Large-scale optimal integration of wind and solar photovoltaic power in water-energy systems on islands

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Abstract

This paper presents a new method based on the Smart Energy System concept to link the water infrastructure and the energy system of an island. The principal aim of this study is to determine whether this new method can increase the contribution of renewables (wind power and photovoltaic) to the primary energy supply of the island. The method considers water production and treatment systems as flexible loads and explores a wide range of possible water supply infrastructures and PV/wind power combinations in the search for an optimal energy-water configuration. The final optimal solution is based on a balance between energy fuel needs and energy excesses, CO_2 emissions, oil consumption, minimization of total annual costs and maximization of the renewable contribution. The proposed method increased the contribution of renewables from 5.14% to 24.6%. This corresponds to, on average, over 35% of the hourly electricity demand throughout 2018 being covered by renewables, against the current 6.6%.

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The study reveals that wind technology integration is of fundamental importance for renewable exploitation in insular water-energy systems, with wind energy contributing more than 70% of the renewable participation in this case study.

Keywords: Renewable energy integration on islands; Energy-water planning; Pareto multi-objective optimization; Energy-water synergies; smart energy-water system approach.

Nomenclature

EEP	Excess electricity production
ERDF	European Regional Development Fund
HRES	Hybrid renewable energy sources
ISTAC	Spanish initials: Canary Islands Institute of Statistics
ip(i,j,k,m)	Vector to save intersection points (Fig. 4).
MAE	Mean absolute error
MAPE	Mean absolute percentage error
O&M	Operation and Maintenance
PES	Primary energy supply
PHS	Pumped-hydroelectric storage
PV	Solar photovoltaic
R^2	R-Squared measure of agreement
REE	Spanish initials of the TSO in Spain: Red Eléctrica de España, S.A.U.
RES	Renewable energy sources
RO	Reverse osmosis
SCs	Synchronous compensators
SSE	Sum of squared errors

SSR	Sum of squared regression
SST	Sum of squared total
TSO	Transmission system operator
x_1	Water storage capacity. Decision variable (Fig. 4).
x_2	Water production capacity. Decision variable (Fig. 4).
x_3	Wind power installed in the system (in % to cover the total electricity demand with wind power). Decision variable (Fig. 4).
x_4	PV power installed in the system (in % to cover the total electricity demand with PV power). Decision variable (Fig. 4).
x_{11}	Current water storage capacity installed in the reference validated scenario. Lower constraint of x_1 (Fig. 4)
x_{12}	Current water production capacity installed in the reference validated scenario. Lower constraint of x_2 (Fig. 4)
x_{13}	Current wind power installed in the reference validated scenario (in % to cover the total electricity demand with wind power). Lower constraint of x_3 (Fig. 4)
x_{14}	Current PV power installed in the reference validated scenario (in % to cover the total electricity demand with PV power). Lower constraint of x_4 (Fig. 4)
x_{I1}	Maximum feasible water storage capacity. Upper constraint of x_1 (Fig. 4)
x_{J2}	Current water production capacity installed in the reference validated scenario. Upper constraint of x_2 (Fig. 4)
x_{K3}	Current wind power installed in the reference validated scenario (in % to cover the total electricity demand with wind power). Upper constraint of x_3 (Fig. 4)
x_{M4}	Current PV power installed in the reference validated scenario (in % to cover the total electricity demand with PV power). Upper constraint of x_4 (Fig. 4)

1 Introduction

Most islands around the world do not have enough natural water resources to cover all their hydric needs [1]. Consequently, they have to desalinate seawater to satisfy the fresh water demand [1–3]. Since desalination is an intensive electricity consumer [2], a water scarcity problem in islands is also an energy problem. The electricity demand to power water supply systems supported by desalination represents on average around 10% of the total electricity demand [3,4] in the respective energy systems. For this reason, the development of strategies to promote desalination powered by renewable energy sources (RES) is considered a question of growing importance for innumerable islands around the world, especially those without hydric resources [5]. Several authors have published studies which have addressed this question from different point of views, but generally linking the electricity and desalination sectors [3]. Some of these studies have been carried out for relatively small islands. A very interesting and representative example of such studies is the one developed by Segurado et al. in the island of S. Vicente, in Cabo Verde [6]. In their study, these authors first analyse the relevant state-of-the-art and then propose two alternative scenarios to deal with the problem of excess wind energy production. The first scenario is based on sending the excess wind power directly to the desalination units. The second uses both desalination units and a pumped hydro storage (PHS) system to store this wind power excess. However, not all islands have a suitable topography for the installation of a PHS system. When no such possibility exists, another strategy needs to be considered aimed at directly linking renewable energy power plants and desalination units. In this respect, a lot of work has been conducted on modelling the combination of hybrid renewable energy sources (HRESs) and desalination plants. The models aim to optimally size the systems considering the energy demand rate and meteorological conditions [7]. Charcosset [8] reviewed a wide variety of RES-powered desalination systems which had been developed. Ma and Lu [9] carried out a specific review focused on the wind-desalination interrelation. They concluded that wind power and reverse osmosis (RO) desalination technology was one of the most promising combinations in this field. This is at least partly because RO presents the lowest energy consumption in the desalination industry [4,6,10]. An additional reason is that RO facilities are usually located in coastal areas where the wind resource is frequently high. The Canary Islands (Spain) have lengthy and extensive experience in this field [11]. The reputation of these islands at European level in matters related to saline water desalination technologies and the management of scarce water resources is well known [12]. The number of desalination plants installed in the Canary Islands per head of population is high [11,12].

Through the use of Machine Learning tools, the latest advances in the desalination industry are facilitating the variable operation of desalination plants [10,13–15], converting them into potential flexible energy consumers. This raises new research questions about the linking of desalination and energy systems [16]. Additionally, the use of these techniques in the prediction of power generation in a wind farm is obtaining interesting results [17,18]. In this new scenario, a desalination plant could be designed to cover water needs whilst at the same time having specific energy goals in mind. Moreover, the flexibility of emerging technologies such as Artificial Intelligence should enable new and feasible energy-water nexus planning strategies. These approaches could be based on oversizing the desalination capacity of a region to integrate more renewables and increase the efficiency of the overall energy system. This is the initial hypothesis of this paper. More specifically, the objective of this research is to develop a new method for the optimal design of water-energy infrastructures which are able to cover energy and water demands and increase the contribution of renewables to the system.

The innovative and original contribution of this research study lies in the fact that the proposed method, with a special focus on islands, is based on the interrelated operation of both the energy and water sectors. An exploration is undertaken of a significantly large number of new optimal energy-water infrastructures, determined in all cases on the basis of balanced solutions. The method gives, as a final solution, an optimal water-energy infrastructure with a balance between energy fuel needs and energy excesses, CO2 emissions, oil consumption, minimization of total annual costs and maximization of the renewable contribution. However, after an exhaustive search of the literature in relation to the renewable water-energy nexus, we detected some gaps in the current body of knowledge. Therefore, the present research study aims to cover the following gaps: (i) in previous approaches the water infrastructures remain unaltered and only strategies based on the energy sector are planned, (ii) consideration is only given to a constant operating mode in the water supply systems, and no consideration is given to the possibilities of a variable and interrelated operating mode in the water sector, and (iii) generally, only a limited number of static energy scenarios are explored. Although the energy planning software used in this study -EnergyPLAN [19]- is a mature software whose reputation is supported by more than 349 references in Scopus and 961 results in Google Scholar [20], the work developed in the present work does not limit its contribution to the application of the EnergyPLAN tool to the water-energy system of an island, which in itself is an innovation. In fact, a new planning method is developed, which uses EnergyPLAN but also includes in its procedure an exhaustive search to generate a large number of feasible alternative optimal scenarios of a target water-energy system. In addition, the method integrates the Pareto-based multi-objective optimization concept to facilitate the decision making process of water-energy system planners and stakeholders. Consequently, no studies were found in the literature survey that could take away from the novel contributions of the proposed general method. These novel contributions comprise an approach to optimally manage the variable interrelation of water-energy systems and a specific method to obtain optimal solutions by varying water and energy infrastructure designs. The proposed method is applied to Lanzarote, an island in the Canary Archipelago (Spain) off the northwest coast of Africa.

The remainder of the article is structured as follows: Section 2 provides the details of the method proposed to substantially increase the RES participation in the energy-water system of islands. In Section 3, the case study used to evaluate the method is introduced. Section 4 provides the results and a discussion based on the proposed method and case study. Finally, Section 5 shows the conclusions of the research.

2 Methods

This section describes the basic principles, the tools employed, the approach followed and the procedures which form the basis of the proposed method to combine the synergies between the water and energy systems with a view to increasing wind and PV participation in a relatively small island.

2.1 Basic principles of the method

The Smart Energy Systems concept, first described in 2012 [21] and used for national energy systems [22], forms the basis for this method. Smart Energy Systems is an approach in which smart electricity, thermal and gas grids are combined and coordinated to identify synergies between them with a view to achieving an optimal solution for each individual sector as well as for the overall energy system. Unlike, for instance, the Smart Grid concept, which puts the sole focus on the electricity sector, this approach takes into account the entire energy system along with the identification of suitable energy infrastructure designs and operational strategies [23]. The method presents certain novelties which make it applicable to water-energy systems on islands. In this sense, the basic principles which lie behind this new method are as follows:

i) The considered approach involves the following energy-water system sectors of the island: electricity, desalination and wastewater treatment.

ii) Due to the inherent fragility of small-sized isolated electric systems (islands), a balanced energy system configuration, with a lower RES share, will be preferable to an energy system with a higher RES share but which is unbalanced [3]. This determines the way of choosing the optimum RES configuration for each analysed alternative. To be more specific, a technical optimization criterion is used based on equaling and minimizing the sum of the energy surplus (defined as excess electricity production (EEP) [22]) and the lack of energy when meteorological conditions are insufficient to meet demand with RES.

iii) A short-term (hourly) approach in the analysis of the behaviour of intermittent RES (wind and solar photovoltaic (PV) power) and energy demand is considered. This is done in order to take into account the fluctuating nature of these energy sources and the potential for making demand more flexible, in this way adapting it to the intermittent nature of these RES [3].

iv) Higher flexibility in desalination plant operation systems is assumed in relation to the current way of operation. Studies have been published supporting this technical possibility [14,24], allowing the exploration of new scenarios in which, for instance, desalination capacity can be oversized with respect to water demand, attending to sustainable techno-economic criteria. So, for example, desalination plants can be managed to satisfy water demand and, when RES are fully available, to generate a surplus amount of fresh water which can then be stored or, when the RES are in short supply, to reduce production.

v) The proposed method is designed for islands, which implies a renewable desalination infrastructure search based not only on water demand criteria but also on obtaining a balanced energy system configuration.

2.2 EnergyPLAN simulation tool

Various models are available to analyse the contribution of renewables in energy systems [25]. However, certain characteristics of EnergyPLAN which are closely related to the basic principles on which this research is based (section 2.1) make it an ideal tool for this study. For example, EnergyPlan allows the empirical modelling of an energy system and performs hourly simulations with a time frame of one year [26]. In addition, it was designed specifically to apply the Smart Energy System concept and is capable of simulating the entire energy system and interrelate the different sectors. Descriptions of the algorithm can be consulted in the different manuals, reports and documents published on the website www.energyplan.eu. EnergyPLAN is capable of considering desalination as a flexible electricity demand and, hence, is able to manage its operation in a smart way to allow the integration of more renewables. However, desalination can also be considered inflexible, and this can also be exploited to determine whether increasing flexibility in the water sector can be used to increase renewable participation in an energy system. Another important feature of EnergyPLAN of interest for this study is its relatively fast capacity to model and simulate each new scenario. The approach presented in this research requires a huge number of simulations to find the optimal scenarios and, hence, computing time is a factor that needs to be taken into account.

2.3 The MATLAB Toolbox for EnergyPLAN designed to automate the analysis of a large number of new alternative scenarios

Although EnergyPLAN has a user-friendly interface, it only allows the user to run a limited number of subsequent executions, varying a limited number of decision variables for a concrete modelled energy system [20]. This manual mode, in which EnergyPLAN combines the optimization of both the operational phase and the planning phase, has been mentioned by other authors [27–29]. To explore new benefits of the tool, many have realized the need to combine EnergyPLAN with other computational tools [28–30]. The MATLAB Toolbox for EnergyPLAN was developed in this context, comprising a set of functions wrapped in a toolbox designed to call and manage EnergyPLAN from MATLAB [20]. In this study, this toolbox plays an essential role by allowing the automated generation of a large number of new alternative scenarios from MATLAB. Additionally, the huge set of results can be analysed using big data techniques available in MATLAB.

2.4 Multi-objective optimization model

In this study, a Pareto-based multi-objective optimization model is applied. This model allows the calculation of a set of acceptable trade-off possible optimal solutions, called Pareto front [29–35]. These solutions are obtained on the basis of all the different conflicting objectives chosen for the evaluated water-energy system [32]. This resulting Pareto front allows the decision makers a better understanding of the overall system, enabling them to explore all the consequences of a decision with respect to the various conflicting objectives [32,36].

According to [37–39], a multi-objective problem can generally be formulated as follows:

$$\begin{array}{ll} \textit{minimize:} & \left| \boldsymbol{y} = \boldsymbol{f}(\boldsymbol{x}) = \left(f_1(\boldsymbol{x}),\ f_2(\boldsymbol{x}), \dots,\ f_k(\boldsymbol{x})\right) \right. \\ \textit{subject to:} & \left| \begin{array}{l} \boldsymbol{g}(\boldsymbol{x}) = \left(g_1(\boldsymbol{x}),\ g_2(\boldsymbol{x}), \dots,\ g_m(\boldsymbol{x})\right) \leq \boldsymbol{0} \\ \boldsymbol{h}(\boldsymbol{x}) = \left(h_1(\boldsymbol{x}),\ h_2(\boldsymbol{x}), \dots,\ h_p(\boldsymbol{x})\right) = \boldsymbol{0} \\ l_i \leq x_i \leq u_i,\ \ i = 1,2,\dots,n \end{array} \right. \\ \textit{where:} & \left| \begin{array}{l} \boldsymbol{x} = (x_{\boldsymbol{1}},\ x_{\boldsymbol{2}}, \dots, x_{\boldsymbol{n}}) \in \boldsymbol{X} \\ \boldsymbol{y} = (y_1,\ y_2, \dots, y_k) \in \boldsymbol{Y} \end{array} \right. \end{array} \quad (1)$$

$\boldsymbol{x}$ is the vector of *n* decision variables (parameters) and $\boldsymbol{y}$ is the vector of *k* objective functions. $\boldsymbol{X}$ is denoted as the decision space and $\boldsymbol{Y}$ is called the objective space. $\boldsymbol{g}(\boldsymbol{x})$ is a set of *m* inequality constraints with feasible solutions $(\boldsymbol{e}(\boldsymbol{x}) \leq \boldsymbol{0})$, and $\boldsymbol{h}(\boldsymbol{x})$ represents a set of *p* equality constraints. l_i and u_i are used to represent the lower and upper limits of the *i*-th variable, respectively.

To compare candidate solutions to the multi-objective problem, the concepts of feasible solution, feasible solution set, Pareto dominance, Pareto optimal solution, Pareto optimal set and Pareto front are introduced [39]:

If a candidate solution $\boldsymbol{x} \in \boldsymbol{X}$ satisfies the constraints in Eq.(1), then $\boldsymbol{x}$ is called a *feasible solution.* All feasible solutions conform the *feasible solution set.*

Formally, it is said that a feasible solution $\boldsymbol{x}$ Pareto dominates another feasible solution $\boldsymbol{x}'$ if and only if:

$$\begin{cases} f_i(\boldsymbol{x}) \leq f_i(\boldsymbol{x}'), & \forall i \in \{1,2,\dots,m\} \\ f_i(\boldsymbol{x}) < f_i(\boldsymbol{x}'), & \exists i \in \{1,2,\dots,m\} \end{cases} \quad (2)$$

Therefore, $\boldsymbol{x}$ is called a *Pareto optimal solution*, or Pareto non-dominated solution, if and only if it is not dominated by any other feasible solution. This means that solution $\boldsymbol{x}$ cannot be improved in one of the objectives without adversely affecting another objective [36]. The set of all Pareto optimal solutions is called the *Pareto optimal set* and the corresponding objective vectors are said to be on the Pareto front (Fig. 1). The analytical expression of the Pareto front cannot usually be obtained in practical problems [36,39].

Fig. 1 represents the Pareto front of a two-objective minimization problem.

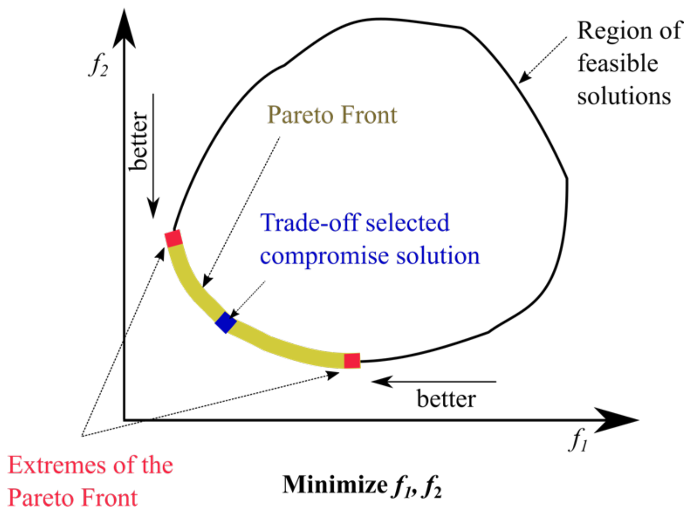


Fig. 1. Representation of the Pareto front for a two-objective minimization problem. Adapted from [36,39].

The solutions above the yellow line have at least one objective function inferior to that of another solution not included in the Pareto front [32]. The selection of solutions situated in the extremes of Pareto fronts (plotted in red in Fig. 1) guarantees the best performance for one objective function criterion but an improveable performance for the others. Conversely, a more centered solution within the Pareto front (trade-off solution plotted in blue in Fig. 1) guarantees a balance between different objective functions criteria which allows a better overall performance of the system attending to different parameters. This trade-off analysis is critical in the decision making process of energy system planners and stakeholders [40]. The method to select this trade-off compromise solution is described in section 2.5.5.

The particular application of the optimization model to the water-energy systems on islands can be represented as follows:

$$
\begin{aligned}
&\textit{minimize:} && \left| \begin{array}{l}
y_1 = total\ annual\ CO_2\ emissions\ (Mt), \\
y_2 = 100\% - RES\ share\ of\ PES\ (\%), \\
y_3 = total\ annual\ fuel\ consumption, PES, (TWh), \\
y_4 = total\ annual\ oil\ contribution\ to\ PES\ (TWh), \\
y_5 = maximum\ required\ hourly\ import\ (MW), \\
y_6 = \ imports/exports\ intersection\ point\ (TWh), \\
y_7 = annual\ variable\ costs\ (M€), \\
y_8 = total\ annual\ costs\ (M€),
\end{array} \right. \\
&\textit{subject to:} && \left| \begin{array}{l}
Current\ water\ storage\ capacity \leq x_1 \leq maximum\ feasible\ value, \\
Current\ desalination\ capacity \leq x_2 \leq maximum\ feasible\ value, \\
Current\ wind\ power \leq x_3 \leq wind\ power\ to\ cover\ 100\%\ electr.demand, \\
Current\ PV\ power \leq x_4 \leq PV\ to\ cover\ 100\%\ electricity\ demand,
\end{array} \right. \\
&\textit{where:} && \left| \begin{array}{l}
x_1 = water\ storage\ capacity\ (Mm^3), \\
x_2 = desalinated\ water\ production\ capacity\ (1000\ m^3/h), \\
x_3 = wind\ power\ installed\ capacity\ (MW) \\
x_4 = PV\ power\ installed\ capacity\ (MW),
\end{array} \right.
\end{aligned}
\tag{3}
$$

This problem is generally formulated by 4 decision variables (water storage capacity, desalination water capacity, wind power capacity installed in the energy system and PV power capacity) and 8 potential objective functions. However, the number of potential objective functions can be increased or reduced depending on data availability or the aims of the decision makers. The potential objective functions are the annual CO_2 emissions, the RES share of PES, the total annual fuel consumption (PES), the total annual oil contribution to PES, the maximum required hourly import, the intersection point of imports and exports for each water infrastructure (which defines the energy storage size required to minimize fossil fuel consumption), the annual variable costs, and the total annual costs. All of these objective functions are calculated by the EnergyPLAN software. Their mathematical model and detailed descriptions can be found in [19,41].

2.5 Detailed description of the procedure

The different steps of the method used in this research are shown in Fig. 2. The procedure can be applied to any island in the world for future studies with similar objectives.

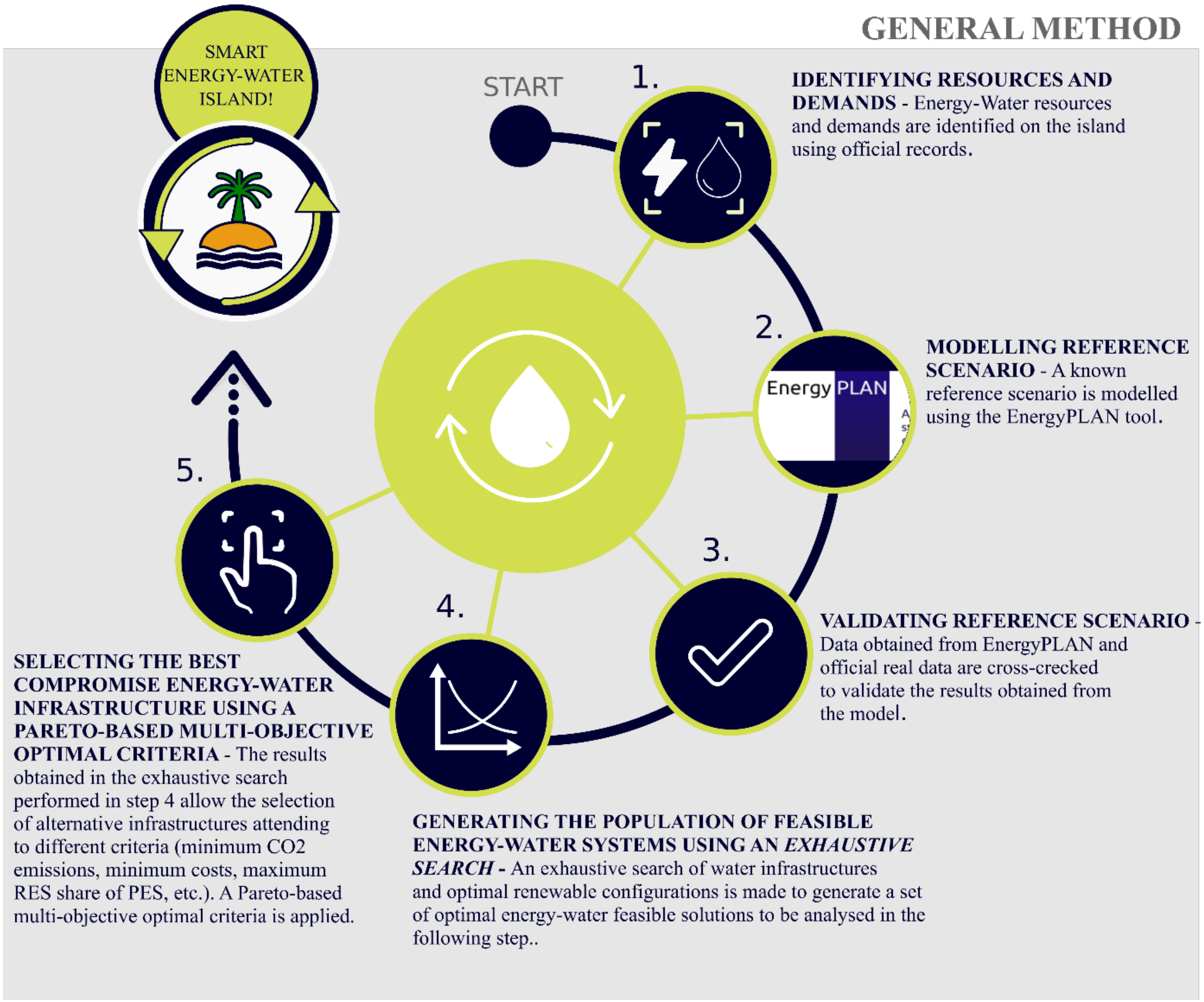


Fig. 2. Graphical step-by-step representation of the general method.

2.5.1 Step 1. Identification of the energy-water resources and demands

First, the current energy-water resources and demands on the target island are identified. The data collected in this step are available in official reports and statistics published by local institutions and governments [42–46]. Additionally, in this first step, it is recommended to map the potential viable growth of the different resources that are available, the potential installation and use of new resources, any particular features of the target island that could benefit or limit the future exploitation of RES, and any existing medium- or long-term energy plans.

2.5.2 Step 2. Reference scenario modelling

In the second step, the EnergyPLAN freeware is used to model a known reference scenario of the target island. This basically involves introducing all energy-water data and hourly distributions into the software and making initial simulations. After this model has been validated, which is carried out in the third step of the approach, alternative scenarios can then be realistically simulated using EnergyPLAN.

2.5.3 Step 3. Reference scenario validation

The validation carried out in the third step consists of cross-checking the results obtained from the EnergyPLAN model and the known real data. This allows a quantification of the deviation between model and reality with the aim of knowing the error in the simulation and presenting the results in a rigorous way.

2.5.4 Step 4. Generation of the population of n alternative feasible optimal solutions using an exhaustive search

The fourth step is the most complex part of the method and is supported by the MATLAB Toolbox for EnergyPLAN [20]. In this step of the process an iterative and layered approach is developed to find the optimal RES configuration for each new alternative water infrastructure. As can be seen in Fig. 3, the MATLAB Toolbox for EnergyPLAN [20] plays a key role in receiving the reference scenario previously validated in EnergyPLAN. The variables which define this reference scenario are divided into two groups: unaltered variables and alterable variables. While the first ones are not changed when new alternative scenarios are built, the alterable variables are modified in an iterative way with the aim of generating the population of optimal solutions, as can be seen in detail in Fig. 4. This search procedure considers the basic principles set out in section 2.1 and is performed as follows:

i) New scenarios are created modifying one of the alterable decision variables related to the water infrastructure. Both the water production and storage capacities on the island are modified in a nested way. For each variation in water storage capacity, water production capacity is modified step by step within a viable range previously calculated for the target island.

ii) For each new scenario, the alterable variables related to installed RES power are changed. A search is made for a new balanced RES configuration for each new alternative water infrastructure. This search is based on the technical optimization criterion proposed by Cabrera et al. in [3]. The procedure equalizes and minimizes the sum of the hourly energy surpluses and the energy shortages when meteorological conditions are insufficient to meet demand with RES [3]. When wind and PV power capacities increase, the possibility of an electricity surplus also increases. This energy surplus (or Export in this study) is defined as the EEP [22]. A fossil fuel energy need (or Import) occurs when wind and solar conditions are insufficient to meet demand, assuming power plant generation is to be completely avoided [3]. The minimum intersection point of imports and exports was obtained for each water infrastructure. In this study, 'Imports' are the hourly electrical needs that renewable sources are unable to satisfy, and 'Exports' corresponds to the hourly electric renewable generation which the system is unable to use because the demand at the moment of production is insufficient to match it. While Imports and Exports are equal and null in ideal balanced energy systems, the optimal configuration is considered to be that which obtains import/export values that are equal and as close to zero as possible [3]. To find this configuration, each water infrastructure was executed 100 times (as the renewable power capacities of both wind and PV are varied 10 times each in an iterative and sequential loop). With the aim of ensuring the stability and security of the electrical power system, an extra generation of electrical energy was considered in each water infrastructure. Since this study was undertaken from an energy planning point of view, the possible reconfiguration of the electric grid —and other problems derived from the massive RES increase in the grid— was not analysed. In this respect, previous studies [3,47] suggest that the use of currently available equipment such as synchronous compensators (SCs) can provide active power [3,47] and serve the needs of all ancillary services of conventional generators except those requiring reactive power (fault current, inertia and voltage support) [47]. The configuration which obtained the minimum intersection point was then analysed in more detail, using the same hourly distribution profiles as in the 2018 reference scenario. This method allows measurement of the PES by fuel type to assess the impact on the energy mix [22], on total annual CO_2 emissions [22], and on other variables such as the minimum export required in each scenario, the variable and total annual costs, and the required wind and PV power capacities (Fig. 3).

iii) In this way, an optimal balanced RES scenario for each water infrastructure proposal is obtained. Each optimal configuration is defined by eight key variables, as shown in Fig. 3.

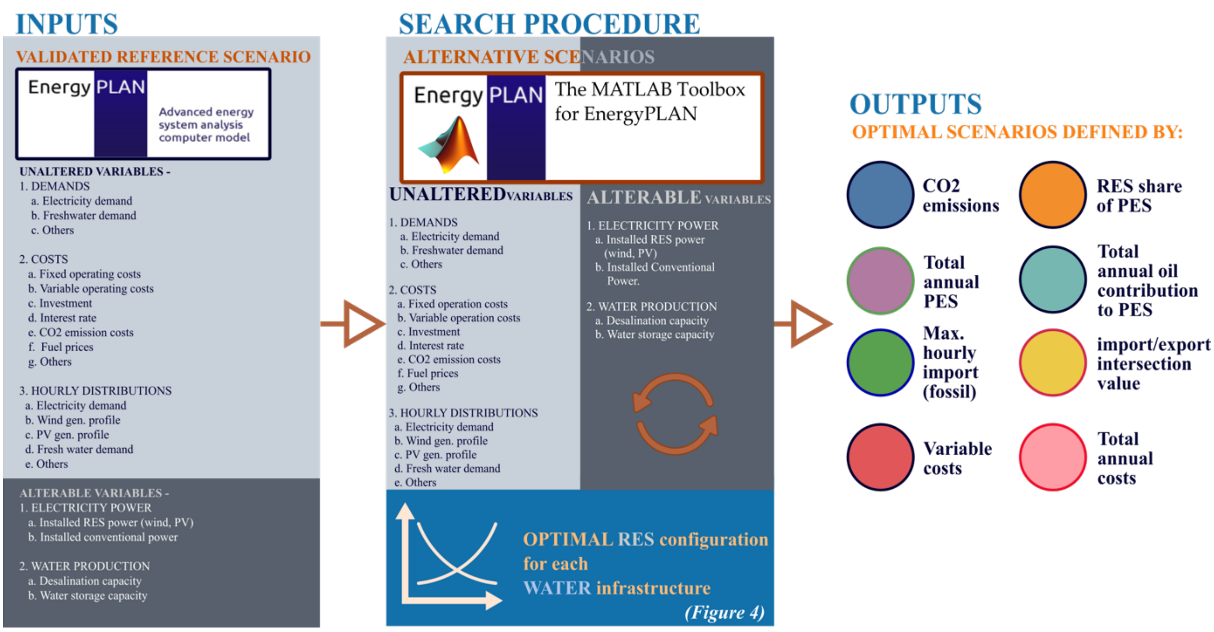


Fig. 3. Software framework and global outline to generate the population of optimal energy-water infrastructures executed in step 4 of the general method.

The search method designed and carried out in this step is described in greater detail in Figure 4. It is presented in the form of a block diagram to make it easier to understand and reproduce. The method begins with the model validated from the reference scenario used in the study (constructed in the previous steps: 1, 2 and 3). On the basis of this model, at the start of the procedure the decision variables are defined: x_1 = water storage capacity; x_2 = water production capacity; x_3 = installed wind power; x_4 = installed PV power. The values are defined following the constraints established for these variables, so that the search method does not exceed the limits imposed for each of them. Subsequently, the *exhaustive search* is initiated to create the feasible optimal solution set. This procedure is carried out in a robust way, through a series of nested loops which explore all the possible values defined for the decision variables. Firstly, for each value of water storage capacity (x_1), water production capacity (x_2) and installed wind power (x_3), all the values defined for installed PV power (x_4) are run. As previously commented, in this study it was determined to increase this decision variable 10 times, from its initial value (current installed PV power) to its final value (installed PV power to cover 100% of the electricity demand in the system).

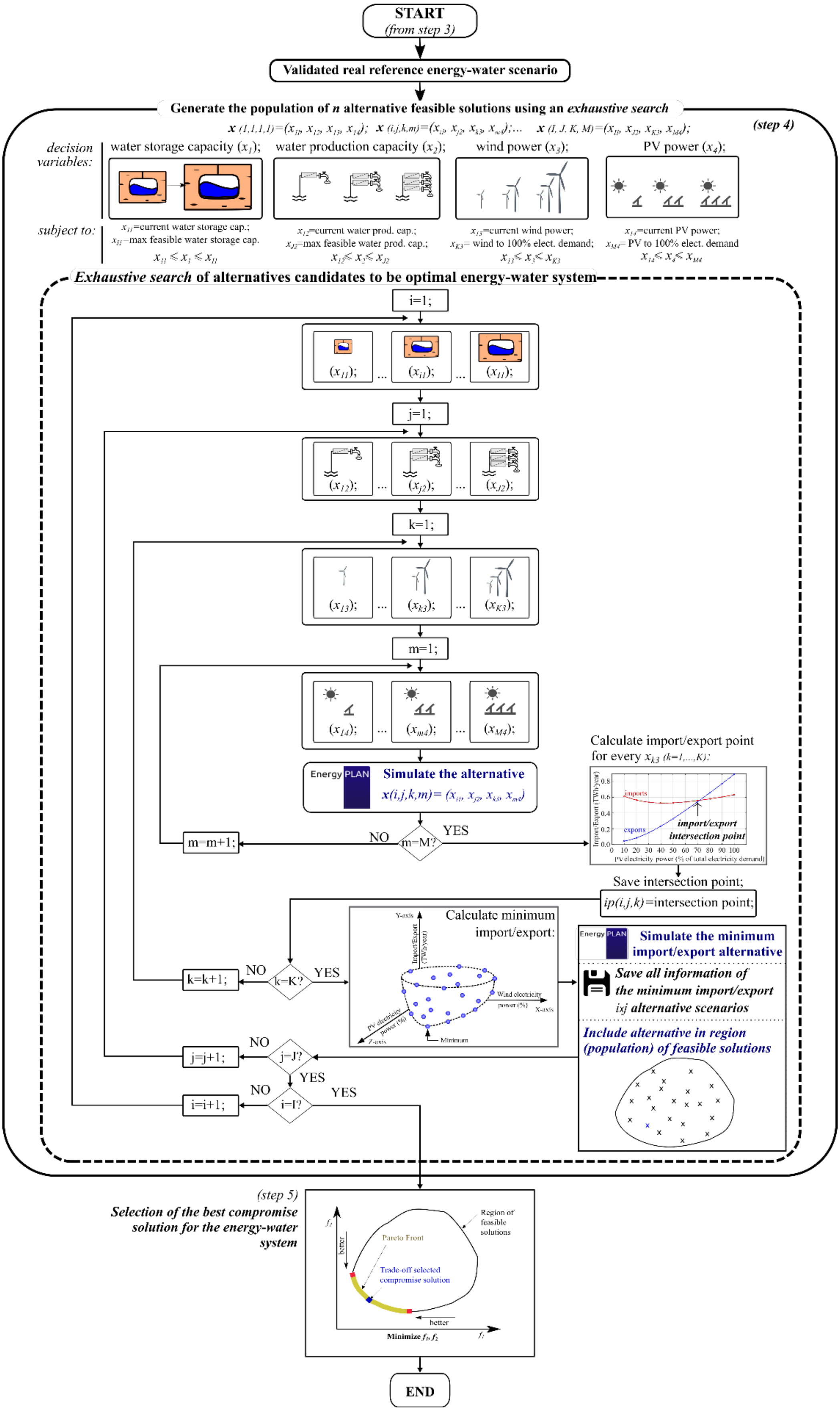


Fig. 4. Detailed diagram of the method designed in this research to generate the population of optimal energy-water infrastructures using an exhaustive search.

With each variation of the decision variables a simulation is executed of the new alternative scenario derived from the initial validated reference scenario. From each of these simulations, the pairs of results in *imports* and *exports*[2] which provide these alternative solutions are stored. Once all the values defined for x_4 have been run, the curves of *imports and exports* are plotted and their intersection point is calculated. The result is also stored of this intersection point obtained for the alternative analysed; for this the vector *ip(i,j,k)* is used. When this procedure is concluded, the index *k* is increased by a value to analyse the following set of scenarios with a new value of x_3. So, the search is repeated of the new intersection point of *imports and exports* for the new value x_3. As described, the variation of x_3 was considered similar to that of x_4. This decision variable (x_3) is also increased 10 times, from its initial value (current installed wind power) to its final value (installed wind power to cover 100% of the electricity demand in the system). When the procedure finishes running all the possible values of x_3, a new three-dimensional representation is constructed which represents the previously calculated intersection points on the Y-axis for the corresponding values of the other decision variables involved, installed wind power on the X-axis and installed PV power on the Z-axis. With this three-dimensional representation, the minimum value of the import/export intersection point is calculated. In this way, the sum of the hourly energy surpluses and the energy shortages is equalised and minimised in accordance with the basic principle ii) of the method (section 2.1). This alternative scenario is again simulated with EnergyPLAN and all the information obtained from that simulation is stored (CO_2 emissions, RES share of the primary energy supply (PES), total annual PES, total annual oil contribution to PES, maximum power necessary from conventional sources (maximum import), import/export intersection value, variable costs, total annual costs, etc.). This alternative scenario is likewise included in the set of feasible optimal solutions that will be explored later (in step 5). In this way, it is possible to have all the

[2] The meaning of the variables *import* and *export* is described in point ii) of section 2.5.4.

information necessary for the multi-objective optimization that is proposed for the global method. Finally, the procedure indicated is repeated for each of the values of x_2 and x_1 defined at the start, varying the indices *j* and *i,* respectively.

2.5.5 Step 5. Selection of the best compromise solution for the energy-water system

The most important decision variables are obtained for each optimal configuration and, hence, in this step a Pareto-based multi-objective optimal criteria is applied. More specifically, an optimal energy-water configuration is reached based on a trade-off of the following criteria: CO_2 emissions, RES share of the PES, total annual PES, total annual oil contribution to PES, maximum power necessary from conventional sources (maximum import), import/export intersection value, variable costs and total annual costs. To find this best compromise solution, the following approach is proposed [48]. Mathematically, the *i*-th objective function $\boldsymbol{y_i}$ is represented by a membership function $\boldsymbol{\mu_i}$ defined by Eq. (3) [48]**:**

$$\mu_i = \begin{cases} 1 & y_i \leq y_i^{min} \\ \dfrac{y_i^{max} - y_i}{y_i^{max} - y_i^{min}} & y_i^{min} < y_i < y_i^{max} \\ 0 & y_i \geq y_i^{max} \end{cases} \tag{3}$$

where y_i^{min} and y_i^{max} are the minimum and maximum value of the *i*-th objective function among all non-dominated solutions (situated in the Pareto front), respectively. For each non-dominated solution *k,* the normalized membership function μ_i^k is calculated as:

$$\mu_i^k = \frac{\sum_{i=1}^{N_{obj}} \mu_i^k}{\sum_{k=1}^{M} \sum_{i=1}^{N_{obj}} \mu_i^k} \tag{4}$$

where M is the number of non-dominated solutions. The best compromise solution is the one with the maximum value of μ_i^k.

3 Case study: application of the method in the island of Lanzarote

Lanzarote is a Spanish island located in the Atlantic Ocean about 125 km off the north coast of Africa and 1,000 km from the Iberian Peninsula [49] (Fig. 5). At the start of 2019, Lanzarote had a population of 152,289 inhabitants [43].

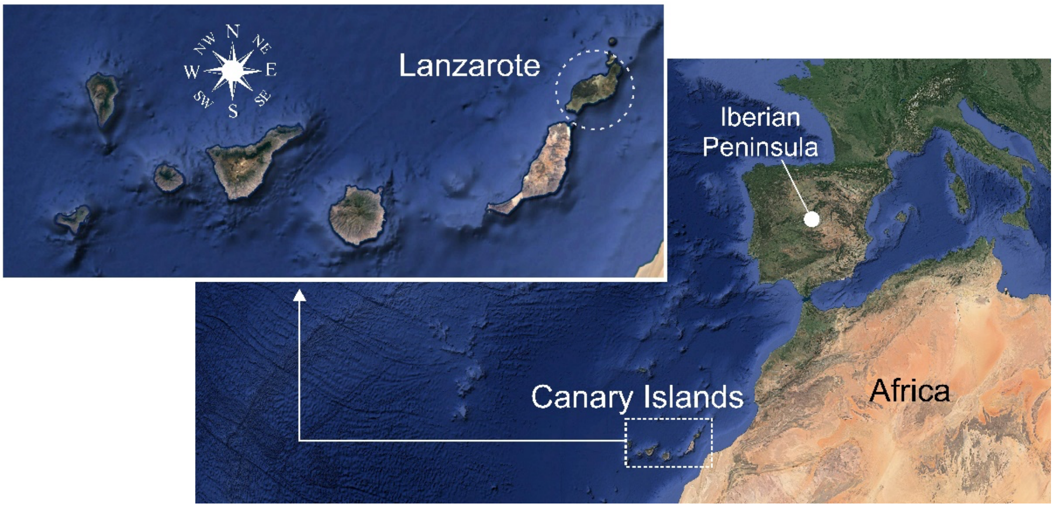


Fig. 5. Geographical location of the island of Lanzarote. [Source of satellite images: Google Earth: ©2020 Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Ladsat/Copernicus, IBCAO ©2020 GRAFCAN].

3.1 Identification of energy-water resources and demands

Firstly, the current energy-water resources and demands of Lanzarote were mapped. Additionally, as suggested in section 2.5, the specific particularities of the island were identified along with the energy-water plans and regulations.

3.1.1 The energy system in Lanzarote

Based on the official energy reports published by the Canary Islands Regional Government [42], the energy system of Lanzarote can be represented by the Sankey diagram shown in Fig. 6. With more than 94.5% of the total PES system based on oil (fundamentally fuel oil, gasoil and gasoline), Lanzarote has a very high dependence on fossil fuels [42]. In 2018, installed wind and solar energy only contributed 5.14% of the energy needs of the island. Finally, natural gas was used to satisfy around 2.9% of the energy requirements. It can be seen in Fig. 6 that the highest amount of fuels were used to feed the power plants responsible for generating electricity

(2175.7 GWh). The transport sector also consumed an important quantity of energy, (1084 and 71 GWh in road and maritime transport, respectively). From the total energy required to feed the power plants (2175.7 GWh), only 854 GWh were generated in the form of electricity which, when added to the 50.96 GWh supplied by wind and the 9.50 GWh by solar PV, satisfied the total electricity demand of 914.46 GWh. Almost 59% of this generation (539.5 GWh) supplied a considerable part of the energy needs of the services, industry and construction sector (with a total energy demand of around 724.3 GWh). The heating and cooling data were not obtained directly from official reports but were estimated from different consumption statistics and energy audit reports drawn up by consumer groups and the Canary Regional Government [45,50]. As a consequence of the above, and the fact that the authors of the present study were unable to find any study that had analysed the heating and cooling demand on the island, it was decided to exclude these data from the analysis undertaken in the present study. Nonetheless, preliminary analyses suggest promising results in terms of increasing renewable integration if new similar studies were able to focus on these sectors and/or the transport sector on the basis of reliable data and statistical analyses. With the currently available data, we estimated heating and cooling demands of approximately 187 and 89.5 GWh. Both are mostly consumed by hotels, commerce and the service sector. More oriented to the particular aim of this research, the desalination sector is entirely powered by electricity and required a total of 91 GWh, which is around 10% of total electricity demand [51,52].

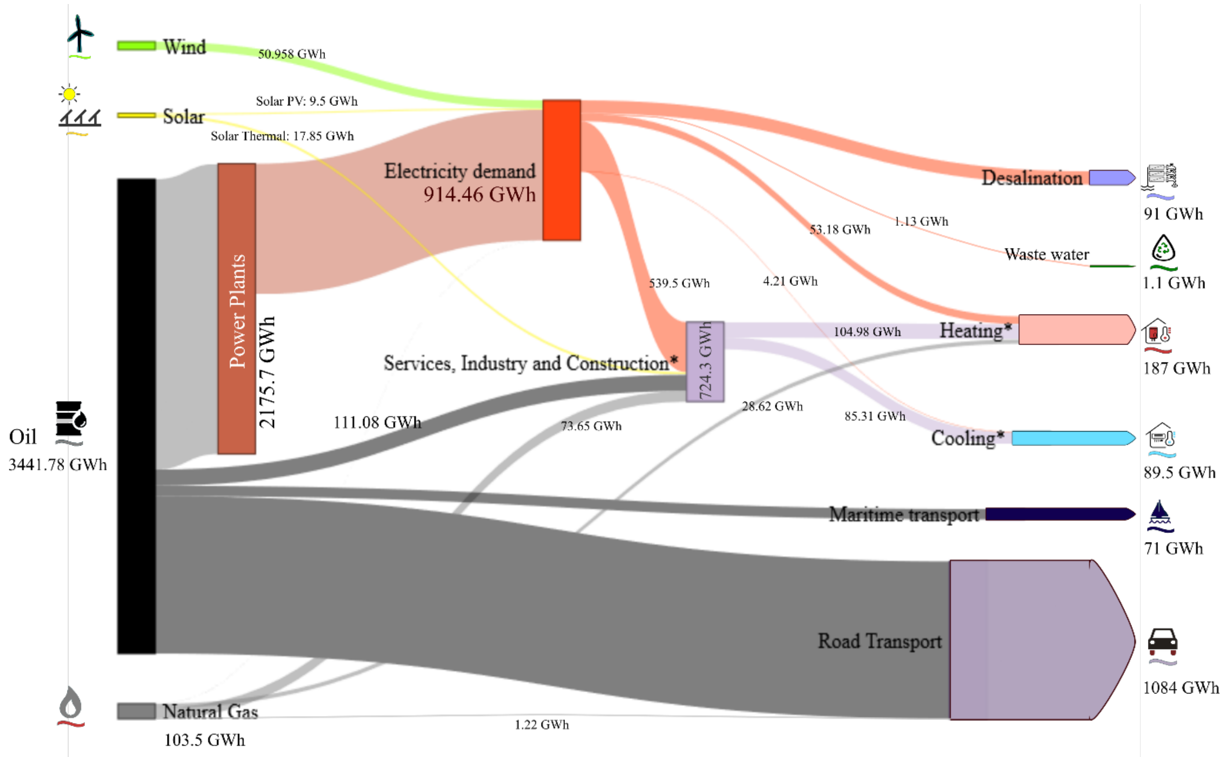


Fig. 6. Sankey diagram of the Lanzarote 2018 energy system. Data sources: [42,43,52,53].
*These energy values are not measured but estimated from statistical data and reports.

After analysing the whole energy system of Lanzarote and the Sankey diagram represented in Fig. 6, it is possible to infer the following interpretations with respect to the target objective of this research:

a) Electricity is the main energy use on Lanzarote

b) Desalination is not the biggest demand on the island. However, it represents an important electrical energy consumption and can be managed as a flexible demand with some relatively easy innovations [3,10,14]

c) The participation of renewables in the current energy system is very low

In the following subsections, we therefore focus on the electricity and desalination systems with the aim of identifying the corresponding demand and resources.

3.1.2 Electricity demand and potential electrical resources in Lanzarote

The electricity demand in Lanzarote shows a peak load at the end of January (around 141 MW) and a minimum load in April (60.8 MW) (Fig. 7). This behavior is highly conditioned by the seasonal nature of tourism on the island. Lanzarote usually welcomes a significant number of tourists in this period [53].

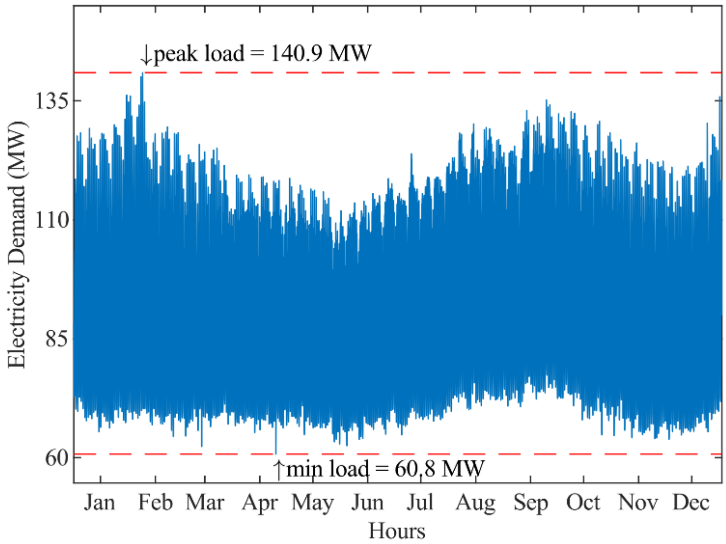


Fig. 7. Hourly average electricity demand in Lanzarote, 2018 [54].

Currently, Lanzarote has 13 generators (11 diesel and 2 gas-based) with a total net power capacity of 204.82 MW [46]. The island is electrically connected via a submarine cable to its neighbouring island, Fuerteventura, which has 159.27 MW of installed power.

Despite the relatively high available sun and wind energy resource in Lanzarote (see Fig. 8a and Fig. 9a, respectively), the current renewable installed power is low. In 2018, the islands had 9 MW installed PV capacity and 22.3 MW installed wind power capacity [46]. Peak PV production in 2018 was only 4.8 MW (Fig. 8b), and the average hourly peak production of 3.6 MW was produced at 14:00 h (Fig. 8c).

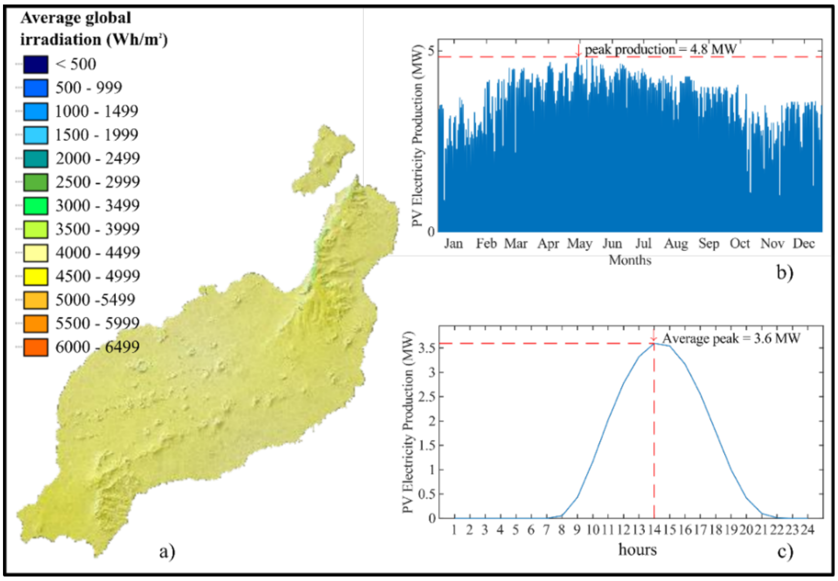


Fig. 8. Photovoltaic energy resource in Lanzarote. a) Average global irradiation map for the island of Lanzarote; b) Mean hourly PV electricity production in Lanzarote, 2018; c) Daily pattern of mean hourly PV electrical power production in Lanzarote, 2018. Source of maps: [55]; Source of electrical power production data: [54].

With only 22.3 MW of installed wind power (Fig. 9a), peak production was at the end of April when a value of 20.9 MW was recorded (Fig. 9c). Peak hourly production averaged 6.7 MW and happened around 20:00 h, while the corresponding minimum value was 5.0 MW at around 08:00 h (Fig. 9b).

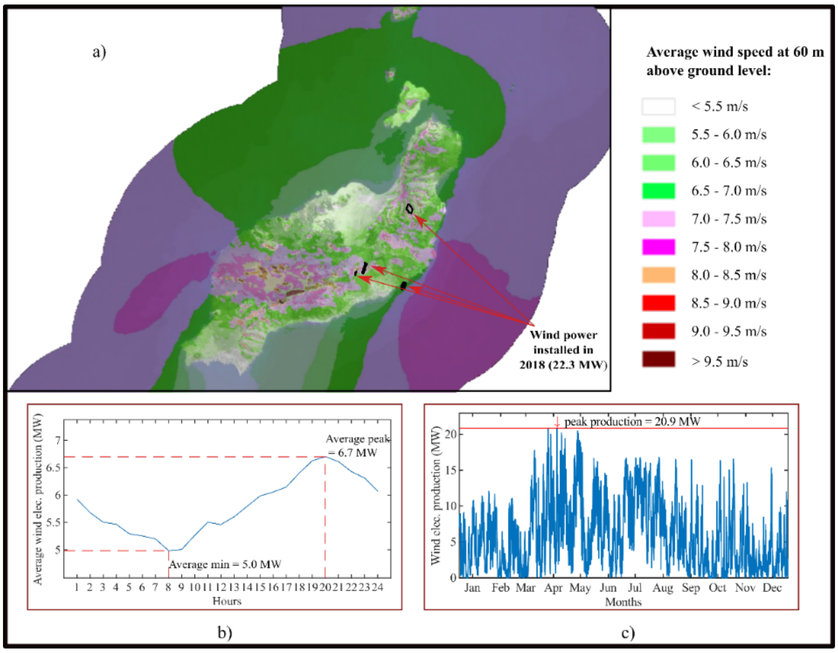


Fig. 9. Wind energy resource in Lanzarote. a) Average wind speed map for the island of Lanzarote; b) Daily pattern of mean hourly wind power production in Lanzarote, 2018; c) Mean hourly wind electricity production in Lanzarote, 2018. Source of maps: [55]; Source of electrical power production data: [54].

3.1.3 *Water sector in Lanzarote*

The resources, needs and particularities of the Lanzarote water system are described below.

3.1.3.1 *Energy demand in the water sector*

Fig. 10 represents the energy resources and needs associated to the 2018 Lanzarote water sector. As can be seen, the total amount of wind energy (50.96 GWh) satisfies part of the annual desalination electricity demand (91 GWh). Solar PV energy also contributes 3.4 GWh to desalination. The wind and PV power facilities which supplied these amounts of energy were installed by the Lanzarote Water Board with the aim of promoting desalination with renewables [56]. As can be seen, in the current water system in Lanzarote there is greater non-metered than metered freshwater consumption. According to the current operating company of the water sector (Canal Gestión Lanzarote S.L.), this is largely due to water leaks in the old distribution grid of Lanzarote [57,58].

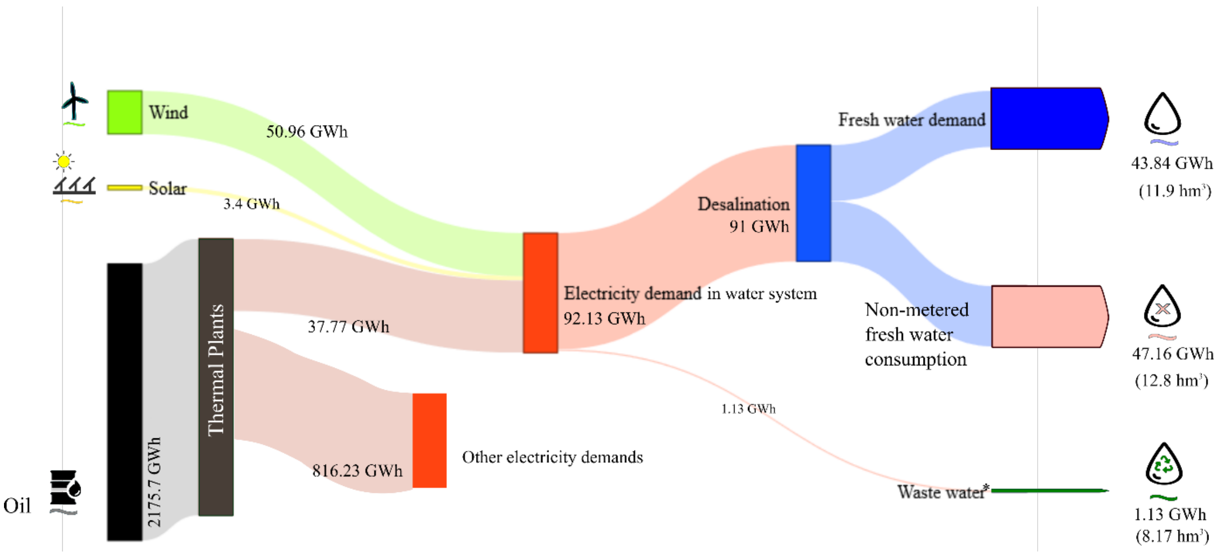


Fig. 10. Sankey diagram of the energy flow in 2018 Lanzarote water system. Data sources: [46,51,53,59,60]
*These energy values are not measured but estimated from specific energy consumptions calculated by previous studies in the area [61].

3.1.3.2 *Water production and distribution*

Fig. 11 shows the water production system in Lanzarote. Water demand on the island is entirely dependent on RO desalination centers installed on the west and east coasts. As can be seen, Lanzarote has an interconnected water distribution grid based on a large number of small water storage tanks and two larger ones situated in the center and south of the island (Fig. 11b) [51,53,62]. Total water storage capacity is around 243,000 m^3. Water demand presents three peaks, two in winter (period with more tourist visits) and one in summer (period with most water needs) (Fig. 11a).

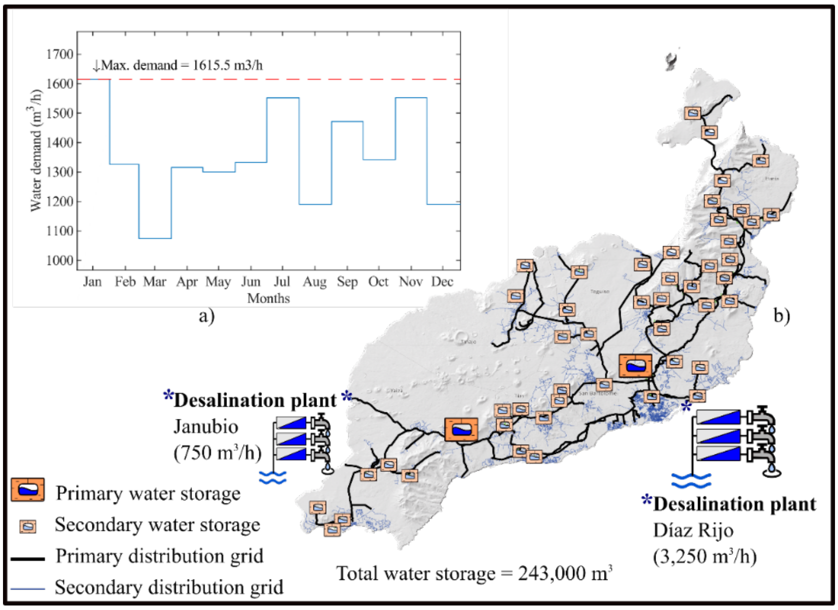


Fig. 11. Water system in Lanzarote. a) Water demand in the island of Lanzarote; b) Water distribution grid in Lanzarote. Source of data: [51,53,59].

3.1.3.3 *Water reuse*

Although the island does have a water reuse infrastructure [56], not all water production is reused (8.17 hm^3 of the total 24.7 hm^3 of freshwater produced) and only a small amount of this reused water passes through a tertiary treatment (2.9 hm^3) to prepare the water for reuse in profitable applications such as irrigation in the agriculture sector. This water infrastructure appears to be a potential candidate for development in terms of increasing efficiency and the renewable contribution to the system. In this respect, it should be noted that an appropriate water reuse system not only could be powered by RES, but could also help to minimize part of the current energy supplied to produce freshwater. However, the difficulty in obtaining accurate and reliable statistical data related to this water use means that a more specific study is required to analyse this topic.

3.2 Cost assumptions for the modelling of the reference scenario in EnergyPLAN

In this step, the reference scenario was modelled in EnergyPLAN after introducing all the identified data in the tool. The cost assumptions considered in this study are based on different real data and assumptions calculated by different institutions, including the Danish Energy Agency [63], the Spanish Institute for Diversification and Energy Saving [64], and other local organizations [46,52,53,65]. The most relevant costs are presented in Table 1. The cost assumptions are total investments before discounts. The fixed operation and maintenance costs are estimated as a percentage of investment costs.

Table 1: Costs of the most important installations considered in the study.

Installation	Investment cost	Fixed O&M (%)	Lifetime (years)
Power plants	0.99 M EUR/MW-e	3.05	20
Wind power	1.2 M EUR/MW-e	2.97	20
Photovoltaic	0.5 M EUR/MW-e	0.6	20
Desalination plants	1000 EUR/m^3 fresh water	3	20
Water storage	113.33 EUR/m^3	1	20

Additionally, a CO2 price of 24.92 EUR/t CO2 is considered based on the historical data of this value for the EU [66]. The most important fuel costs considered are presented in Table 2.

Table 2: Fuel costs considered in the study.

Fuel	Price (EUR/GJ)
Diesel	15
Fuel oil	11.9
Natural gas	9.1

3.3 Validation of the reference scenario modelled in EnergyPLAN

After identifying the energy system and modelling the reference scenario in EnergyPLAN, the operating simulation which EnergyPLAN performs was validated. As shown in Table 3, Table 4, Fig. 12, Fig. 13, Table 5 and Table 6, a comparison was made between the results of the 2018 Lanzarote energy system and the simulation performed by EnergyPLAN at a 1-h time resolution. The monthly energy electricity demands obtained from EnergyPLAN and from the actual data gathered from official data reports are compared in Table 3. The comparison of peak electricity powers supplied is shown in Table 4, the difference between the electricity produced from various units in actual data and simulations in Table 5, and annual fuel consumption by energy source in Table 6.

Table 3: Average monthly electricity demand obtained from the EnergyPLAN model and actual values for the year 2018 in Lanzarote.

Month	Actual 2018 (GWh)	EnergyPLAN 2018 (GWh)	Difference (GWh)	Difference (%)
January	72.98	75.03	2.05	2.81
February	66.70	66.46	-0.24	-0.36
March	71.13	69.83	-1.30	-1.83
April	68.06	67.51	-0.56	-0.82
May	69.03	68.49	-0.55	-0.79
June	67.47	66.74	-0.73	-1.09
July	72.30	73.37	1.07	1.48
August	76.31	73.96	-2.35	-3.08
September	74.62	74.51	-0.10	-0.14
October	75.03	75.37	0.34	0.45
November	68.83	70.50	1.66	2.42
December	72.61	72.28	-0.33	-0.46
Total	855.08	854.05	-1.04	-0.12

Table 3 shows that the maximum absolute differences obtained between the modelled monthly electricity energy demands and their actual values are produced in August (2.35 GWh), January (2.05 GWh) and November (1.66 GWh), respectively. These values are relatively low if their relative percentages are considered (all differences present relative values below 3.5%). These small differences in energy demands are produced because in the real data the power consumption for water systems is integrated into the overall power consumption of the electricity systems. However, the EnergyPLAN model analyses this specific power consumption separately from the electricity sector and achieves a similar water production with slightly fewer energy resources.

Table 4: Peak of electrical power obtained from the EnergyPLAN model and actual values for the year 2018 in Lanzarote.

Month	Actual 2018 (MW)	EnergyPLAN 2018 (MW)	Difference (MW)	Difference (%)
January	136.17	136.00	-0.17	-0.12
February	140.90	138.00	-2.90	-2.06
March	125.80	123.00	-2.80	-2.23
April	119.42	118.00	-1.42	-1.19
May	118.67	117.00	-1.67	-1.40
June	118.63	114.00	-4.63	-3.91
July	123.85	122.00	-1.85	-1.49
August	130.12	124.00	-6.12	-4.70
September	135.17	132.00	-3.17	-2.34
October	132.68	130.00	-2.68	-2.02
November	126.77	126.00	-0.77	-0.60
December	135.85	132.00	-3.85	-2.83
Peak electricity power (MW):	128.67	126.00	-2.67	-2.07

Table 4 shows the differences obtained between the modelled peaks of electrical power generated by months and their actual values. In this case, the maximum differences are detected in summer months, when renewable resources are higher. In these circumstances, EnergyPLAN reduces the power contribution of conventional generation taking advantage of the maximum renewable energy resource.

Fig. 12 shows a sample representation of the electricity demand data of the 2018 Lanzarote energy system and the simulation performed by EnergyPLAN at a 1-h time resolution for the central days in the months.

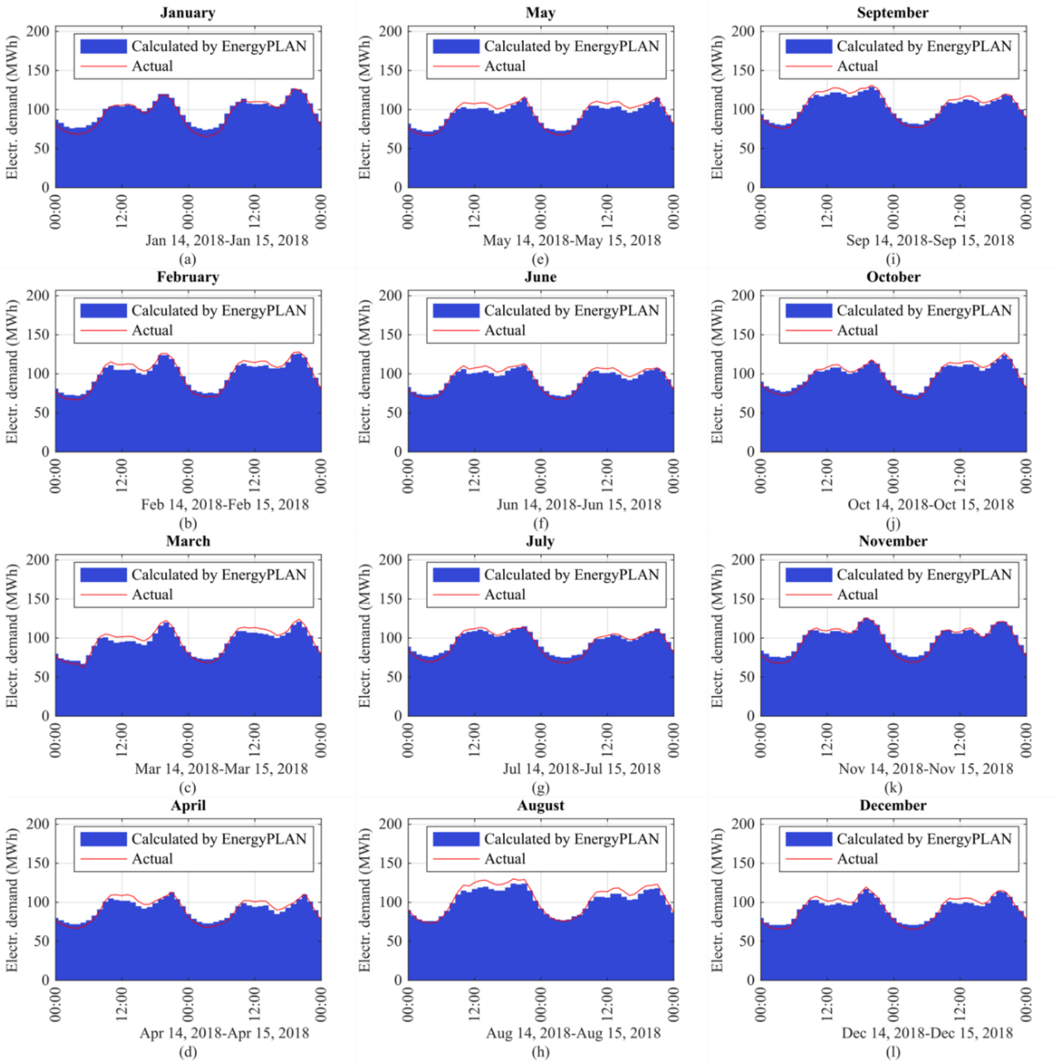


Fig. 12. Sample representation of the behavior of actual 2018 hourly electricity demand and 2018 hourly electricity demand calculated by EnergyPLAN, for days 14-15 in each month.

In Fig. 13, the abscissa axis represents the estimations of electricity demand (measured in MWh) performed by EnergyPLAN. The ordinate axis represents the actual values observed for each estimation carried out by the model. Consequently, interceptions between actual and estimated values are obtained for each sample of data (represented by blue asterisks. The red line (with a slope of 45 degrees) represents the best possible estimation. A blue asterisk above the red line means that the observed and estimated values are equal and that a perfect match has been achieved between model and reality in that individual estimation. In this figure, it can be seen that that there are small differences between estimations and actual values. These differences were statistically quantified using three metrics: the Mean Absolute Error (MAE), the Mean Absolute Percentage Error (MAPE) and R-Squared.

MAE is defined by Eq. (5) where the *n* estimated values are represented by the letter “e” and the *n* observed values by the letter "o". MAE is expressed in the same units as the parameters it compares [67].

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|o_i - \hat{e}_i\right| \tag{5}$$

MAPE is defined by Eq. (6) and is a relative measurement that expresses the error as a percentage of the observed data [67].

$$MAPE = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{o_i - \hat{e}_i}{o_i}\right| \tag{6}$$

R-Squared is defined by Eq. (7) and indicates the proportionate amount of variation in the response variable, y, explained by the independent variables, x [68].

$$R^2 = \frac{SSR}{SST} \cdot 100 = \left(1 - \frac{SSE}{SST}\right) \cdot 100 \tag{7}$$

where SSE is the sum of squared errors, SSR is the sum of squared regression and SST is the sum of squared total.

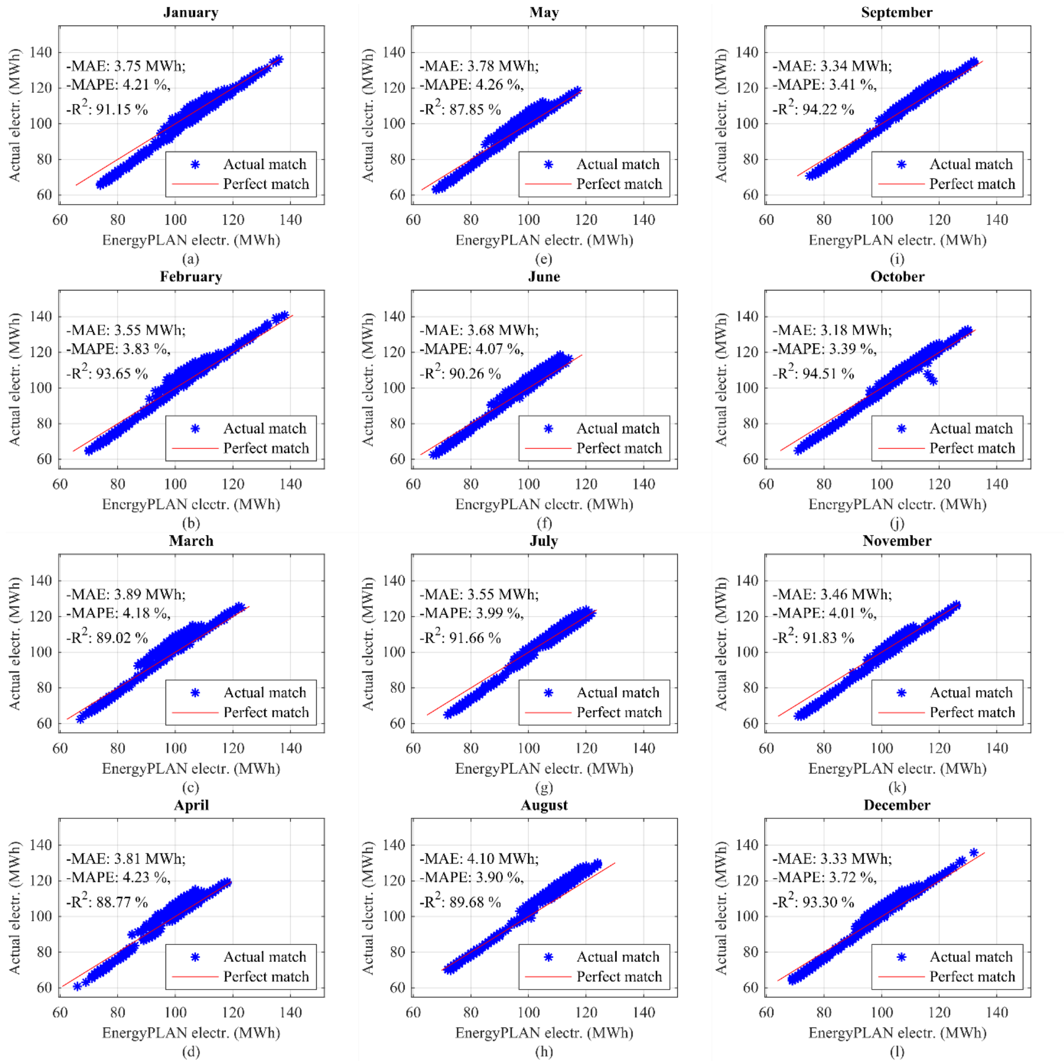


Fig. 13. Statistical comparison between actual 2018 hourly electricity demand and 2018 hourly electricity demand calculated by EnergyPLAN.

Table 3: Electricity produced for Lanzarote in 2018 and the EnergyPLAN simulation for this data.

Production unit	2018 Production (GWh)	EnergyPLAN 2018 (GWh)	Difference (TWh)	Difference (%)
Power-plants	926.20	943.98	17.78	1.9%
Wind	50.96	50.95	-0.01	0.0%
PV	9.50	9.43	-0.07	-0.7%

Table 4: Electricity produced for Lanzarote in 2018 and the EnergyPLAN simulation for this data.

Fuel	2018 Fuel consumption (GWh)	EnergyPLAN fuel consumption 2018 (GWh)	Difference (GWh)	Difference (%)
Oil	3,441.78	3,430.00	-11.780	-0.3%
Natural gas	103.500	100.00	-3.500	-3.5%
Renewable	60.458	60.38	-0.078	-0.1%

After all the comparisons between the reference model and the actual 2018 data had been completed and analysed, the accuracy of the model was accepted. As the largest relative difference found was just 4.7%, the reference model of the existing energy system of Lanzarote can be used as the first step for the investigation carried out in this paper.

3.4 Smart energy-water infrastructures analysis and Pareto-based optimization

After validation of the Lanzarote reference model, step 4 in the process was carried out. A MATLAB program was developed to obtain the optimal renewable water infrastructures using the framework shown in Fig. 3, the detailed method described in Fig. 4 and the Pareto-based optimization model presented in Section 2.4.

This Pareto-based optimization model is specifically formulated as follows:

$$
\begin{aligned}
&\textit{minimize:} && \left|\begin{array}{l}
y_1 = total\ annual\ CO_2\ emissions\ (Mt),\\
y_2 = 100\% - RES\ share\ of\ PES\ (\%),\\
y_3 = total\ annual\ fuel\ consumption, PES, (TWh),\\
y_4 = total\ annual\ oil\ contribution\ to\ PES\ (TWh),\\
y_5 = maximum\ required\ hourly\ import\ (MW),\\
y_6 = imports/exports\ intersection\ point\ (TWh),\\
y_7 = annual\ variable\ costs\ (M€),\\
y_8 = total\ annual\ costs\ (M€),
\end{array}\right.\\
&\textit{subject to:} && \left|\begin{array}{l}
0.243\ hm^3 \le x_1 \le 24.3\ hm^3,\\
4000\ m^3/h \le x_2 \le 8000\ m^3/h,\\
22.3\ MW \le x_3 \le 379.74\ MW,\\
9\ MW \le x_4 \le 475\ MW
\end{array}\right.\\
&\textit{where:} && \left|\begin{array}{l}
x_1 = water\ storage\ capacity\ (Mm^3),\\
x_2 = desalinated\ water\ production\ capacity\ (1000\ m^3/h),\\
x_3 = wind\ power\ installed\ capacity\ (MW)\\
x_4 = PV\ power\ installed\ capacity\ (MW)
\end{array}\right.
\end{aligned}
\tag{8}
$$

In this study, the decision variables (water storage capacity, desalination water capacity, wind power capacity installed in the energy system and PV power capacity) were modified on the basis of the following criteria:

a) Water storage capacity: in 10 steps, from its 2018 installed capacity (0.243 hm^3) to 100 times this value (24.3 hm^3).

b) Total water desalination capacity: in 10 steps, from its 2018 installed capacity (4000 m3/h) to 8000 m3/h.

c) Wind power capacity: in 10 steps of equal increments, from its 2018 installed capacity (22.3 MW) to the value which would satisfy all the electricity demand with this kind of power (379.74 MW).

d) PV power capacity: in 10 steps, from its 2018 installed capacity (9 MW) to the value which would satisfy all the electricity demand with this kind of power (475 MW).

The same general procedure was applied to determine the minimum intersection point between imports, i.e. fossil fuel energy needs, and exports, i.e. excess electricity production (EEP), in each water infrastructure when wind and PV are increased sequentially. This intersection point is important for any future development of the energy system as it defines the energy storage size required to minimize fossil fuel consumption. For each water infrastructure configuration (water storage and desalination capacity binomial), a search was performed for the optimal wind/PV power capacity configuration. This procedure was carried out in MATLAB using the MATLAB Toolbox for EnergyPLAN [20].

4 Results and discussion

Table 5 shows a sample of the results obtained and, more specifically, the following data gathered from the EnergyPLAN output files:

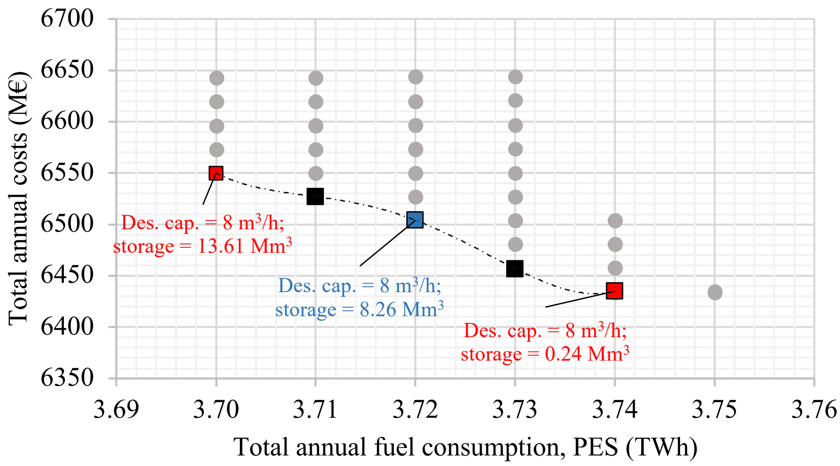
- Desalinated water production capacity (1000 m3/h).
- Water storage capacity (Mm3).
- PV power capacity required (MW) and in percentage (%) of total electricity demand.
- Wind power capacity required (MW) and in percentage (%) of total electricity demand.
- Total annual CO2 emissions (Mt).
- RES share of PES (%).
- Total annual PES (TWh).
- Total annual oil contribution to PES (TWh).
- Maximum required hourly import (MW).
- Import/export intersection value, in TWh and in percentage (%) of total electricity demand.
- Variable costs of the energy system, in millions of euros (M€).
- Total annual costs of the energy system, in M€.

All the optimal feasible solutions shown in Table 5 are also represented in three charts (Fig. 14 a, b and c) using only two potentially conflicting target variables in each. More specifically, Fig. 14a shows the results of the optimal solutions in terms of total annual costs (M€) vs. total annual fuel consumption (TWh), Fig. 14b represents the obtained solutions in terms of total annual costs vs. annual CO_2 emissions (Mt), and Fig. 14c shows total annual costs for the solutions vs. import/export intersection values (TWh), which are equivalent to the annual energy storage needs to avoid fossil fuels in the system. In Fig. 14, the three Pareto fronts are represented by discontinuous lines.

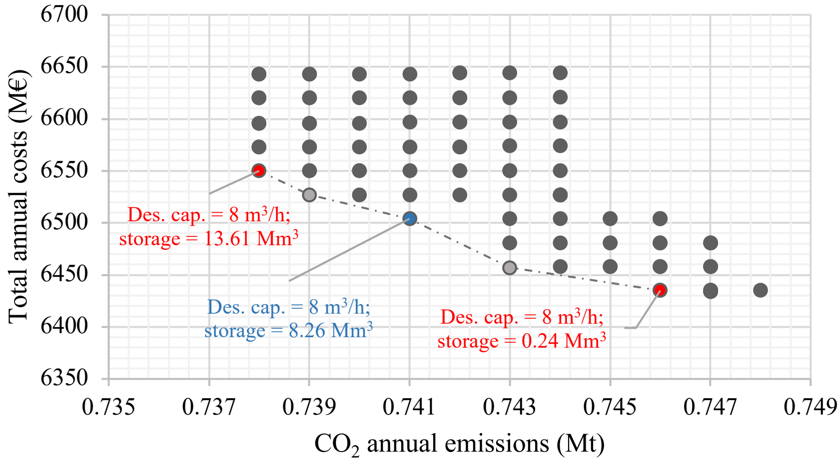
Table 5: Representative sample of the total set of optimal feasible smart energy-water infrastructures obtained after applying the proposed method on the island of Lanzarote.

Desal. cap.	**Water storage**	**PV power**		**Wind power**		**CO_2**	**RES of PES**	**Total annual PES**	**Total annual oil**	**Max Imports**	**Import/Export**		**Var. Costs**	**Total annual costs**
1000 m3/h	Mm^3	MW	%	MW	%	Mt	%	TWh	TWh	M€	TWh	%	M€	M€
4.00	**0.24**	**9**	**2**	**22.30**	**5.87**	**0.929**	**5.14**	**3.59**	**3.40**	**133**	**0.78**	**92.86**	**201**	**6424**
4.00	0.24	95	20	272.28	71.70	0.748	24.5	3.75	2.73	137	0.535	63.68	167	6435
4.00	2.92	95	20	272.30	71.71	0.747	24.5	3.74	2.73	137	0.534	63.59	167	6458
4.00	5.59	95	20	272.30	71.71	0.747	24.5	3.74	2.73	137	0.534	63.59	167	6481
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
4.44	8.26	95	20	272.23	71.69	0.746	24.5	3.74	2.73	137	0.533	63.45	167	6504
4.44	10.94	95	20	270.66	71.27	0.744	24.5	3.73	2.72	137	0.530	63.05	166	6527
4.44	13.61	95	20	269.12	70.87	0.743	24.4	3.72	2.71	136	0.528	62.91	166	6550
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
4.89	16.28	95	20	268.77	70.78	0.742	24.4	3.72	2.71	136	0.527	62.80	166	6573
4.89	18.95	95	20	268.78	70.78	0.742	24.4	3.72	2.71	136	0.527	62.80	166	6597
4.89	21.63	95	20	268.78	70.78	0.742	24.4	3.72	2.71	136	0.527	62.80	166	6620
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
5.33	24.30	95	20	268.71	70.76	0.742	24.5	3.72	2.71	136	0.527	62.69	166	6644
5.78	0.24	95	20	272.30	71.71	0.747	24.5	3.74	2.73	137	0.534	63.53	167	6435
5.78	2.92	95	20	272.29	71.70	0.746	24.5	3.74	2.73	137	0.533	63.43	167	6458
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
6.22	5.59	95	20	272.32	71.71	0.746	24.5	3.74	2.73	137	0.532	63.37	167	6481
6.22	8.26	95	20	272.18	71.67	0.745	24.5	3.74	2.72	137	0.531	63.27	167	6504
6.22	10.94	95	20	271.02	71.37	0.743	24.5	3.72	2.71	137	0.528	62.83	166	6527
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
7.11	13.61	95	20	269.25	70.90	0.739	24.5	3.71	2.70	136	0.523	62.25	165	6550
7.11	16.28	95	20	268.42	70.69	0.739	24.5	3.70	2.70	136	0.522	62.19	165	6573
7.11	18.95	95	20	268.49	70.70	0.739	24.5	3.70	2.70	136	0.522	62.20	165	6596
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
7.56	21.63	95	20	268.48	70.70	0.738	24.5	3.70	2.70	136	0.522	62.12	165	6620
7.56	24.30	95	20	268.47	70.70	0.738	24.5	3.70	2.70	136	0.522	62.12	165	6643
8.00	0.24	95	20	272.60	71.79	0.746	24.5	3.74	2.73	137	0.532	63.37	167	6435
8.00	2.92	95	20	272.30	71.71	0.743	24.6	3.73	2.71	137	0.529	62.92	166	6457
8.00	5.59	95	20	272.17	71.67	0.743	24.6	3.73	2.71	137	0.529	62.92	166	6481
8.00	8.26	95	20	271.99	71.62	0.741	24.6	3.72	2.71	137	0.526	62.62	166	6504
8.00	10.94	95	20	270.45	71.22	0.739	24.6	3.71	2.70	136	0.523	62.24	165	6527
8.00	13.61	95	20	268.94	70.82	0.738	24.6	3.70	2.70	136	0.522	62.13	165	6550
8.00	16.28	95	20	268.57	70.73	0.738	24.5	3.70	2.70	136	0.522	62.11	165	6573
8.00	18.95	95	20	268.64	70.74	0.738	24.5	3.70	2.70	136	0.522	62.11	165	6596
8.00	21.63	95	20	268.67	70.75	0.738	24.5	3.70	2.70	136	0.522	62.11	165	6620
8.00	24.30	95	20	268.65	70.75	0.738	24.5	3.70	2.70	136	0.522	62.11	165	6643

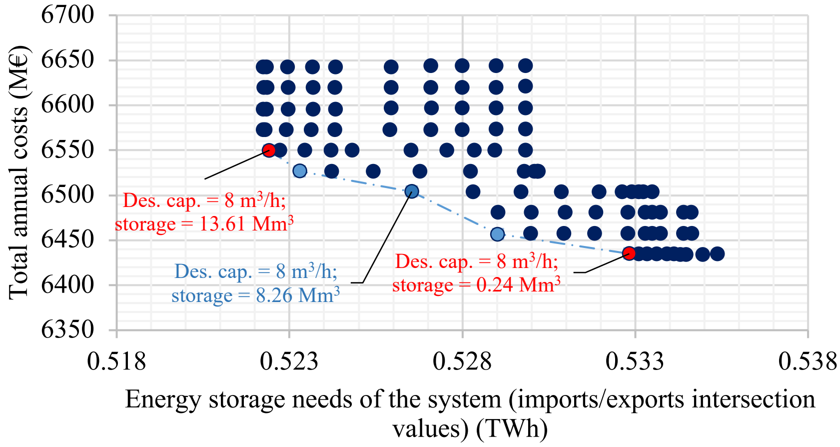
* **in bold** are represented the results obtained for the reference scenario.
* in red are represented the optimal configurations situated in the extremes of the Pareto fronts.
* in blue is represented the trade-off Pareto-optimal solution.



(a)



(b)



(c)

Fig. 14. Optimal solutions and Pareto fronts shown as total annual costs (M€) vs.: a) Total annual fuel consumption (TWh); b) CO_2 annual emissions and; c) Annual energy storage needs to minimize fossil fuels in the system (import/export intersection value).

Shown in blue in Fig. 14 and Table 5 is the most balanced energy-water infrastructure obtained after applying the proposed method to the island of Lanzarote. It is based on:

- a desalination capacity of 8,000 m^3/h,
- a water storage capacity of 8.26 M m^3,
- an installed PV power capacity of 95 MW, capable of satisfying 20% of total electricity demand, and
- an installed wind power capacity of 271.99 MW, capable of satisfying 71.62% of total electricity demand.

This configuration would increase the participation of renewables in the primary energy supply of the energy system from the current 5.14% of the reference energy system to 24.6%. This corresponds to, on average, over 35% of the hourly electricity demand throughout 2018 being satisfied by renewables compared to the actual value of 6.6%, with maximum hourly renewable contributions of up to 65%.

It can be seen that the optimal solutions generally propose a PV/wind power combination based on 20% of annual electricity demand being satisfied by PV and 71.62% by wind. These results concur with conclusions obtained in previous studies which analysed the best PV/wind power combination [3,69,70] with a view to minimizing excess electricity problems.

Fig. 15 shows the PES distribution and CO_2 emissions for the three Pareto-optimal solutions (located in the extremes and the center of the Pareto front) and for the reference scenario. For the trade-off Pareto-optimal scenario, despite the increase in total PES (from 3.59 to 3.72 TWh/year), the total oil contribution to the PES is reduced from 3.40 TWh/year to 2.71 TWh/year. Importantly, wind and PV power contributions are considerably increased, and annual CO_2 emissions reduced from 0.929 Mt to 0.741 Mt.

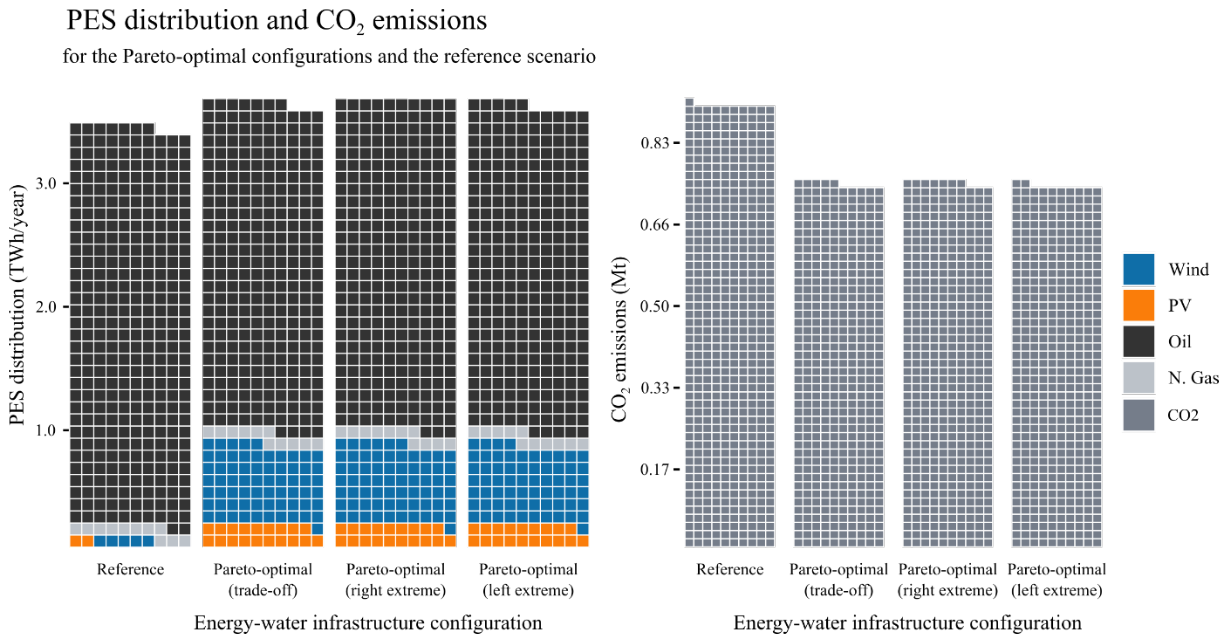


Fig. 15. PES distribution and CO_2 emissions for the reference scenario and the optimal configurations obtained in the Pareto front.

In Fig. 16, the optimal solutions are represented in terms of installed desalination, water storage and wind power capacities (X-axis), and CO_2 emissions, oil consumption and import/export intersection (Y-axis). Additionally, all the optimal solutions are drawn using a color code corresponding to their total annual cost.

The solutions with the lowest CO_2 emissions have higher total annual costs (Fig. 16a). This is because to satisfy the criteria of low CO_2 emissions and high desalination capacity it was necessary to increase water storage to its highest values, which significantly increased the total costs in the system.

All the graphs plotted in the second column of Fig. 16 offer confirmation of this. In this respect, it could be inferred that, in general terms, lower water storage capacity implies a lower total cost in the system. However, Fig. 16 (a), (d) and (g) show optimal solutions in green with very good performances in terms of the import/export intersection obtained on the basis of CO_2 emissions, total annual costs, oil consumption and import/export intersections. In addition, as can be seen in Fig. 16 (b), (e) and (h), these good performances were obtained with mid-range water storage solutions. Likewise, Fig. 16 (c), (f) and (i) show that lower total annual costs were obtained when wind contributions were higher, but very good performances were obtained with mid-range wind power solutions.

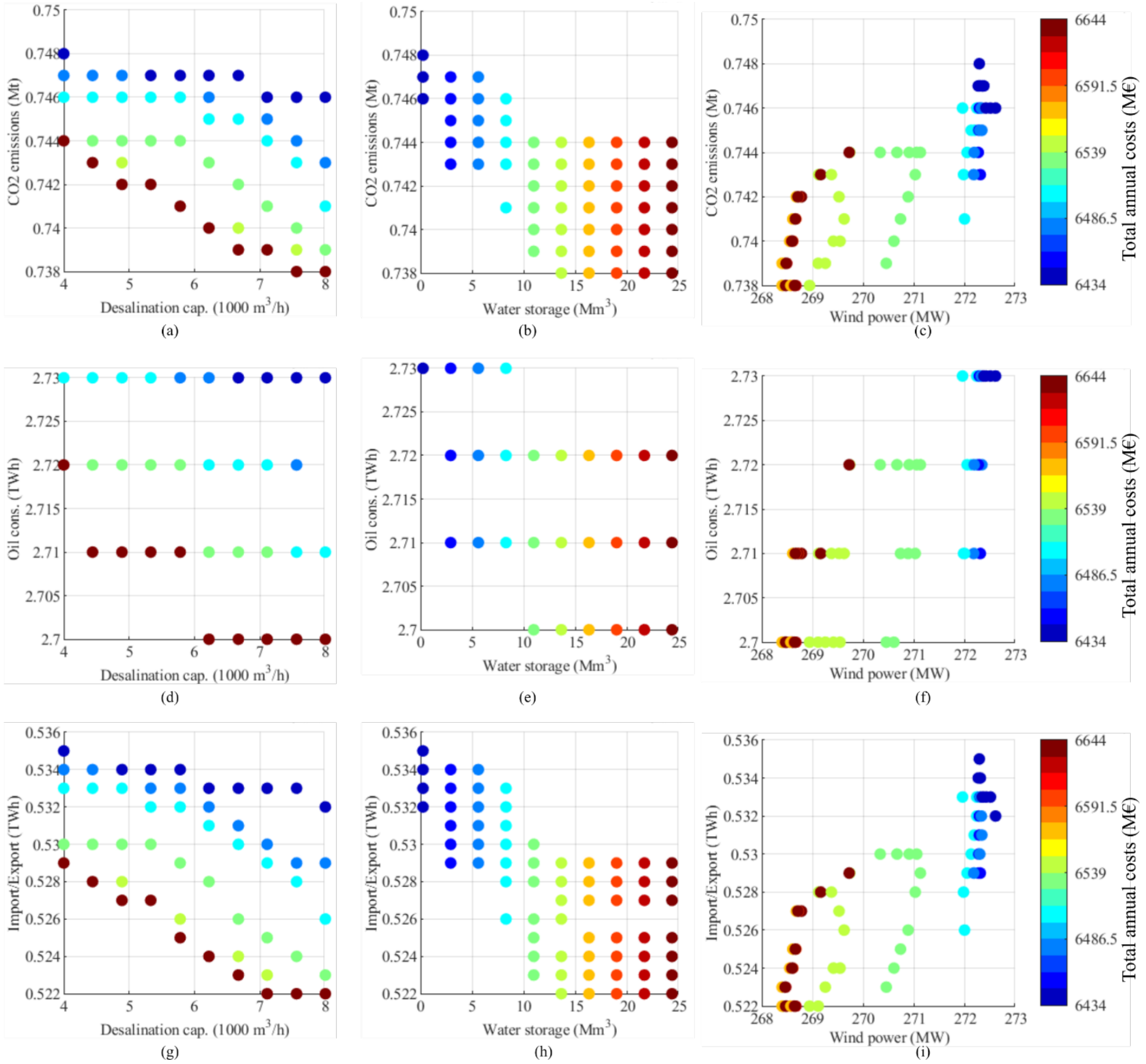


Fig. 16. Representation of each individual energy-water configuration (solutions) in terms of: desalination capacity and total annual costs (first column); water storage and total annual costs (second column); and wind power and total annual costs (third column), vs. CO_2 emissions; oil consumption; and import/export intersections (energy storage needs).

5 Conclusions

In this paper, an overall method is proposed to plan island energy-water infrastructures on the basis of the interrelation between the electricity and desalination sectors with the aim of increasing the renewable energy contribution to the whole energy system. The method is inspired by the Smart Energy System concept which promotes interconnections between different sectors to take advantages of their synergies. Since, in principle, the method is focused on islands, it has been designed to include an optimal renewable configuration search to minimize the balance between fuel energy needs and electricity excesses.

After applying the method to the Lanzarote case study, an island in the Canary Archipelago (Spain), a number of specific and relevant results were obtained. First, the analyses confirm the initial hypothesis with respect to the positive potential contribution that flexible desalination can make to renewable integration in an energy system. As result of the application of the proposed method, it is concluded that the most appropriate solution —in terms of maximizing renewable energy contribution and minimizing CO2 emissions, fossil fuel use and total annual costs— is a trade-off optimal solution chosen in accordance with the Pareto-efficiency concept. This solution consists of a balanced energy-water infrastructure based on a bigger but not the biggest selected water storage capacity, a higher but not the highest selected wind power capacity, and the highest, in size, selected desalination water capacity. This solution achieves an increase in the total contribution of renewables from 5.14% in the current reference scenario to 24.6%. This corresponds to, on average, over 35% of the hourly electricity demand throughout 2018 being covered by renewables, against the current 6.6%. The optimal solutions suggested by the method propose a PV/wind power combination based on 20% of annual electricity demand being satisfied by PV and 71.62% by wind, concurring with conclusions obtained in previous studies which analysed the best PV/wind power combination with a view to minimizing excess electricity problems.

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