumption for 2018 in São Jorge

Table 16 Data for cadmium telluride photovoltaic system sizing for Flores

Number of CdTe panels	14,784
Tilt angle	90º
Maximum power installed	827.9 kW
Annual photovoltaic production	650 MWh

Storage

According to the records for January 2019, it can be seen that the maximum crow tip recorded was 295 kW (EDA 2019). Thus, taking into account the expressions 1 and 2, it is concluded that this island needs 7 battery banks.

Results

After projecting to the systems, it is needed to evaluate the economic results, considering the costs for each island. In the end, a conclusion will be state what should be the best solution in terms of economic and socio-economic impacts.

Total electricity costs and turnaround time of solutions presented

Considering the region's 3-h tariffs shown in Table 19, it is possible to verify that for 1 day there are 4 rush hours, 10 full-time hours and 10 empty hours. However, it was not possible to obtain the details of the hourly consumption, in order to estimate of the annual consumption at the different tariffs and so that, an estimative is done, since the data are obtained for each month. After that an average price per hour is calculated in order to be used to perform the economic study, resulting a price of 128 €/MWh.

Results analysis

Based on the consumption information presented in Table 20, it is possible to estimate the revenue per year, in this case using the data for 2018.

Table 17 Corvo system design data with polycrystalline photovoltaic panels

Number of polycrystalline panels	3000
Tilt angle	31º
Azimuth angle	4º
Total losses	− 12.6%
Maximum power installed	840 kW
Annual irradiance	1550 kWh/m^2
Annual photovoltaic production	1130 MWh

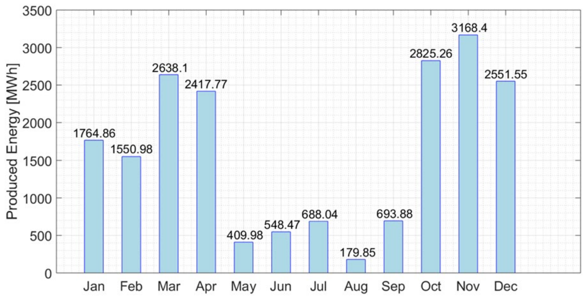


Fig. 14 Annual wind energy production on Pico island

In order to assess the total investment made for each project, it was necessary to calculate the levelised cost of energy LCOE, the net present value (NPV), respectively, from expressions 3 and 4, where I_t is the total investment on the project, i is the inverse of the discount factor, k_a, (in this case the discount factor is 7%, a regular value for this type of projects), cOM is the annual percentage of the operation and maintenance costs, E_a is the annual energetical consume, R is the annual revenue (Curto et al. 2020).

To conclude that the overall project is economical practicable, it is necessary that the LCOE be less than the average price of electricity, meaning that the consumer will pay less than he actually pays (Curto et al. 2020).

$$\text{LCOE} = \frac{I_t(i + \text{cOM})}{E_a} \tag{3}$$

$$\text{NPV} = (R - \text{cOM})k_a - I_t \tag{4}$$

To perform the calculations, regular values for the factors and costs are assumed. First, a discount factor of 7% is assumed and an operation and maintenance cost estimative of 5% of each island projected. On top of that, a cost reserve is considered as 2% of each island investment.

Moreover, for the sizing of each island, it is possible to obtain the payback time, considering the initial investment on the system components, based on expression 5.

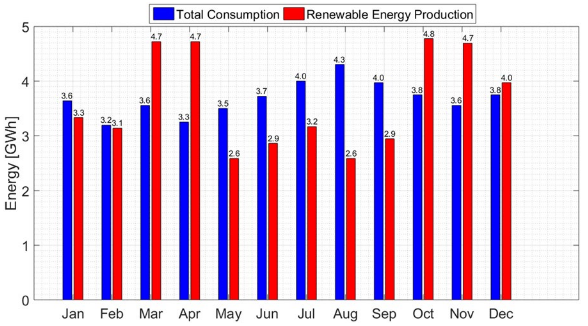


Fig. 15 Estimated total renewable energy emission and monthly consumption for 2018 in Pico

Table 18 Data for cadmium telluride photovoltaic system sizing for Corvo

Number of CdTe panels	1824
Tilt angle	90º
Maximum power installed	102.14 kW
Annual photovoltaic production	81.1 MWh

$$\text{Payback time} = \frac{\text{Total investement}}{\text{Total cost of the electricity per year}} \tag{5}$$

In Table 21 the VAL, LCOE and the payback time are presented, considering only the solution with polycrystalline panels and wind turbines. The reason it is divided into two solutions (separating the CdTe panels from the polycrystalline panels and wind turbines) is because there are islands where its implementation is advantageous and there are other islands where this solution is not so advantageous as expected. Thus, it is possible to conclude independently about each solution, having in Table 22 the results determined to do the economic study.

In these tables the total cost for each solution per island is also presented, it is determined in Table 29 of Appendix 4, where the price of each component is detailed and, according to the previous sizing for each island, the overall cost is calculated.

It can be concluded that all the projects are feasible, because all the NPV are greater than zero. It means that all the initial investment, estimated in Appendix 4, is recovered. Even more, as the LCOE is less than the average estimated electricity cost, the consumers will pay less than what they actually pay.

Socio-economic impacts discussion

After presenting a study on various renewable energy sources, it can be stated that the most obvious positive impacts are environmental ones, although it is also

Table 19 Tariffs in the autonomous region of the Azores—2019 data.nnn Sourced from Precarious (2019)

Active energy application	Tariff type	Energy price (€/kWh)
Medium voltage	Rush hour	0.1251
	Full time	0.1064
	Empty time	0.0733
Low tension	Rush hour	0.1452
	Full time	0.1268
	Empty time	0.0830
Street lighting	Rush hour	0.2237
	Full time	0.1651
	Empty time	0.1000

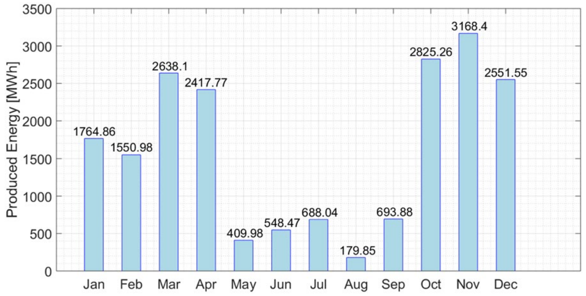


Fig. 16 Annual wind energy production on Pico island

necessary to mention the importance of social and economic impacts for the Azores archipelago.

Emissions associated with raw material processing are also the reason for increased environmental impacts in the freshwater ecotoxicity and eutrophication categories, as well as human toxicity. Recycling metallic resources after decommissioning system components may be an interesting option to reduce the demand for primary metallic resources and thus improve the overall environmental performance of renewable electricity systems (Stenzel et al. 2017).

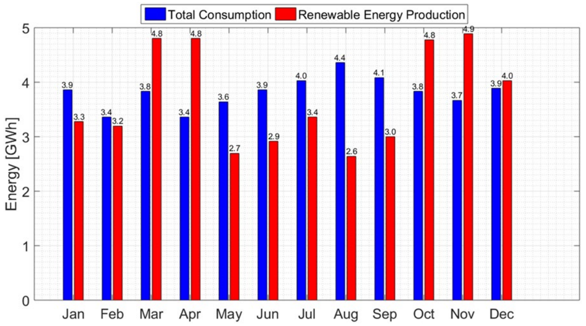


Fig. 17 Estimated total renewable energy emission and monthly consumption for 2018 in Faial

To increase the produced power, CdTe photovoltaic panels will be installed, that imply a considerable and a never saw logistic community programme, because it would be necessary to talk to the residents, show them the project, presenting the pros and cons and change the windows of the houses inhabited by panels. However, due to the high installation costs a huge financial support from governmental institutions is needed. It is important to note that the mentioned costs, presented in Table 29 of Appendix 4, do not include ancillary services to power the plants and substations. On the other hand, it is necessary to state that the composition of CdTe panels can be toxic. It can be a disadvantage to this project (the worst one, in our point of view), since Azores has a huge seismic activity, that under an earthquake event these panels can break or crack and affect human health. However, new techniques to build the panels and to recycle them are emerging, decreasing the risks of human poisoning.

In short, these isolated hybrid systems can bring more benefits than cons. The local and national industry, the economy and the environment benefit as emissions of CO_2 from the diesel plant are reduced with long-term

Table 20 Consumption and total cost of electricity in the Azores in 2018

	Annual consumption [GWh]	Total revenue [M€]	Total investment [M€]
Santa Maria	19.48	2.131	22.4
São Miguel	411.12	43.772	456.1
Terceira	176.45	18.662	158.2
Graciosa	12.72	1.398	4.88
São Jorge	26.80	2.920	39.1
Pico	41.63	4.595	46.4
Faial	43.78	4.735	47.0
Flores	10.86	1.199	6.9
Corvo	1.44	0.161	2.3

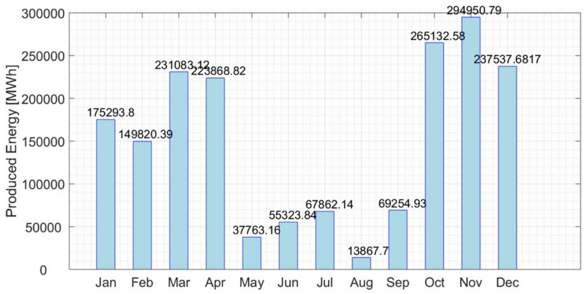


Fig. 18 Annual wind energy production on Flores island

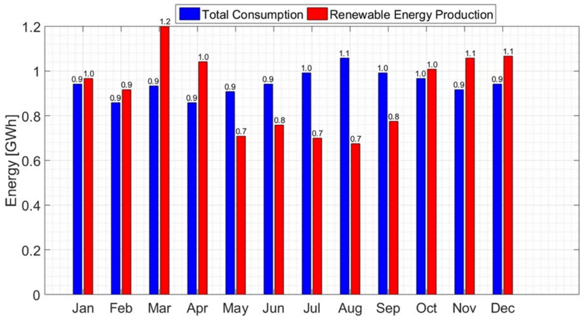


Fig. 19 Estimated total renewable energy emission and monthly consumption for 2018 in Flores

Table 22 Summary of data evaluating the investment made on each island for the second solution

Island	Total costs [M€]	NPV	LCOE [€/MWh]	Return [years]
Santa Maria	9.2	13	68.19	4.32
São Miguel	307.7	156	108.07	7.03
Terceira	66.5	131	54.42	3.56
Graciosa	1.89	13	21.46	1.35
São Jorge	19.9	11	107.21	6.82
Pico	20	29	69.37	4.35
Faial	20.5	30	67.62	4.33
Flores	3	9.7	39.87	2.50
Corvo	0.9	0.8	90	5.59

effects. Regarding the security of energy supply, there are improvements in the medium term.

Conclusions

Energy production from fossil fuels is sometimes not feasible due to environmental problems, high costs and even consistently difficulty in transport to remote places such as islands. Alternatively, there are renewable energies, and this is where the subject of this article fits.

An isolated micro-network responsible for supplying the 9 islands which composed the Azores archipelago has been developed. The objective was to replace the diesel thermoelectric power plant with a hybrid power system consisting of wind turbines, photovoltaic panels and a storage system. This system will help to increase the electrical sustainability of each island and of the whole archipelago. The developed work, which is presented in this article, allows to understand the importance of such environment friendly and renewable-green sources projects, considering important factors such as the growth of electricity consumption, availability of endogenous energy sources and the security of electricity supply, which tend to increase and weaken our actual supply chain and production sources.

Table 21 Summary of data evaluating the investment made on each island for the first solution

Island	Total costs [M€]	NPV [M€]	LCOE [€/MWh]	Return [years]
Santa Maria	13.2	94	97.84	6.19
São Miguel	148.4	315	52.12	3.39
Terceira	91.7	106	75.04	4.91
Graciosa	2.99	12	33.94	2.14
São Jorge	19.2	12	103.44	6.58
Pico	26.4	22	91.57	5.75
Faial	26.5	24	87.41	5.60
Flores	3.9	8.8	51.83	3.25
Corvo	1.4	0.3	140	8.70

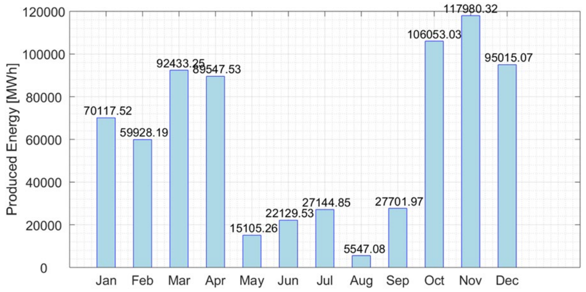


Fig. 20 Annual wind energy production on Corvo island

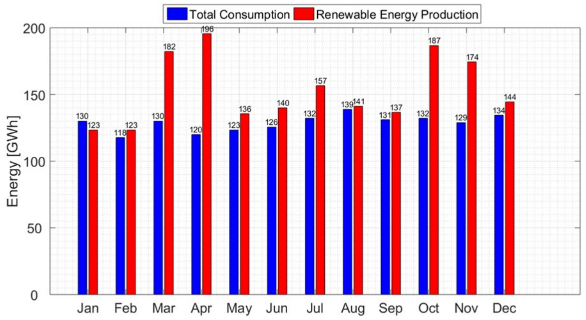


Fig. 21 Estimated total renewable energy emission and monthly consumption for 2018 in Corvo

The designed production system ensures the improvement of each island and of the archipelago sustainability, providing the conditions for local socio-economic development through lower electricity supply costs, greater security of supply and substantially reduced the environmental impact associated to the energy production and our human ecological footprint.

This study allows to estimate the amount of money and the main components needed to create a renewable-sources system to the archipelago of Azores, Portugal. An overall cost of 783.28 million euros is estimated, not only to generate energy from the sun and the wind, but also to store it in battery banks, useful to conserve the surplus, which can be used on the worst production days. Moreover, it is demonstrated that today's renewable technologies are not totally reliable, due to the impossibility to predict natural phenomenon, such as the sun irradiation or the wind velocity. Thus, despite the fact that each island system can ensure the energy production, it is not a good idea to completely stop the energy production due to fossil fuels, but it is demonstrated in this study that it is possible to reduce it considerably, without compromising the energy supply chain, without an investment with no monetary return and creating tremendous socio-economic and environmental advantages.

Acknowledgements

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Authors' contributions

IM was responsible to write the original draft, JPNT and CAFF are her supervisors. JPNT and RAML analysed the results and they were responsible to review and editing the final manuscript. All authors read and approved the final manuscript.

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Competing interests

The authors declare no conflict of interest.

Author details

[1] Department of Electrical and Computer Engineering, Instituto Superior Técnico, 1049-001 Lisbon, Portugal. [2] Instituto de Telecomunicações, 1049-001 Lisbon, Portugal.

Appendix 1

See Tables 23 and 24

Table 23 Electrical characteristics of Vision 60P model panel from SolarWatt. Sourced from Solarwatt-polycrystalline panels 280Wp (2019)

Characteristic	Value
Maximum power (P_{mp})	280 (W_{peak})
Maximum power voltage (V_{mp})	31.30 V
Maximum power current (I_{mp})	9.02 A
Open-circuit voltage (V_{OC})	38.90 V
Short-circuit current (I_{SC})	9.68 A
Efficiency (η)	17%

Table 24 Electrical characteristics of PS-CT-56 (CdTe) panel with 30% of transparency. Sourced from Provisional Annual Estimates of Resident Population (2011)

Characteristic	Value
Maximum power (P_{mp})	56 (W_{peak})
Maximum power voltage (V_{mp})	87 Vs
Maximum power current (I_{mp})	0.64 A
Open-circuit voltage (V_{OC})	116 V
Short-circuit current (I_{SC})	0.68 A
Efficiency (η)	11.9%

Appendix 2

See Tables 25 and 26

Table 25 Specifications of the charge controller with MPPT, BlueSolar model 150/35. Sourced from Bluesolar Charge controller + MPPT 150/35 (2019)

Characteristic	Value
Efficiency (η)	98%
Maximum DC power (P_{max})	1500 W
Output nominal voltage (V_{DC})	36 V
Short-circuit current (I_{SC})	40 A

Table 26 Specifications of the inverter, Sunny Boy 1.5 from SMA. Sourced from SMA Solar Inverters (2019)

Characteristic	Value
Efficiency (η)	97.2%
Maximum DC power (P_{max})	1600 W
Input nominal voltage (V_{DC})	600 V
Short-circuit current (I_{SC})	10 A

Appendix 3

See Tables 27 and 28

Table 27 Specifications of the AC/DC inverter installed on the battery centre. Sourced from SMA Solar Inverters (2019)

Characteristic	Value
Efficiency (η)	98.6%
Output voltage range	634–1000 V
Input voltage range	347–520 V
Nominal power	2515 W
Frequency range	47–53 Hz

Table 28 Specifications of the LG Chem's R800 battery bank. Sourced from LG Chem-Battery Banks (2019)

Characteristic	Value
Nominal voltage	725 V
Nominal capacity	60 Ah
Energy	44.96 kWh
C-Rate	2

Appendix 4

See Table 29

Table 29 Total costs: bill of materials

	Unit price	Santa Maria	São Miguel	Terceira	Graciosa	São Jorge	Pico	Faial	Flores	Corvo
Polycrystalline panels	0.2 €/W	1.68 M€	5 M€	11.2 k€	672 k€	2.35 M€	2.8 M€	2.8 M€	560 k€	168 k€
Turbines	1 M€/MW	4 M€	90 M€	28 M€	–	6 M€	107 M€	10 M€	450 k€	300 k€
MV aluminium cables	20 €/m	60 k€	600 k€	80 k€	–	340 k€	140 k€	160 k€	100 k€	40 k€
Battery banks	275 €/kW	964.39 k€	19.45 k€	8.53 M€	–	1.35 M€	2.09 M€	2.19 M€	531.65 k€	86.55 k€
Inverters (Panels)	500 €	3 M€	10 M€	20 M€	1.2 M€	4.2 M€	5 M€	5 M€	1 M€	300 k€
Charge Controllers + MPPT	370 €	2.22 M€	7.4 M€	14.8 M€	888 k€	3.1 M€	3.7 M€	3.7 k€	740 k€	222 k€
Inverters (Batteries)	120 k€	240 k€	4.8 M€	2.16 M€	–	360 k€	600 k€	600 k€	120 k€	120 k€
Transformers 4.5 MVA	25 k€	50 k€	175 k€	350 k€	25 k€	75 k€	100 k€	100 k€	25 k€	25 k€
Transformers 4 MVA	20 k€	20 k€	440 k€	140 k€	–	20 k€	40 k€	40 k€	–	–
Transformers 3 MVA	15 k€	30 k€	600 k€	270 k€	–	45 k€	75 k€	75 k€	30 k€	15 k€
Transformers 2 MVA	10 k€	–	10 k€	–	–	10 k€	10 k€	10 k€	–	–
Transformers 0.5 MVA	2.5 k€	–	–	–	–	–	–	–	2.5 k€	2.5 k€
TPU S430 Protection	2.65 k€	5.3 k€	5.3 k€	5.3 k€	–	5.3 k€	5.3 k€	5.3 k€	5.3 k€	5.3 k€
TPU D500 Protection	10 k€	20 k€	20 k€	20 k€	–	20 k€	20 k€	20 k€	20 k€	20 k€
Installation Costs	–	614.5 k€	6.93 k€	4.28 k€	139.3 k€	894.2 k€	1.23 M€	1.24 M€	179.3 k€	65.3 k€
Reserve	–	258.1 k€	2.9 M€	1.79 k€	58.5 k€	375.6 k€	516.2 k€	518.7 k€	75.3 k€	27.4 k€
Sub-total	–	13.2 M€	148.4 M€	91.7 M€	2.99 M€	19.2 M€	26.4 M€	26.5 M€	3.9 M€	1.4 M€
PS-CT-56 (CdTe) panels	0.4 €/W	506.42 k€	12.38 M€	5.03 M€	388.51 k€	766.62 k€	1.24 M€	1.33 M€	331.16 k€	40.86 k€
Inverters (panels)	500 €	706.5 k€	17.28 M€	7.02 M€	542 k€	1.07 M€	1.74 M€	1.85 M€	462 k€	57 k€
Charge Controller + MPPT	370 €	522.81 k€	12.78 M€	5.19 M€	401.08 k€	791.4 k€	1.28 M€	1.37 M€	341.88 k€	42.18 k€
Transformers 5 kVA	400 €	565.2 k€	13.82 M€	5.61 M€	433.6 k€	855.6 k€	1.39 M€	1.48 M€	369.6 k€	45.6 k€
Installation Costs	–	381.7 k€	14.36 M€	3.10 M€	88.3 k€	926.3 k€	931.3 k€	956.5 k€	138 k€	38.5 k€
Reserve	–	160.4 k€	6.03 M€	1.30 M€	37.1 k€	389 k€	391.2 k€	401.7 k€	58 k€	16.2 k€
Sub-total	–	9.2 M€	307.7 M€	66.5 M€	1.89 M€	19.9 M€	20 M€	20.5 M€	3 M€	0.9 M€
Total	–	22.4 M€	456.1 M€	158.2 M€	4.88 M€	39.1 M€	46.4 M€	47 M€	6.9 M€	2.3 M€
		783.28 M€								

Appendix 5

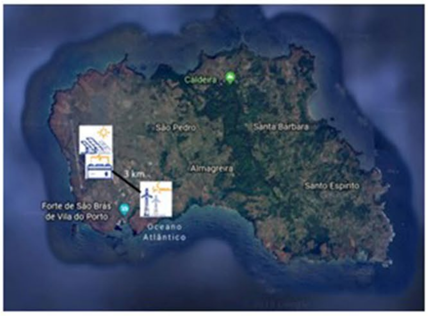

Figure 22.1 Santa Maria Island Hybrid System

Figure 22.2: Terceira Island Hybrid System

Figure 22.3: Graciosa Island Hybrid System

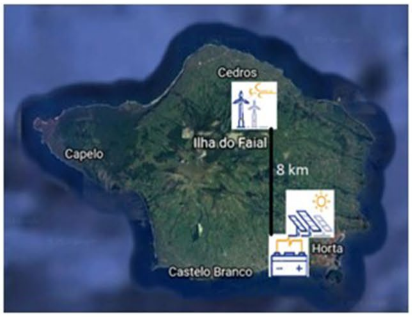

Figure 22.4: Faial Island Hybrid System

Figure 22.5: São Jorge Island Hybrid System

Figure 22.6: Pico Island Hybrid System

Figure 22.7: Corvo Island Hybrid System

Figure 22.8: São Miguel Island Hybrid System

Figure 22.9: Flores Island Hybrid System

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