Renewable and Sustainable Energy Reviews 101 (2019) 221–230

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

# Assessment of Hybrid Renewable Energy Systems to supplied energy to Autonomous Desalination Systems in two islands of the Canary Archipelago

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ARTICLE INFO

*Keywords:*
Renewable energy
Desalination
Reverse osmosis
Hybrid energy systems
Canary Islands

ABSTRACT

In the following work the hybrid systems with base in the renewable energy (RE) are modeled to compare many different design options based on their technical and economic merits. The power requirements will be guaranteed to reverse osmosis Autonomous Desalination Systems (ADS), with a capacity of up to 50 $m^3$ of daily production. The HOMER Hybrid Optimization Model Tool has been used to create optimal designs for these renewable energy systems. The input assumptions in the model were: the electric demand of the desalination plant, the technical specifications of the equipments, as well as the potentials of solar radiation and the wind speeds. Although this study could be applied to different scenarios where an isolated system is found, in this work it has been applied to two islands. In particular these islands have got a relative high wind profile, along with a high a solar radiation profile. Several configurations have been considered by this simulation software and different optimal results attending to the use of renewable energy have been obtained for this particular case. In fact, real data from two particular islands (Lanzarote and Fuerteventura) have been used, although the results could be extent to other similar scenarios.

## 1. Introduction

Water is indispensable for human beings, animals and plants, is the fluid of life. Every day peoples perform a significant variety of activities which involve the use of water. It is needed in all aspects of life, in agriculture, for domestic use and in all industrial activities.

In recent decades, increasingly regions around the world have experienced water shortages. Because of this, many countries have taken the seawater desalination as an alternative non-conventional source of the lack of drinking water, proving to be an economically and sustainable water resource since the end of the past century [1]. The greater percent of these desalinations systems are on arid climate regions, being able to be desert or semi-desert, with good radiation and wind potentials, such as, Persian Gulf region, the Red Sea, Algeria or the North Africa's. On the Iberian Peninsula the higher production of freshwater via desalination are located on the Mediterranean coast and the Balearic Islands. The North Atlantic presents desalination systems in many islands such as Cabo Verde, Madeira and Canary Islands, being this archipelago where will be development the study of the Hybrid Renewable Energy Systems (HRES) to supplied energy to Autonomous Desalination Systems (ADS) for the possible application in others region with similar characteristics [1,2].

The sea water desalination technology is present in Spain since 1964. That year was built in Lanzarote Island the first plant of sea water desalination of Europe. This technology has proven to be one of the most suitable methods for solving water scarcity in regions such as Mediterranean and the Canary Islands, for a notably increased in the efficiency and competitiveness, and for the flexibility water production of its factories [3].

The Canary Islands can be considered pioneer in production of fresh water from seawater in the world, being a referent point at global level for its know-how in the different technologies. Currently, through the desalination is possible to produce around 121 $hm^3$ of fresh water per year in the islands, it represent the 19% of the total water consume required for the archipelago [4,5].

In islands such as Lanzarote and Fuerteventura, desalinated water is practically the only source to supply fresh water to the population and tourism [5]. In the past, during periods of drought, the water in these islands was supplied by marine vessels [6,7]. This share achieves the 99% in Lanzarote, 86% in Fuerteventura, more than 50% in Gran

*Abbreviations:* ADS, Autonomous Desalination Systems; RES, Renewable Energy Systems; RO, Reverse Osmosis; HRES, Hybrid Renewable Energy Systems; HOMER, Hybrid Optimization Model for Electrical Renewable; PV, photovoltaic; WT, wind turbine; DG, diesel generator; dc, direct current; ac, alternating current

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https://doi.org/10.1016/j.rser.2018.11.009
Received 19 February 2018; Received in revised form 12 October 2018; Accepted 4 November 2018

Canaria and the 9.0% in Tenerife [4,7].

The main limitation of desalination is its high energy requirement, and the increase in environmental pollution due to the use of fossil fuels. Around 98% of primary energy consumption in the archipelago comes from imported fuel, which are more expensive due to its remoteness, and obviously an isolated electrical system increases the difficulty of its optimization [7–9].

The energy required to desalt seawater in the public Canary Islands installation can be suppose between 5% and 10% of the total electricity generated by the electrical system of the islands. The most consumed islands are: Lanzarote with a 10% and Fuerteventura with a 6.6% of the total power energy generated. This data show the total dependence of these islands the desalination of seawater [5].

The employ of renewable energy sources (RES) for the production of fresh water from seawater or brackish water results a novel technology, being able to minimize the environmental impact that desalination processes can create due to their huge energy consumptions coming from fossil fuels.

Even though the renewable energies only play an insignificant role in desalination (The amount of desalination systems based on renewable energy is less than 1.0% of the total desalination plants that work whit conventional energy) [1,10], renewable energies are a good option for Autonomous Desalination Systems (ADS), especially in arid and coastal areas where the conventional energy supply can be very expensive or shortage. ADS refer to desalination practices coupled with appropriate renewable energy systems (RES). Renewable energies allow avoiding external dependence of the fossil fuels for the energy generation [10].

In islands or regions suffering from fresh water scarcity, the solar radiation and the wind potential is usually very good and allowing a high use of the renewable energies. For that reason it is safe to say that the use of RES for powering desalination systems is an excellent option [10]. This is the case of Canary Islands, which presents high renewable energies availability such as solar irradiation and wind speed.

In this study the hybrid energy systems with support in the renewable energies are modeled to evaluate different designs according to their economic and technical qualities. The energy needs or power requirements will be guaranteed to the reverse osmosis Autonomous Desalination Systems, with a daily production capacity of up to 50 $m^3$ of water per day. To obtain the optimal designs of renewable energy systems to power the desalination systems the specialized HOMER software [11] has been used. The starting hypotheses in the model were: the technical specifications of the equipment, the electrical requirement of the Reverse Osmosis (RO) plant, as well as the renewable energy potential consisting of solar radiation and wind speed in the islands which is being investigated. Lanzarote and Fuerteventura islands were selected for this study due to their high hydric stress, total dependence of sea water desalination to supply fresh water to population and tourism and, the excellent renewable energy sources in these islands.

Currently, many software's have been developed to evaluate the techno-economic feasibility of the Hybrid Renewable Energy Systems (HRES), to make the best use of the renewable energies and simplify the design of the systems. Some examples of these tools are: TRNSYS, Dymola/Modelica, HOMER, HYBRID 2, RETScreen, Hybrid Designer, etc. [12,13]. Although, several simulation software tools could be used as it is pointed out above, in this paper the HOMER has been chosen, which has been used previously in several similar studies developed in different regions around the world, to determine the possibility of supplanting part of the conventional energy by renewable energies. As an example of this we can mention the following projects: On islands of the Indic Ocean as the Maldives where determine the possibility to supplanting part of the conventional energy by renewable energies [14]. For the biggest island of Turkey the electricity need is analyzed, in order to define the optimal renewable energy hybrid system that can insurance the load [15]. A general view that how it is possible using hybrid energy systems in Newfoundland, Canada can be found in [16,17]. To Bangladesh the potential of renewable energy resources for power generation has been evaluated [18]. For the Arabian Peninsula many analysis for the implementation of the HRES was made, especially in Saudi Arabia [19–23]. In [24,25] a general view of the application of the renewable energy systems under Malaysian conditions can be found. The National Renewable Energy Laboratory (NREL) and the Department of Energy of the United Stated (DOE) working with Hawaii Clean Energy Initiative (HCEI) to assessment the technical-economic contribution of renewable energy in Hawaii, Pacific Ocean [26]. Dalton, Lockington and Baldock in [27] delivers a feasibility analysis of renewable energy supply for a hotel located on Queensland, Australia. In Iraq the software was used to find the renewable system to power a health clinic, and it was justified on technical-economic and humanitarian grounds [28].

The main contribution of this paper will be to propose the "best renewable hybrid system" from the technician-economic point of view, to guarantee the power requirements of the reverse osmosis Autonomous Desalination Systems (ADS), with a daily production capacity of up to 50 $m^3$ of desalinated water in isolated systems with a scenario of relative high wind and solar radiation profile. In fact, two real cases have been dealt with the Lanzarote and Fuertenventura islands in Canary Archipielago. This paper is a first step of researching in the search of Hybrid Renewable Energy Systems (HRES) standard to supply energy to ADS in regions with similar renewables energies condition and water scarcity. Different scenarios with these characteristics could be find nearshore regions of the North Atlantic (Cabo Verde, Madeira, Canary Islands, Morocco, Sahara, Mauritania, etc.).

This paper is structured as follows: first was make a general description about the subject in the introduction section, then, at point two, the demographic and water problems in Canary Islands are explained. The third section discusses the desalination based on Hybrid Renewable Energy Systems. In section four and five the proposed software for the technical and economical modeling is described and the input variables are shown. The analysis of the results is carried out in section six. Finally, the conclusions of the work are presented in the last section.

## 2. Demographic and water problems in Canary Islands

The Canary Islands are an archipelago located on the Atlantic Ocean, near the southern coast of Morocco. It is autonomous community of Spain consisting of seven main islands: El Hierro, La Gomera, La Palma, Tenerife, Gran Canaria, Fuerteventura and Lanzarote (Fig. 1). The population it is around 2,101,924 inhabitants. The number of tourists visiting these islands each year exceeds 13 million, and preserving this tourism industry in a region with lack of drinking water, like Canary Islands, is only possible by desalination of sea water [7,8,29].

In the eastern islands such as Lanzarote and Fuerteventura where the average the desalted water is more than 90% of the fresh water produced and the number of tourists per year exceeds the 6.0 million, the electrical supply of these islands suffers a really high overload. This excess of electrical demand increases the environmental pollution due to the use of fossil fuels. Renewable energies can be basically used in this region as an alternative answer to the dependence on oil and its great polluting power [5,29].

The Autonomous Desalination Systems (ADS) supplied by means of Hybrid Renewable Energy Systems (HRES) can be a good option to produce fresh water on islands similar to Lanzarote and Fuerteventura, which have high availability of renewable energies such as solar irradiation and high wind speeds.

## 3. Desalination with Hybrid Renewable Energy Systems (HRES)

Desalination can be defined as the process of removing dissolved

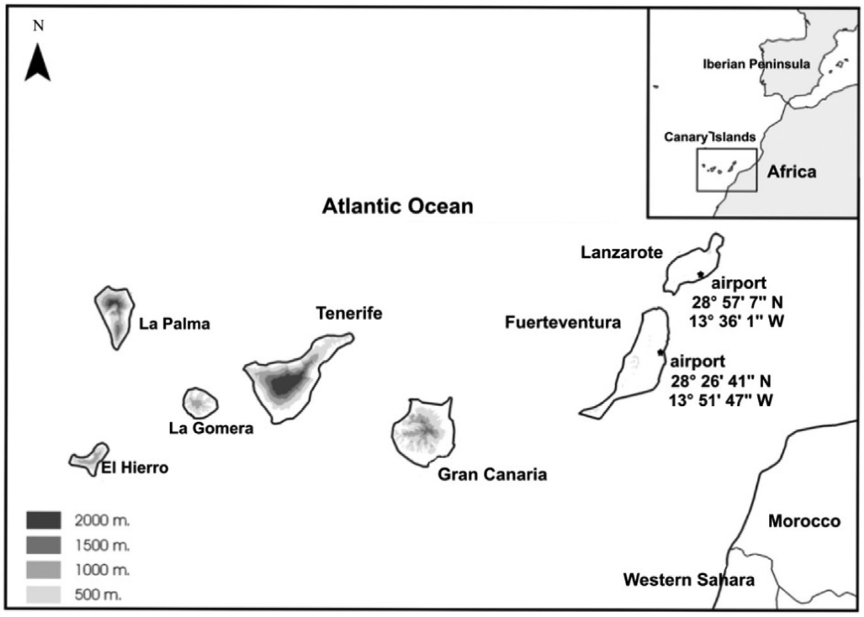


**Fig. 1.** Canary Islands. Lanzarote and Fuerteventura airports.

salts from saline water to make it useful for human consumption, with agricultural, domestic, or industrial purposes. In many countries in the world, the desalination represents an important alternative for the supply of potable water to the population [6].

The Autonomous Desalination Systems (ADS) are basically a desalination system in combination with a Hybrid Renewable Energy System (HRES). The ADS are a possible solution for the regions suffering from water scarcity or, a very good opportunity for rural houses and small hotels in areas with water shortage that want to be more generous with the environment avoiding the pollution for the use of fossil fuels in the desalination [6,10].

Hybrid Renewable Energy System (HRES) combines the renewable energy sources with each other or with conventional energy sources. These systems can work in standalone way or connected to the electrical grid. The relevant characteristic of HRES is to achieve efficiencies higher than a single renewable power source [30,31].

The most useful installations for the seawater or brackish water desalination systems coupled with renewable energies are the Autonomous Desalination Systems (ADS) for small hydric demands, up to 50 $m^3$/day [1,32]. These ADS can supply around 330 inhabitants, with a maximum per capita fresh water of 150 l/day, considering only human consumption and hygiene needs. The approximate electrical energy required is 5.0 kW h/$m^3$ of fresh water produced [1,10,33].

PV and wind energy have proven to be the most successful to build a HRES for powering the ADS with RO systems. In the Hybrid Renewable Energy Systems is necessary to ensure a continuous power flow, storing excess energy from the renewable sources in batteries or, inject the excess of electricity in the electrical grid. This problem is solved with control mechanisms that manage the intermittent nature of these energy sources [34].

## 4. Input variables to the computer model

In the present work, the proposition, selection, and sizing of the components of hybrids renewable power systems has been done using the specialized HOMER software (Hybrid Optimization Model for Electrical Renewable). The objective of this computer model is to help in the design and implementation of Hybrid Renewable Energy Systems. The principal tasks that can be developing by this software are: simulation, optimization, and sensitivity analysis. Within these tasks, the software models and optimizes the total cost of installation and operation of the system during its period of useful life, according to its technical and economic advantages [35].

The Hybrid Renewable Energy System (HRES) simulated in the present investigation consists of different combinations of photovoltaic (PV) modules and different wind turbines supplemented with battery banks. In addition, it would be possible to include diesel generators if necessary, as shown in Fig. 2.

The objective of this HRES is supplied the necessary energy to provide power to a small autonomous reverse osmosis desalination systems, with a production up to 50 $m^3$/day. The energy requirement of a particular desalination process is also one of the major factors affecting its cost. The energy requirements assumed are 5.0 kW h/$m^3$.

### 4.1. Electrical loads

A small RO desalination system with a capacity of 50 $m^3$/day, may consume around 250 kW h/day, with an average demand of 10.5 kW and a peak demand of nearly 16.0 kW [11]. The monthly average of electric load variation of the RO desalination systems is shown in Fig. 3.

The highest demand for electricity takes place in August, and the lowest one in February.

### 4.2. Solar radiation in Lanzarote and Fuerteventura Islands

The monthly solar radiation values of Lanzarote and Fuerteventura are obtained with the HOMER software from NASA. The coordinates for

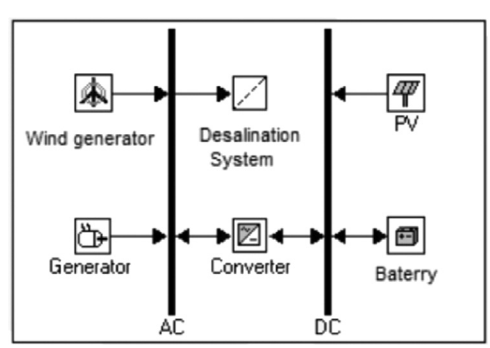


**Fig. 2.** HOMER model of the Hybrid Renewable Energy System (HRES).

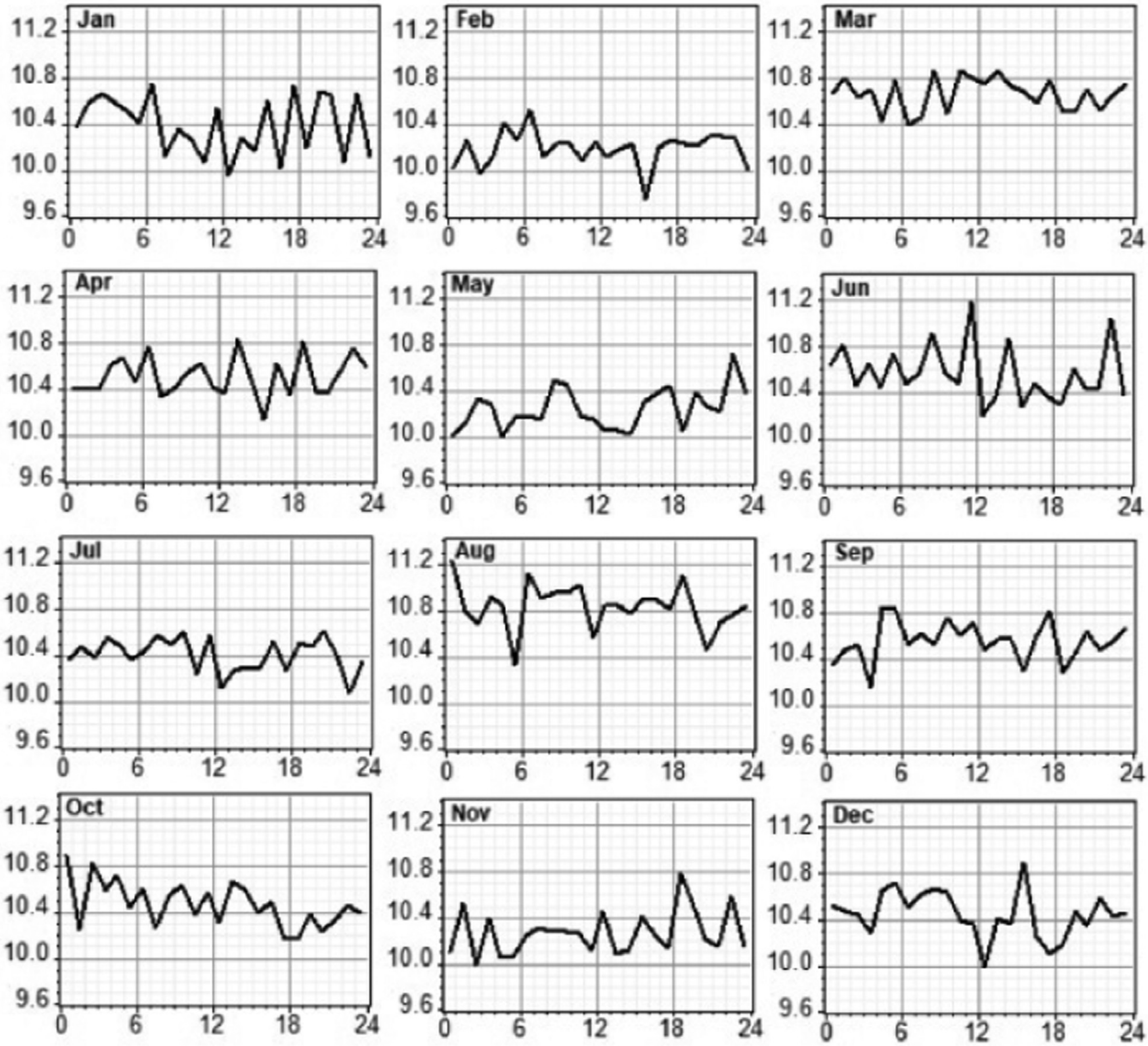


**Fig. 3.** Monthly average of electric load variation (kW).

Lanzarote are: 28°57'7" North latitude and 13°36'1" West longitude. The Fuerteventura coordinates are: latitude 28°26'41" North and longitude 13°51'47" West. HOMER uses the Graham algorithm to synthesize solar radiation values for each hours of the year [15].

Monthly average values of solar data from Lanzarote and Fuerteventura are shown in Figs. 4 and 5.

The average solar radiation data are very similar for both islands, Lanzarote and Fuerteventura.

### 4.3. Wind speeds in Lanzarote and Fuerteventura Islands

A monthly average wind dataset from Lanzarote airport (28°57'7" N to 13°36'1" W) and Fuerteventura airport 28°26'41" N and 13°51'47" W was collected, on 10 m over the earth level in the airports locations (Fig. 1). This is a dataset for more than 40 year and indicates that annual average wind speed in Lanzarote and Fuerteventura airports is approximately 6.28 m/s and 5.82 m/s, respectively. For these data, the Weibull distribution for both places is shown in Figs. 6 and 7.

The Weibull probability density function is one of the most commonly used statistical distribution in wind data analysis. The Weibull distribution is based on two parameters: the shape factor ($k$), and the scale factor ($c$). The Weibull probability density function can be calculated as [13,16,18,36,37]:

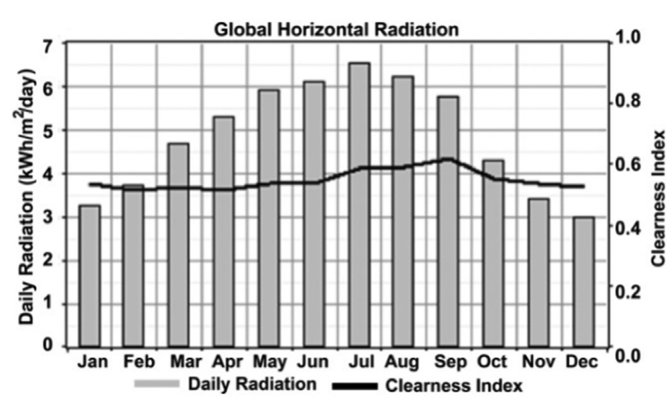


**Fig. 4.** Average solar radiation data for Lanzarote.

$$f_v = \left(\frac{k}{c}\right)\cdot\left(\frac{v}{c}\right)^{k-1}\cdot exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{1}$$

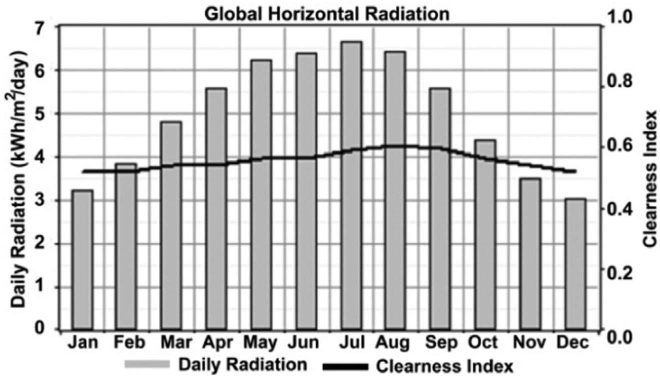


**Fig. 5.** Average solar radiation data for Fuerteventura.

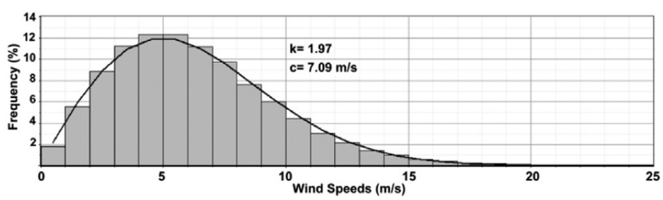


**Fig. 6.** Weibull distribution of wind speeds (m/s). Lanzarote.

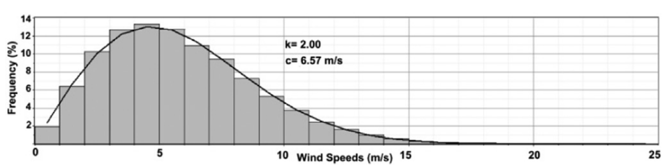


**Fig. 7.** Weibull distribution of wind speeds (m/s). Fuerteventura.

In HOMER, the speed at any height can be calculated using the hypothesis of a neuter atmosphere and is given by the expression [36,37].

$$\frac{v_1}{v_2} = \left(\frac{h_1}{h_2}\right)^{\alpha} \tag{2}$$

Where, $v_1$ is the real wind speed measured at a height of $z_1$; $v_2$ the wind speed at the required or extrapolated height $z_2$. The exponent α depends on the surface roughness ($z_o$).

### 4.4. Photovoltaic system

The PV array is modeled in HOMER independently of the voltage and temperature to which it is exposed. The software assumes that direct current (dc) output of the photovoltaic (PV) panel is linearly proportion to the incident global radiation upon it [35].

The energy produced by the PV array is determinate using the following equation:

$$P_{PV} = f_{PV} \bullet Y_{PV} \bullet \left(\frac{I_T}{I_s}\right) \tag{3}$$

In this equation $f_{PV}$ is the debating factor, $Y_{PV}$ is considered as the total installed capacity of the PV array (kW), $I_T$ is the incident global radiation (kW/m$^2$) and $I_s$ is the amount of radiation used to rate the capacity of the PV array, equal to 1.0 kW/m$^2$ [35].

The Initial Capital Cost *($ICC_{PV}$)* and Replacement Costs ($RC_{PV}$) for the photovoltaic panels considered in HOMER are the same for both, 7000 dollar per installed kilowatts. This cost includes shipping, tariffs, installation, and dealer mark-ups. The PV size considered for the system can vary between (0 ÷ 50) kW (Table 1). The lifetime of the PV arrays is taken as 20 years and no tracking system is included in the PV system.

### 4.5. Wind turbine system

As indicated by [35,36], in the wind generator is applied the standard procedure to model this kind of devices, assuming that the kinetic energy of the wind converts into electricity according to a particular power curve.

HOMER calculate the average wind turbine power, ($P_{wind}$) or energy output, based on Weibull probability density function can be expressed as follows:

$$P_{wind} = \frac{1}{2}\tau \bullet \rho \bullet C_p \bullet A \bullet \sum_{x=1}^{j} f_{(v)} \bullet v_x^3 \tag{4}$$

where *Cp* is the capacity factor of the wind generator, $\tau$ is the time analyzed (one year), *v* is the wind speed, *f(v)* is de Weibull distribution and *j* is the class number of the data [36].

Three wind turbines (WT) were considered for the simulations, with 2.5 kW, 10 kW and 30 kW of nominal power. The power curves of these wind turbines are shown in Figs. 8–10 respectively. The types of wind turbines used can be acquired in Canary Islands and they appear in HOMER's database. The characteristics of the selected wind turbines are shown in Table 2.

The Initial Capital Cost *($ICC_{wind}$)* and Replacement Costs ($RC_{wind}$) for the wind turbines in HOMER are shown in Table 1.

### 4.6. Generator

A generator is the combination of a fuel engine with an electric generator to produce electricity, in many cases is possible used the heat as a by-product. In the HOMER software is possible to model a wide variety of generators, including the traditional internal combustion engine generators, fuel cells, micro-turbines, etc. [35].

The generator used in this study was an internal combustion engine. The fuel used was diesel, with a price of 0.90 $/liter. Table 1 shows all the assumed properties in the system, including the size considered for the system that might vary between 0 and 40 kW.

The dispatch strategies used per HOMER will be “load-following”. When is used the load-following strategy, an electric generator produces only a sufficient amount of energy to serve the load, never produce energy to charge the battery bank [35].

### 4.7. Converter

An electric converter is a device that converts electric energy from direct current (dc) to alternating current (ac), or just changing the frequency or voltage. The process carried out in the converter is called inversion. HOMER can model different sizes of converters, rotary converters or solid- state [35].

The sizes of converters that are taken in to account in this model vary between 0 and 30 kW. Lifetime of a unit is considered to be 20 years with an efficiency of 90% (Table 1).

### 4.8. Battery bank

The battery bank is a collection of one or more individual batteries that store energy in electrochemical form [38]. The battery is modeled for HOMER software as equipment that can store a quantity of direct current (dc) at fixed round-trip energy efficiency. The software checks when it is necessary to change the battery, considering the number of charge and discharge cycles through it [35].

The batteries included in this analysis are a commercial lead-acid battery model which is available for 360 A h in the versions of 6.0 V and 1075 kW h. The battery bank may contain a number of batteries between 0 and 240 units. The economical characteristics appear in Table 1.

**Table 1**
System component considered.

| Components | Size | I. Capital Cost (*ICC*)$ | Replacement Cost (*RC*)$ | O&M Cost ($) | Lifetime |
|---|---|---|---|---|---|
| PV panels | 0–50 kW | 7000 $/kW | 7000 $/kW | 0.015*$ICC_{PV}$ | 20 year |
| Wind Turbines | WT – 2.5 kW | 14,950 $/unit | 11,000 $/unit | 0.025*$ICC_{Wind}$ | 25 year |
| | WT – 10 kW | 48,000 $/unit | 34,000 $/unit | | |
| | WT– 30 kW | 130,000 $/unit | 80,000 $/unit | | |
| Batteries (360 A h/6 V) | (0–240) batteries. | 350 $/unit | 350 $/unit | 8.00 $/year | 10 year |
| Generator | 0–40 kW | 700 $/kW | 700 $/kW | 0.40 $/hour | 15,000 h |
| Converter | 0–30 kW | 1000 $/kW | 1000 $/kW | 50 $/year | 20 year |

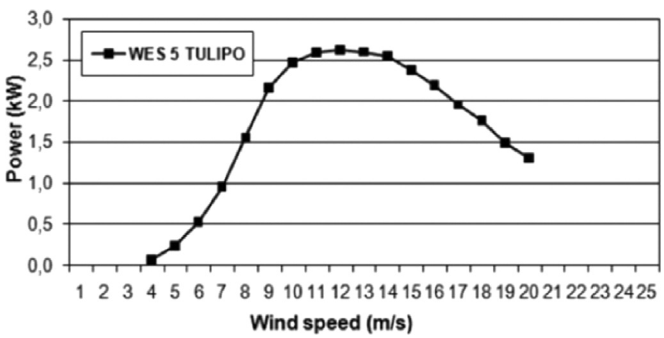


**Fig. 8.** Power curve of 2.5 kW wind turbine.

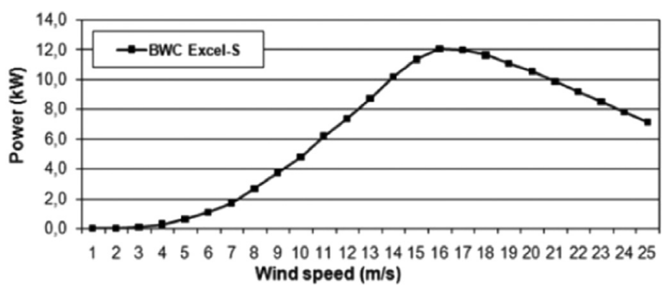


**Fig. 9.** Power curve of 10 kW wind turbine.

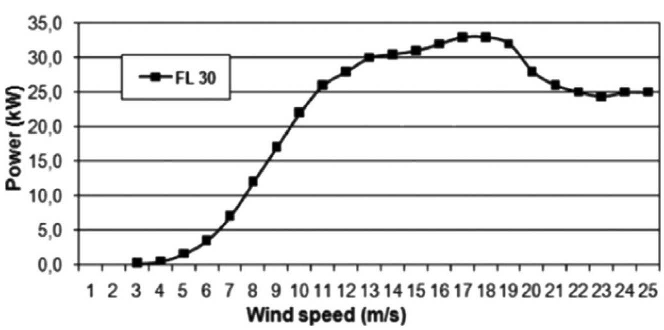


**Fig. 10.** Power curve of 30 kW wind turbine.

**Table 2**
Main characteristics of the 2.5 kW, 10 kW and 30 kW wind turbines.

| Technical parameter | WES 5 TULIPO | BWC Excel- S | FL 30 |
|---|---|---|---|
| Nominal Power (kW). | 2.5 | 10 | 30 |
| Hub height (m) | 12.25 | 18 | 18 |
| Rotor diameter (m). | 5.0 | 7.0 | 13 |
| Cut-in wind speed (m/s) | 3.0 | 2.5 | 3.0 |
| Cut-out wind speed (m/s) | 20 | – | 25 |

## 5. Economic analysis

Conventional and renewable energies have different costs; and renewable energies are usually more expensive. For this reason, the governments of many countries give subsidies for the development of renewable sources of electricity, such as wind turbines, solar farms, hydroelectric and geothermal plants.

The conventional generation sources (thermoelectric power plant, fuel generator, etc.) normally have low initial capital costs and the operating costs tend to be high. In the renewable energies the initial capital costs is high, but the operating costs is low respect to conventional energies. HOMER, in the optimization process compares the economics characteristics for renewable and conventional energies sources, taking into account a wide range of configurations in order to propose the most economical systems [35].

### 5.1. Net Present Cost (NPC)

As reported by Demiroren and Yilmaz in [15], HOMER uses the total Net Present Cost (*NPC*) to represent the cost of installation and operation of any system ($). The *NPC* includes all costs and income within the life of the project (20 years). The *NPC* is determined using the following equation:

$$NPC = \frac{C_{a,t}}{CRF(i, N)} \tag{5}$$

In this expression $C_{a,t}$ is the total annualized cost ($/year), *CRF* is capital recovery factor, given by Eq. (6).

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{6}$$

Where $i$ is the annual real interest rate (%) and $N$ is the lifetime of the project (years).

### 5.2. Levelized Cost of Energy (COE)

The Levelized Cost of Energy (*COE*) is defined by HOMER as the average (cost/kW h) of useful electrical energy produced by the system. The software uses the following equation to calculate the *COE* [15].

$$COE = \frac{C_{a,t}}{E_{pr,AC} + E_{pr,DC} + E_{gr,sales}} \tag{7}$$

In this equation: $C_{a,t}$ is total annualized cost ($/year), $E_{pr,AC}$ is ac primary load served (kW h/year), $E_{pr,DC}$ is dc primary load served (kW h/year), $E_{gr,sales}$ is total grid sales (kW h/year). This study does not consider any sale of energy to the grid.

## 6. Results and discussions

One of the main difficulties that come with the design of Hybrid Renewable Energy Systems (HRES) to supply the Autonomous Desalination Systems (ADS) is the large number of variables to be considered, including the size of each of the components. HOMER helps

**Table 3**
Technical simulation results.

| Island | PV (kW) | WT (number), (Type) | Battery (number) | Converter (kW) | DG(kW) | Diesel (L) | GEN (h) | Ren. Frac.(%) |
|---|---|---|---|---|---|---|---|---|
| **Lanzarote** | 5.0 | 1 – (FL30) | 160 | 15 | 10 | 2029 | 743 | 96 |
| **Fuerteventura** | 5.0 | 1 – (FL30) | 200 | 15 | 15 | 3822 | 1152 | 92 |

**Table 4**
Economical simulation results.

| Island | Initial Capital ($) | Operating Cost ($/year) | Total NPC ($) | COE ($/kW h) |
|---|---|---|---|---|
| **Lanzarote** | 243,000 | 17,993 | 473,013 | 0.404 |
| **Fuerteventura** | 260,500 | 23,448 | 560,247 | 0.478 |

in this task, since the software will simulate several different system configurations, ranks those that are viable using the Total Net Present Cost (*NPC*), discards the non-viable ones, and shows the feasible one with the lowest *NPC* as the optimal system configuration.

### 6.1. Optimization results

Tables 3, 4 show the technical and economical simulation results of HOMER, for the HRES with total generation approximated of 250 kW h/day to supply an ADS with a capacity up to 50 $m^3$/day. The energy requirement assumed for the RO processes is 5.0 kW h/$m^3$ of desalted water. The dispatch strategy used per HOMER was "load-following".

#### 6.1.1. Lanzarote

The most economic Hybrid Renewable Energy Systems (HRES) to supply to the Autonomous Desalination Systems (ADS) obtained for HOMER to the Lanzarote Island were PV – wind turbine (WT) – diesel generator (DG) hybrid system. This HRES is composed for: one wind turbine FL-30 of 30 kW of nominal power, 5.0 kW of PV panels and a diesel generator (DG) of 10 kW of nominal power, all this system is supplemented with 160 batteries of 360 A h (Table 3). The economical simulation results shown in Table 4 represent a Total Net Present Cost (*NPC*) of the system equal to 473,013 $, and a Cost of Energy (*COE*) value equal to 0.404 $/kW h.

Fig. 11 shows the monthly average electric production. In this case, the energy produced from the renewable energy system cover the 96% of the annual electrical production, 90% from wind turbine, 6.0% from PV system and 4.0% from diesel generator.

In the summer month occurs the major penetration of the renewable energy in the total electrical production.

#### 6.1.2. Fuerteventura

In agreement with Fuerteventura scenarios (Table 3), the most economic HRES found is PV – WT – DG hybrid system. The electrical generator elements that compose this system are: one wind turbine FL-30 of 30 kW of nominal power, 5.0 kW of PV panels, a diesel generator (DG) of 15 kW of nominal power and a battery bank of 200 batteries, 360 A h. The *NPC* of the system is found as 560,247 $ and the Cost of

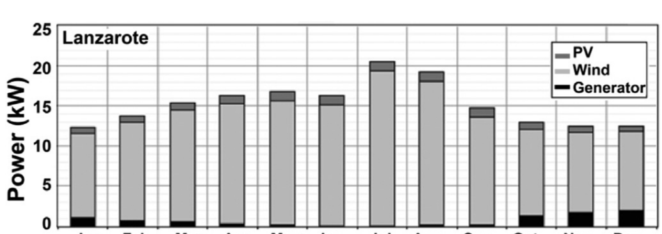


**Fig. 11.** Monthly average electric production. Lanzarote.

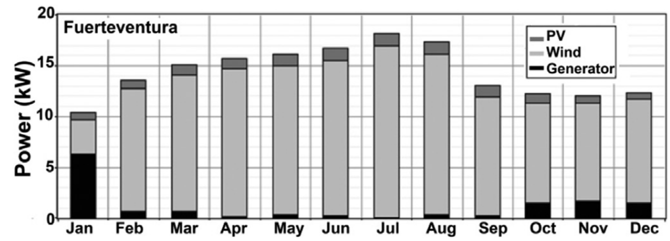


**Fig. 12.** Monthly average electricity production. Fuerteventura.

Energy is 0.478 $/kW h (Table 4).

In this particular case, the monthly average electric production for Fuerteventura is shown in Fig. 12. Renewable electric power covers up to 92% of the annual electricity production.

Of this energy, the 85% is produced per wind turbine and 7.0% from PV panels. The rest of the annual energy production (8.0%) is supplied by a diesel generator with a nominal power of 15 kW.

On the island of Fuerteventura, January is the month with the lowest rate of renewable energy throughout the year, only 36% of the total energy production in the month. In the summer months occurs the major penetration of the renewable energy in the total electrical production.

The optimized HRES to supply the ADS obtained for HOMER to the Lanzarote and Fuerteventura Islands are rather approximated. They present similar renewable energy systems, one wind turbine FL-30 of 30 kW of nominal power and 5.0 kW of PV panels. The differences are shown in the diesel generator and the battery bank. The nominal power for the generators of Lanzarote and Fuerteventura systems is 10 and 15 kW, respectively. Finally, and regarding the storage capacity of direct current, Lanzarote would have a battery bank consisting of 160 units while the battery bank of Fuerteventura would be composed by 200 units. As can be seen, there is not much difference between both systems.

### 6.2. Gas emissions

Gas emissions due to combustion pollute the environment and affect humans, animals and plants, which increases climate change.

The hybrid energy systems proposed to supply the ADS in Lanzarote and Fuerteventura can bring down the quantity of the total pollutants until 164,902 kg per year, approximately 84,872.15 kg/year and 80,029.88 kg/year, respectively. The concentrations of various constituents of pollutants like $CO_2$, CO, $SO_2$, etc. are summarized in Tables 5, 6.

The pollution avoided for the Hybrid Renewable Energy Systems in

**Table 5**
Pollutants avoided by the HRES in Lanzarote.

| Pollutant | Emissions (kg/yr) |
|---|---|
| Carbon dioxide | 82,651 |
| Carbon monoxide | 203.8 |
| Unburned hydrocarbons | 22.64 |
| Particulate matter | 15.41 |
| Sulfur dioxide | 159.3 |
| Nitrogen oxides | 1820 |
| **Total** | 84,872.15 |

**Table 6**
Pollutants avoided by the HRES in Fuerteventura.

| Pollutant | Emissions (kg/yr) |
|---|---|
| Carbon dioxide | 77,929 |
| Carbon monoxide | 192.2 |
| Unburned hydrocarbons | 21.35 |
| Particulate matter | 14.53 |
| Sulfur dioxide | 156.8 |
| Nitrogen oxides | 1716 |
| **Total** | 80,029.88 |

Lanzarote are greater than HRES in Fuerteventura, because the renewable energy penetration is major in the first one, 96%, respect to 92% in the second one. As can be seen, the achieved results in both cases show a considerable improvement in the decreasing of the pollution degree. Because of that reason, it could be concluded that it would be convenient to extend this strategy to other similar scenarios in other geographical locations. Furthermore, this ecological feature is very desirable in these environments where nature conservation should be an essential objective for human being. On the other hand, it is important to stress that this kind of strategies contribute to obtaining the $CO_2$ bonus, which as is well known is very interesting from the economic point of view.

### 6.3. Sensitivity analysis

In both islands, a sensitivity analysis was performed to study the effects of the average annual variation of wind speed and load demand, although HOMER software took in to account the variables such as annual solar irradiation or diesel prices. Some results of that analysis are shown in Figs. 13 and 14.

The computer model simulates all possible systems for each of the sensitivity values. A time series simulation for each possible system is made for one year period. HOMER defines hybrid systems capable of covering the load required for the RO desalination systems. The software ranks the feasible systems according to the increase of the *COP* and discards the infeasible systems.

The optimization results displayed in graphical above show four types of optimal systems, according to different sensitivity parameters in Lanzarote Island. The system composed of PV panels, diesel generators (DG) and batteries (white color), is the hybrid system proposed for HOMER to annual average wind speed less than 4.3 m/s and low load demand. The graphic grid area represents the systems composed of wind turbines (WT), photovoltaic panels (PV), diesel generator (DG)

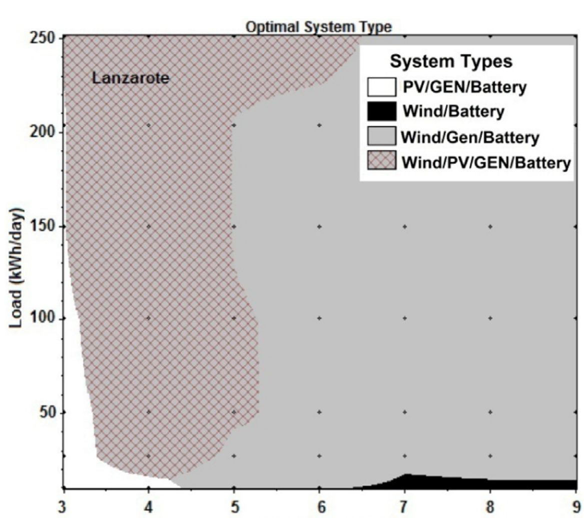


**Fig. 13.** Result of sensitivity analysis for Lanzarote.

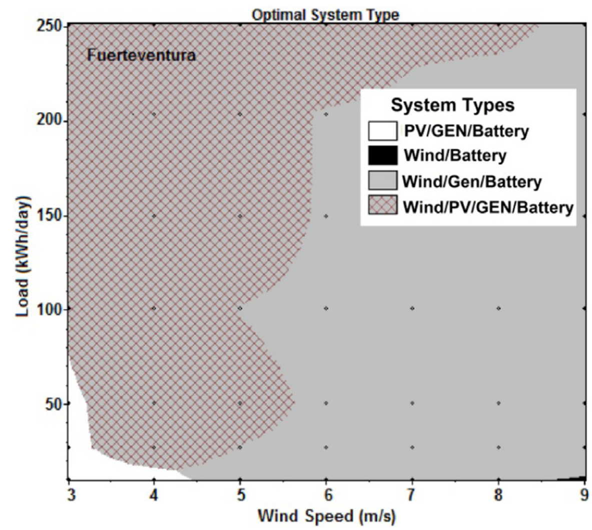


**Fig. 14.** Result of sensitivity analysis for Fuerteventura.

and a battery bank. This is the proposal of HOMER for the case of a high demand for electric charge and a wind speed of 3.5 m/s up to or 6.5 m/s. The gray color zone represents the systems made up of WT, DG and a battery bank. These systems are suitable for an annual average wind speed greater than 6.5 m/s and high load demand. The system formed by wind turbine and battery bank becomes feasible only above an annual average wind speed of 6.5 m/s and low load demand (black color).

Fig. 14 represents a HOMER sensitivity scenario for the island of Fuerteventura. The graphical zone with white color represents the systems composed for PV panels, diesel generators (DG) and a battery bank. This system comes into the picture only when wind resource is very limited and there are low load demands. The system composed for PV panels, wind turbines (WT), diesel generators (DG) and batteries (grid area), is the hybrid system proposed by HOMER for an annual average wind speed between 3.0 m/s and 5.8 m/s, and for loads greater than 80 kW h/day. This system is also useful for high wind speeds and high load demands. The graphical zone with gray color represents the systems composed for WT, diesel generators and a battery bank. This is the HOMER proposition when the annual average wind speed is major than 5.8 m/s. Sometimes, this proposal could be useful for low load demands and wind speed major than 4.3 m/s. An important observation is that a WT-battery bank system may not be useful for the conditions of these islands.

## 7. Conclusion

This research analyzed the techno-economic feasibility of the Hybrid Renewable Energy Systems (PV-wind- generator) to guarantee the energy requirements for the Autonomous Desalination Systems (ADS), with a daily production capacity of up to 50 $m^3$of water per day in an environment with a relative high wind and solar radiation profile. Currently, these renewable energy systems are not cost-competitive compared to conventional fossil fuel, but could be a very good opportunity for isolated places like small towns, rural houses or small hotels, in areas with water scarcity that want to be more generous with the environment, avoiding the pollution by the use of fossil fuels in the desalination of water. In this paper, the study has focused on two real scenarios (Lanzarote and Fuerteventura islands). Different conclusions could be made from this particular analysis.

The most economic Hybrid Renewable Energy System (HRES) to supply the Autonomous Desalination Systems (ADS) for a production up to 50 $m^3$of desalinated water per day on the island of Lanzarote, with a Cost of Energy (*COE*) value equal to 0.404 $/kW h is PV – wind turbine (WT) – diesel generator (DG) hybrid system. This HRES is composed for one wind turbine (WT) FL-30 of 30 kW of nominal power, 5.0 kW of PV panels and a diesel generator (DG) of 10 kW of nominal power, supplemented with 160 batteries of 360 A h. The energy produced from this renewable energy system covers the 96% of the annual electrical production.

According to Fuerteventura renewable energy source, the most economic HRES found is PV – WT – DG hybrid system. The elements that compose this system are one wind turbine (WT) FL-30 of 30 kW of nominal power, 5.0 kW of PV panels, a diesel generator (DG) of 15 kW of nominal power and a battery bank of 200 batteries of 360 A h. The *COE* of the system is found as 0.478 $/kW h. The electrical energy obtained from renewable energy reaches up to 92% of the annual electrical production.

The optimized HRES to supply the ADS obtained for HOMER for the Lanzarote and Fuerteventura islands are rather approximated. They present similar renewable energy systems, one wind turbine FL-30 of 30 kW of nominal power and 5.0 kW of PV panels. The nominal power for the generators of Lanzarote and Fuerteventura systems is 10 and 15 kW, respectively. The battery banks for Lanzarote system would have 160 batteries and the Fuerteventura system would have 200 batteries.

Taking into account all results pointed out above, it is possible propose a standard HRES to supply the energy Autonomous Desalination Systems (ADS) from the technical and economic point of view. These results could be extended to so many areas where conditions of wind and solar radiation are similar. The proposed system is: one wind turbine of 30 kW of nominal power, 5.0 kW of PV panels, 200 batteries (6.0 V, 360 A h) and a generator of nominal power of 15 kW. For regions with similar characteristics of wind velocity and solar radiation, as the islands taken into account for this study, the renewable energy penetration in this system could be around of 92%.

The proposed HRES in this paper to supply the ADS bring down the quantity of the total pollutants to 164,902 kg per year, approximately. As can be seen, a significant reduction of pollutants is achieved. This is an additional advantage to apply this proposal in similar scenarios. Finally it is important to say that the optimization results obtained for HOMER, according to different sensitivity parameters, are four in total. The hybrids systems proposed for HOMER can be composed for: (PV, DG and batteries), (PV, WT, DG and batteries), (WT, DG and batteries) and (WT-batteries). This analysis shows that in spite of a wide variability of load and wind conditions, a solution based on renewable energies is feasible.

The achieved results have shown as the developed strategies could be convenient in many similar scenarios. For future work would be necessary to better adapt the design strategies to other cases. In this sense, new strategies based on Artificial Intelligent Techniques could be very useful to extend the obtained results to other geographical areas, taking into account a greater variability of the parameters for finding out the optimal configuration for each case and include other variables that can affect the system.

## Acknowledgements

“This research has been co-funded by FEDER funds, INTERREG MAC 2014-2020 Programme of the European Union, within the DESAL + Project (MAC/1.1a/094).

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