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Research paper

Advantages of geothermal energy in the power supply of large-scale desalination and wastewater treatment processes. A case study

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ABSTRACT

Achieving sustainability in the water-energy nexus is a major challenge in regions with high dependence on desalination processes. These processes consume significant amounts of energy and have a high specific weight in electricity systems, especially those that are not large in size. The *in situ* use of non-dispatchable renewable energies in desalination processes has been widely studied in the scientific literature. In this paper, a method is developed to identify the technical and environmental advantages of the direct interaction of high-enthalpy geothermal energy, as a dispatchable renewable energy source, in continuous water treatment processes in comparison with non-dispatchable renewable energy sources. The method is applied to a case study in the Canary Islands. The incorporation is proposed of an on-grid renewable energy system to supply a set of hydraulic complexes equipped with desalination and wastewater treatment plants. Different simulations are carried out, and trade-off solutions are identified and compared on the basis of the results obtained for different technical, economic and sustainability parameters. It was found that the geothermal energy requires less renewable energy effort to cover the demand of the water processing systems, for example 4 times less power than solar PV, as well as 6.5 times less land area. The latter additionally contributes to the sustainability of the territory.

1. Introduction

Renewable energy sources (RES) have significant potential to mitigate the detrimental effects of carbon [1]. Consequently, their use has become very attractive in the goal of achieving sustainability in the water-energy nexus [2]. The significant availability of wind and solar resources has led to several studies that seek to increase the contribution of these RES to the energy demand of desalination processes. However, using such types of non-dispatchable RES is problematic in that they make it difficult for the energy system to achieve a balance between the electricity demand and the intermittent power supply [3].

To mitigate these problems, demand side management (DSM) and energy storage [3] are the most valued solutions in the scientific literature. Cabrera et al. [4], after searching for an optimal energy-water configuration for the island of Lanzarote (Canary Islands, Spain), concluded that, by providing the system with a certain water storage capacity and adapting the demand of the desalination processes to the intermittent nature of solar photovoltaic (PV) and wind power, RES participation is significantly increased. However, it should be noted that the least polluting solutions are also the most expensive ones due to the need to expand water storage capacity. Segurado et al. [5] analysed different ways to increase RES penetration on São Vicente Island (Cape Verde) by coupling the energy and water supply systems. One way involves the new electrical connection between its wind farms and seawater reverse osmosis (SWRO) desalination units, which makes it possible to use surplus wind energy to desalinate water and store it in reservoirs before being supplied to the population. Although it is true that this solution increases the penetration of wind energy, it is strongly

Abbreviations: CAPEX, capital expenditure; CF, capacity factor; CIATF, Spanish initials: Tenerife Water Board; COD, chemical oxygen demand; CRF, capital recovery factor; DME, demand meeting effort; DSM, demand side management; DSS, degree of self-sufficiency; EEP, excess electricity production; LCOE, levelized cost of energy; MED, multi-effect distillation; OPEX, operational expenditure; ORC, organic Rankine cycle; PE, population equivalent; PSH, peak solar hours; PV, photovoltaic; PVGIS, Photovoltaic Geographical Information System; RES, renewable energy source; RO, reverse osmosis; SEC, specific energy consumption; SED, share in total electricity demand; SWRO, seawater reverse osmosis; WWTP, wastewater treatment plant.

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affected by the capacity of the water reservoirs, since, if they are full, wind power is curtailed. Melián-Martel et al. [6] studied the possibility of driving the water cycle of the island of El Hierro (Canary Islands, Spain) solely with surplus energy from wind power, both for the case of the current decentralised water cycle and for a proposed centralised water cycle. The results showed that, while the decentralised system would use 39 % of the wind energy surplus, the centralised system would use 84.3 % of it, increasing wind energy penetration by 22 % and 83.5 %, respectively. However, the centralised system implies a significant modification of the water cycle, including having to replace the three SWRO desalination plants currently in the three municipalities of the island with a new desalination plant of larger capacity. Meschede [3] chose La Gomera, another island of the Canary archipelago, as a particular case study to quantitatively assess the flexibility potential of demand shifting in the water sector, comprising a single SWRO desalination plant with flexible operating mode. The implemented model includes energy supply with solar PV and wind, considering scenarios in which they participate both alone and in combination. The author concluded that the demand shifting potential is not noticeably influenced by probabilistic solar radiation, whereas it becomes saturated with wind power, especially in scenarios with a higher share of renewables. Therefore, this DSM strategy is not entirely effective for those cases with high RES penetration. The author also stressed that the demand coverage with RES was maximised with the use of both solar PV and wind. This reaffirms that the combination of different types of RES, in such a way that they supplement each other, can mitigate the general limitations of intermittency and variable supply [7]. Groppi et al. [8] studied the water-energy nexus of the island of Favignana (Italy), as well as its flexibility potential, taking into account the synergies between reverse osmosis (RO) desalination and water storage to accumulate surplus energy from solar PV. The results showed that water tanks are filled in summer when peak solar PV production occurs. The authors also commented that the installation of storage depends on the trade-off between its cost and the cost of curtailing the electricity.

Numerous industrial processes require high quality, constant, and round-the-clock energy [9]. Supplying the energy demand of these processes with RES such as wind or solar PV faces significant challenges and obstacles given their intermittent nature. In order to increase coverage of the energy demand, it is common to oversize the installation. This solution has negative effects such as overproduction of energy, increased land occupation and higher economic costs. For example, in [10] a system with an installed PV capacity 3.5 times the peak power load of a desalination plant is proposed, obtaining a renewable energy fraction of 38.2 %. This rises to 53.8 % if solar PV is combined with wind energy and the excess of renewable energy approaches 20 %. In Dallavalle et al. [11], a hybrid wave/PV system with an installed capacity 8.8 times the peak power demand of a desalination plant is sized to satisfy 85 % of its energy needs. In addition, the system has a maximum surplus power equivalent to 73.5 % of its installed capacity. In this sense, hybrid renewable systems are able to increase renewable penetration but do not totally eliminate the need to oversize the installation or incorporate energy storage. In addition, other specific challenges related to integration complexity, resource availability and inconsistency in policies and regulations [12] need to be considered in the hybridization of renewable energy systems.

Among others, the aforementioned problems, related to the energy sector on islands, have led to the *Clean energy for EU islands* initiative [13], which seeks sustainable and economic energy generation for such islands. Some of these islands, mainly those of volcanic origin, show high potential for the development of geothermal energy [14]. In this regard, the Azores archipelago (Portugal) is a success story, as 21 % of the total electricity demand of the archipelago in 2022 was covered by geothermal energy [15]. In the Canary Islands, where this renewable energy resource has not yet been exploited, there are underground reservoirs which, according to different research studies, have high- and medium-temperature geothermal resources that could be used to generate electricity [16,17]. In a context in which the integration of geothermal energy in island energy systems is foreseen, it is necessary to analyse the benefits of the direct interaction of this RES in the energy-water binomial. In this regard, a water-exergy nexus analysis found that only geothermal energy could compete with conventional thermal generation [18]. The persistent nature of geothermal energy makes its use attractive for desalination systems under continuous operation, usually located in grid electricity areas [19]. Additionally, its land area occupation ratio is significantly lower than other RES such as wind or PV [20]. The latter is especially important on islands, as the available surface area for renewable energy exploitation is usually limited [21]. The high energy intensity of water treatment processes makes the supply of inexpensive energy crucial [2]. In this regard, Shokri and Sanavi Fard [22] state that for the large-scale operation of desalination plants it is more cost-effective to explore stable energy resources such as geothermal energy than to use energy storage systems, such as batteries, combined with non-dispatchable RES. All of these positive qualities can make geothermal energy the most suitable option for a sustainable energy supply for continuous water treatment processes.

Geothermal energy is used in both thermal and membrane desalination techniques. Thermal desalination techniques are based on the direct use of geothermal heat, while membrane desalination techniques require the conversion of geothermal energy into mechanical and electrical energy. In the scientific literature, various applications of desalination using membrane desalination processes with geothermal energy can be found. Geng et al. [23] studied the performance of a low-enthalpy organic Rankine cycle (ORC) coupled to an SWRO system sized to satisfy a demand of 78 m^3/day. In [24], a techno-economic analysis was performed of the production of desalinated water through the use of low-enthalpy geothermal energy. Assuming an installed capacity of 30, 000 m^3/day, RO was compared to multi-effect distillation (MED), both being driven by geothermal energy. The results showed that RO coupled to a geothermal binary plant is more cost effective than MED through the direct use of geothermal heat. Pietrasanta et al. [25] developed a nonlinear programming model for the optimization of geothermal energy-powered seawater desalination systems. A single- or double-flash geothermal plant can be selected for electricity production, while MED or RO subsystems are considered for desalination. The authors found that MED desalination is appropriate for low freshwater demands, while combining MED and RO processes would be the preferred option for higher demands (above 4320 m^3/h).

Various studies have proposed the supply of geothermal heat and electricity to wastewater treatment plants (WWTPs). Di Fraia et al. [26] undertook an exergoeconomic analysis of a system that uses geothermal heat for a sludge drying process and generates electricity, through a geothermal ORC, to meet the internal demand of a WWTP designed for a 10,000 population equivalent (PE). Gürtekin [27] modelled an advanced biological WWTP for a 720,000 PE self-supplied through a 2.85 MW PV plant, 107 thermal solar panels and a geothermal heat pump. Myszograj et al. [28] developed an energy optimization process for a WWTP designed for a 90,000 PE, using biogas to produce electricity and heat, solar PV to produce electricity, and geothermal energy for heat recovery. These studies show that the use of available onsite RES in WWTPs can achieve high levels of reliability in covering demand [29] as well as increasing environmental efficiency.

After a careful review of the scientific literature, it was found that the most studied solutions to increase the renewable contribution to meeting the energy demand of water processing are: i) oversizing the installed renewable capacity in relation to the nominal peak power demand; ii) combining different types of RES through hybrid systems; iii) incorporating energy storage systems; and iv) adapting the demand to the variable generation of non-dispatchable RES. While it is true that these solutions make it possible to increase the share of renewable energy in meeting demand to a certain extent, their negative effects should not be ignored. These include higher economic costs, increased land requirements, and the difficulty of achieving acceptable levels of demand supply. This paper aims to identify the technical and environmental advantages of integrating geothermal energy as a dispatchable RES, without altering the operating regime of the water processing plants or modifying the water cycle. The general objective of the work developed is to study the originality of using high-enthalpy geothermal resources to supply electricity to a complex of high capacity water processing facilities, namely two SWRO desalination plants and a wastewater treatment system, connected to an isolated island electricity system, thus boosting distributed electricity generation. This study analyses the dispatchable nature of geothermal energy in terms of its ability to satisfy the high energy consumption of these water processing facilities under continuous operation and compares, using different technical and sustainability parameters, its benefits compared to another of the most studied alternatives in the scientific literature, namely the use of PV installations. It is applied to a case study of the water-energy nexus on the island of Tenerife (Canary Islands, Spain). Additionally, the results obtained for the trade-off solution of the geothermal installation are compared with those of other studies found in the scientific literature in which hybrid renewable energy systems are used.

2. Case study

The island of Tenerife is located in the Atlantic Ocean, off West Africa (see Fig. 1), and is the largest (2034 m^2) and most populated (948,815 inhabitants in 2023) [30]) island in the Canary Archipelago. It is subject to high touristic pressure [11], welcoming >6.5 million tourists per year [31]. It has an isolated electricity system, not connected to any other island in the archipelago or to the mainland, with an installed capacity of 1445 MW in 2022 [32], of which 23 % is from renewable sources. Practically all the installed renewable capacity is wind (15.4 %) and solar PV (7.5 %). Renewable energies covered 19.2 % of the island's electricity demand in 2022 [32]. According to the energy plans of the Canary Islands Government, both the installed renewable capacity and its contribution to demand are expected to increase significantly in the medium term [33]. Taking into account the negative effects that non-dispatchable renewable energies have on the electricity system, the renewable integration strategy must include both dispatchable renewable sources and energy storage systems. According to the geothermal resource studies that have been carried out, the island has significant potential for the exploitation of high-enthalpy geothermal energy, making it a dispatchable renewable source of interest for incorporation into the island's electricity system [16].

With regard to the water sector, Tenerife's groundwater accounts for 80 % of the island's water resources according to the current hydrological balance [34]. A significant amount of this water is freshwater, with the rest treated in brackish water desalination plants. For its part, desalinated seawater accounts for 16 % of the current water resources. The rest of the supply is supplemented by recycled and surface waters [35]. As for wastewater treatment, it should be noted that 47 % of the volume of wastewater currently generated in the Tenerife basin is treated, but only 9 % adequately so [34]. Currently, the island is in a situation of water stress due to a constant decline in groundwater [36]. In consequence, agricultural irrigation has had to be modulated in some areas of the island and desalinated water is expected to make an increasingly greater contribution to meeting the island's total demand [37].

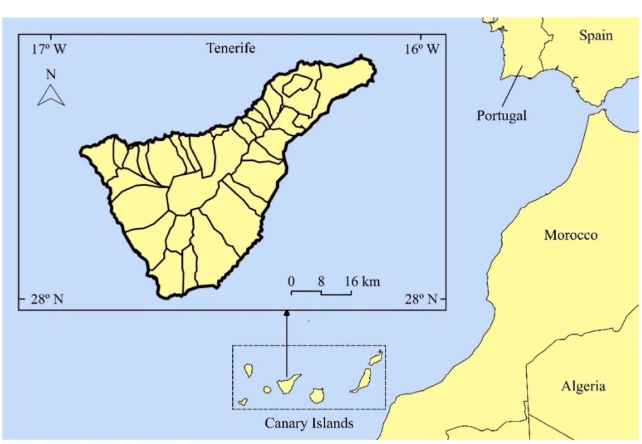

Fig. 1. Geographical location of Tenerife.

2.1. Description of the study area

The selected study area includes the water infrastructure complexes responsible for the provision of water services in the southwest of Tenerife, namely the municipalities of San Miguel de Abona, Arona, Adeje and Guía de Isora [34]. The Tenerife Water Board (CIATF by its initials in Spanish) is the administrative body that manages the waters of the island [38]. The CIATF is the owner of the SWRO desalination plants and manages the entire water sanitation and treatment system of the area covered by this study.

Fig. 2 shows the location of the water processing plants, the power system infrastructure, and a deep-seated high-enthalpy geothermal reservoir (at 2000 m below sea level). The detection of this reservoir was reported by the authors in a previous paper [39] after using a model that combined two geophysical techniques (magnetotelluric method and seismic tomography) to characterise the subsurface of Tenerife. Both techniques are widely used in geothermal resources exploration [40,41]. Based on applications of geothermometry, it is estimated that the temperature of the geothermal resource ranges between 180 and 220 °C [17]. It should be noted that the area of the reservoir partially overlaps with *Garehagua II* and *Garehagua*, the two mining licenses of Tenerife which show the highest potential to contain geothermal resources according to the results of a geochemical exploration [42]. *Garehagua II*, which partially overlaps with the western part of the identified reservoir, is defined in the Canary Islands Geothermal Strategy [16] as a priority area for the realization of geothermal energy research and development boreholes.

In order for the incorporation of potential geothermal plants to be adapted to the current electricity system with the least possible difficulty, the location of the electricity substations and their available access capacities for synchronous generation modules, which are provided by the Spanish electricity system operator [43], have been taken into

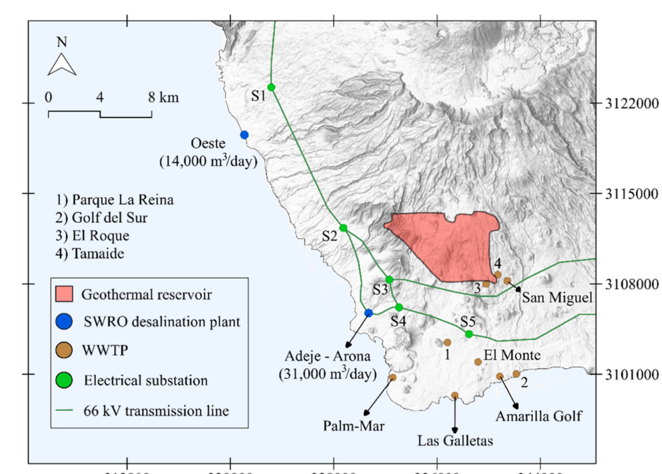

Fig. 2. Study area. Location of the water processing plants, the deep-seated high-enthalpy geothermal reservoir, and the infrastructure of the electrical system in the southwest of Tenerife.

account. The primary voltage of the five substations represented is 66 kV. The *Vallitos* substation (S3 in Fig. 2) is the closest to the geothermal reservoir and has an access capacity of 57 MW, which makes it an attractive option as a possible connection point between the geothermal generation system and the island grid. Currently, 91 % of conventional thermal power is installed in the municipalities of Candelaria and Granadilla [32] (both situated outside the study area), which explains the high degree of centralisation of the island's electricity system. In this sense, the incorporation of a renewable generation system in the study area would be in line with the objectives of distributed and decentralised generation, an important necessity in non-robust island electricity systems as is the case of Tenerife [33].

Water and energy consumption is significantly increased due to the touristic pressure of the study area. The municipalities of Adeje and Arona have the largest equivalent tourist population (40,898 and 30,626, respectively [34]), reflected by the daily number of tourists who, in addition to the local population, would inhabit the area [44]. These are the two municipalities with the highest water consumption on the island [34]. Water production in this area is dominated by seawater desalination processes in public infrastructures. These processes (see Section 2.2) accounted for 7.27 % of the total electricity consumption of the two municipalities in 2022 [32].

2.2. Energy consumption of the water processing plants

Table 1 shows the installed freshwater production capacity, annual energy consumption (including consumption for pumping to the storage reservoir), and specific energy consumption (SEC) of the CIATF's two SWRO desalination plants in 2022. The CIATF reports that both maintain a practically continuous energy demand regime for 360 days a year, given the constant flow and pressure conditions in their operation. For its part, the district wastewater treatment system had an energy consumption of 14.80 GWh in the same year, which includes wastewater pumping. The capacity of each WWTP can be consulted in the Hydrological Plan of Tenerife [45]. Fig. 3 represents the daily profile of the average hourly energy demand of all the water processing plants in 2022.

2.3. Description of the geothermal technology to be implemented

The Canary Islands Government considers the ORC with recovery circuit to be the most versatile and most feasible alternative for installation in the archipelago [16]. This technology works with separate circulating systems, inside which the geothermal fluid and a working fluid are confined, and heat exchangers to transfer heat from the geothermal fluid to the working fluid. The working fluid evaporates and delivers energy to a turbogenerator to produce electricity. In view of the island's water stress situation, air-cooled condensers would be used, thereby avoiding the use of water for cooling purposes [46]. Fig. 4 shows a schematic representation of the air-cooled geothermal binary plant. Considering its significant influence on the performance of ORC plants with dry cooling systems, the average monthly ambient temperature in the study area was consulted [47].

Geothermal resources are classified by three standard temperature ranges: low (<90 °C), medium (90–150 °C) and high (>150 °C) [48]. As mentioned above, the geothermal resource identified in the study area of this paper is high temperature. Although the ORC is recognised as a promising electricity production technology for the exploitation of low and medium heat sources [49], commercial ORC units have already been developed for high-temperature geothermal resources with power ratings between 5 and 30 MW [50]. When low and medium temperature resources are exploited, the installed capacities range from hundreds of kW to a few MW [51]. At present, ORC geothermal units have an average output of 13 MW [52].

Table 1
Installed capacity, energy consumption and SEC of the SWRO desalination plants in 2022 [38].

SWRO plant	Installed capacity (m^3/day)	Energy consumption (GWh/year)	*SEC* (kWh/m^3)
Adeje-Arona	31,000	60.20	5.39
Oeste	14,000	13.14	2.70

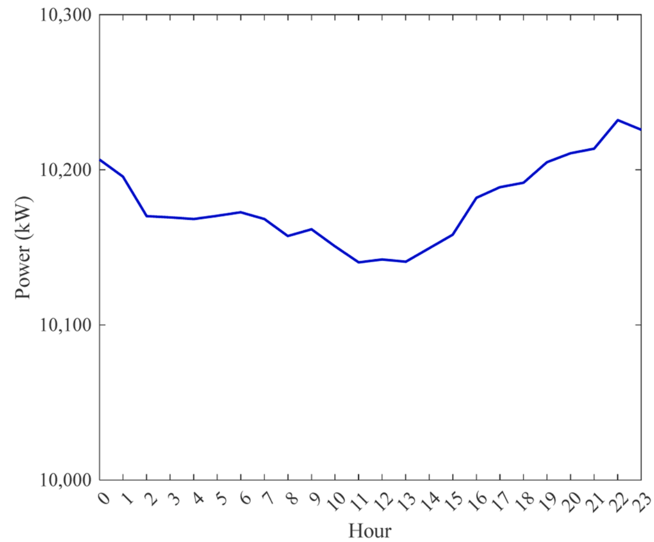

Fig. 3. Daily profile of the average energy demand of the set of water processing plants in 2022. Data source: [38].

2.4. Energy capacity of non-dispatchable RES

Fig. 5 shows the wind potential of the island of Tenerife [53]. It is significantly lower in the southwest of Tenerife compared to the east and northwest, where most of the wind turbines are situated at the moment [32]. For this reason, wind energy is discarded as a possible RES for the energy supply of the water processing plants. However, high levels of solar radiation [54] (see Fig. 6) are available in this area, making solar PV a potential alternative for the energy supply of the water processing plants.

The Photovoltaic Geographical Information System (PVGIS) [55] was used to determine the monthly average hourly values of solar irradiation at the different locations of the water processing plants. Taking into account the seasonal nature of the solar potential, in this study the average values obtained for the months from June to September, identified as 'summer', were differentiated from the rest of the year, identified as 'winter' (see Table 2).

3. Method

The method followed for the development of the present research work is shown in Fig. 7. The sectors included in this method are the energy and water sectors, with the aim of addressing their nexus in island systems. Electricity is the only segment involved in the first sector, while desalination and wastewater treatment are those related to the second sector. The seawater desalination and wastewater treatment systems considered in this methodology: (i) belong to the main hydraulic complexes of an island; (ii) are connected to the island's electricity grid; and (iii) operate under continuous operation. The method is particularly targeted at island systems with a weak electricity grid and limited management of surplus energy from non-dispatchable renewable sources.

To study the supply of energy from renewable sources to the hydro

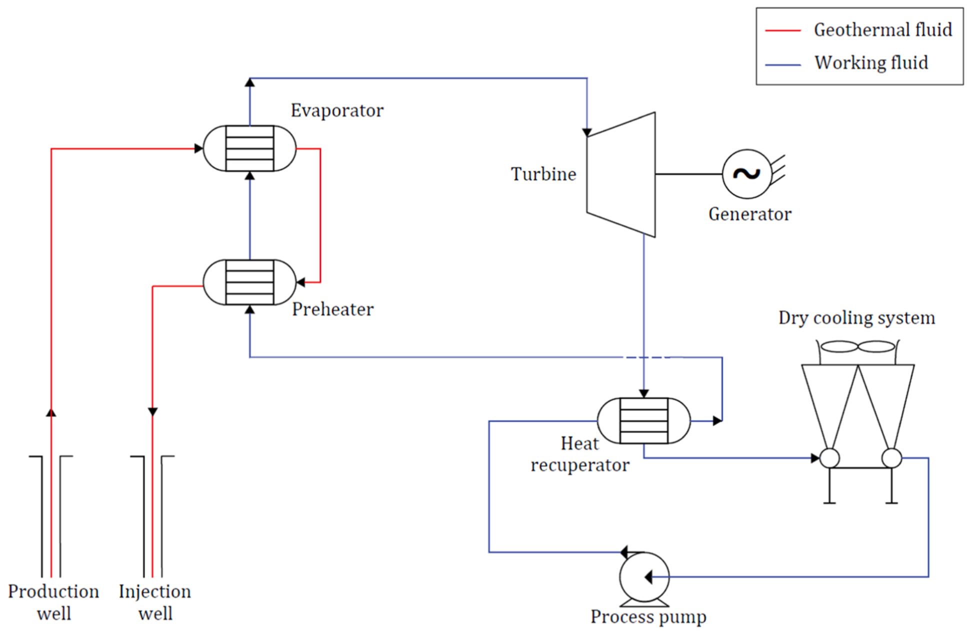

Fig. 4. Layout of the air-cooled geothermal binary plant.

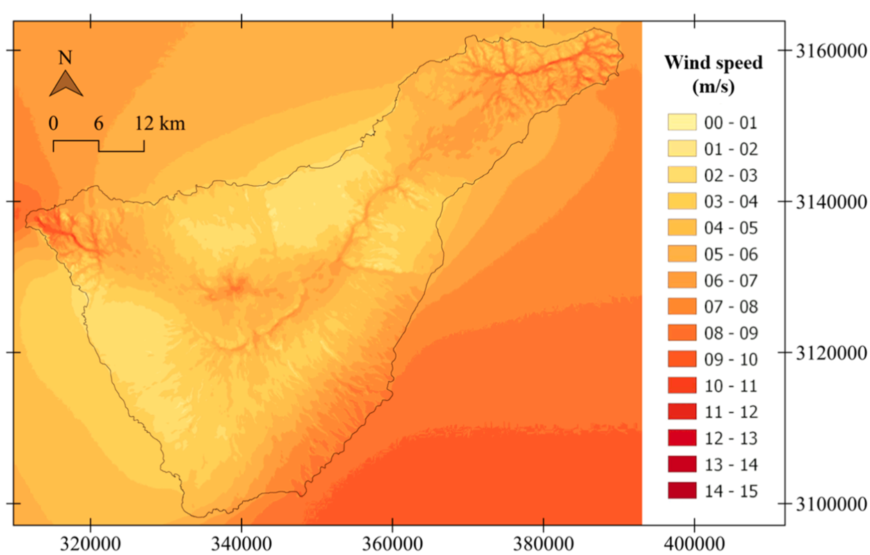

Fig. 5. Average wind speed map for Tenerife at 100 m above ground level. Data source: [53].

complexes, an energy balance modelling is performed, as well as an evaluation of possible solutions. This is necessary in order to select the option that guarantees a balance between different objectives, which are mainly technical, economic and environmental in nature.

3.1. Energy balance modelling

An energy balance model was implemented in Matlab to analyse the behaviour of the RES in its incorporation into the island's water-energy nexus. The energy balance considers the renewable energy supply to water infrastructure complexes, such as the SWRO desalination plants and/or WWTPs, connected to the island's electricity grid. To construct the energy balance, it is necessary to define the area of the island where the hydro complexes are located. The island's electricity grid must be sufficiently robust to provide a connection between the hydro complexes via high-voltage lines. Despite supplying energy to water processing plants with mostly continuous operation, the model takes into account the small variations in water production during the course of each day. In the same way, the energy balance also takes into account the fluctuations in electricity generation that the type of RES used may present. In this regard, an hourly-resolution model is implemented for the energy balance. The analysis includes calculation of the excess electricity production (EEP) [56], Eq. (1), to address the imbalance between electricity generation and consumption and its impact on grid stability. If the electricity produced by the renewable generation system is less than or equal to that demanded by the water processing plants, there is no EEP. In this case, the electricity necessary to cover the part of the demand that the RES is unable to satisfy is absorbed from the grid. If, on the other hand, it is higher, the surplus energy produced will be discharged into the grid to cover the energy demand of other sectors of the island.

$$\mathrm{EEP_t}\begin{cases} 0 \; for \; \mathrm{E_{RES,t}} \leq \mathrm{E_{d,t}} \\ \mathrm{E_{RES,t}} - \mathrm{E_{d,t}} \; for \; \mathrm{E_{RES,t}} > \mathrm{E_{d,t}} \end{cases} \tag{1}$$

where $E_{RES,t}$ and $E_{d,t}$ are the electricity produced by RES and consumed

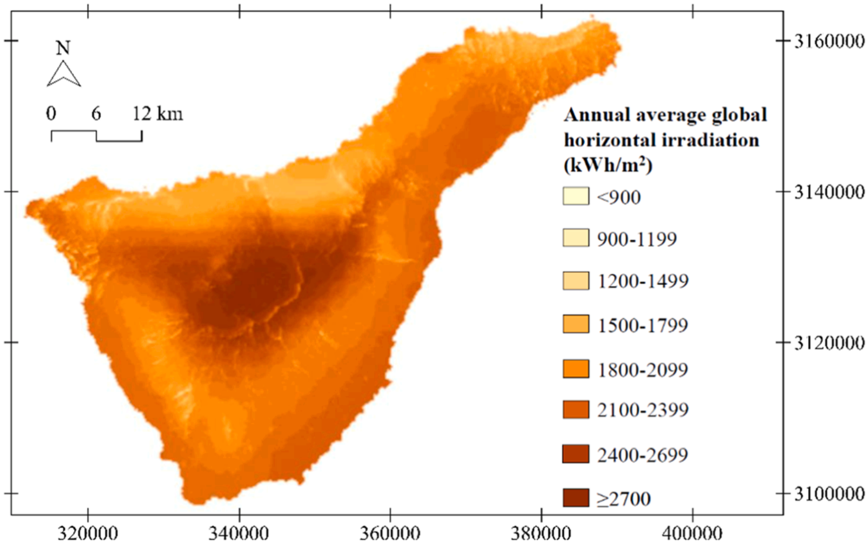

Fig. 6. Map of the annual average global horizontal solar irradiation of Tenerife. Data source: [54].

Table 2
Mean hourly solar radiation (in Wh/m^2) on a typical winter and summer day.

Hour	Winter	Summer
7	10	37
8	119	212
9	357	421
10	567	618
11	719	764
12	787	861
13	800	891
14	751	848
15	664	760
16	514	607
17	321	410
18	106	204
19	8	40

by the water processing facilities, respectively, at time 't'.

The required electrical power P_m (in kW) of an SWRO desalination plant of capacity Q_m (in m^3/day) and a given SEC (in kWh/m^3), is calculated through Eq. (2) [57]. For the case of the WWTP, the SEC can be regarded as the energy consumed to treat one cubic volume of wastewater (in kWh/m^3), or as the energy consumption per unit of chemical oxygen demand (COD) removed (in kWh/kg COD) [58].

$$P_m = SEC \cdot \left(\frac{Q_m}{24}\right) \tag{2}$$

3.1.1. Estimation of geothermal power generation

In the first mode, the geothermal plant supplies baseload electricity to the conventional grid and the water processing plants are treated as system loads (see Fig. 8). In the instances when EEP>0, geothermal energy covers other parts of the island's electricity demand in addition to the demand from the water processing plants, thereby enhancing the benefits for the system of distributed electricity generation.

The calculation model developed includes an analysis to estimate the geothermal power generation under real operating conditions. For this, plant performance is measured using the second law of thermodynamics in the form of the utilization efficiency, η_u, which is defined as the ratio of the actual net plant power to the maximum theoretical power obtainable from the geothermal fluid in the reservoir state [46] (Eq. (3)).

$$\eta_u = \frac{\dot{W}_{net}}{\dot{m} \cdot e_R} \tag{3}$$

where $\dot{W}_{net}$ is the net power output (in kW), $\dot{m}$ is the mass flow rate of the geothermal fluid (in kg/s), and e_R is the specific exergy of the geothermal fluid, Eq. (4), (in kJ/kg).

$$e_R = h_R - h_0 - T_0 \cdot (s_R - s_0) \tag{4}$$

where h is the specific enthalpy (in kJ/kg), s the specific entropy (in kJ/kg·K), and T the temperature (in kelvins). The subscript R refers to the condition of the geothermal fluid in the reservoir and the subscript 0 to the ambient conditions or the dead-state. The geothermal fluid is assumed to be pure water and to be in a saturated liquid state in the reservoir [46]. The specific enthalpy and specific entropy values of the saturated liquid at the reservoir temperature are taken from the steam tables [59]. The local dry-bulb temperature is chosen as dead-state temperature when using an air-cooled condenser [46]. The specific enthalpy and specific entropy at the dead-state conditions are close to the saturated liquid values at T_0 [46], which are taken from the steam tables [59].

A sensitivity analysis is developed in this study to identify the impact of various parameters on the performance of the geothermal plant. More specifically, the uncertainty factors to be studied are the reservoir temperature, the total mass flow rate of geothermal fluid, and the dead-state temperature. For the particular case of the present paper, the reservoir temperature range estimated from the applications of geothermometry (see Section 2.1) is considered. As productivity index values are not available at the current state of exploration, the total mass flow rates of 100, 150 and 200 kg/s of geothermal fluid are taken as a reference. These values are close to those recorded in existing high-temperature geothermal binary plants [60]. Geothermal binary plants typically have a utilization efficiency between 25 and 45 % [46]. In the present study, a utilization efficiency of 30 % is assumed.

Binary power plants are limited by the temperature of the surroundings to which waste heat must be rejected [61]. The relatively large amounts of waste heat that must be removed in ORC geothermal plants give rise to a significant energy consumption of its cooling system. In this regard, the fluctuation of ambient temperature causes the geothermal ORC system to deviate from the rated-design condition [62]. The air-cooling mode is more sensitive to the ambient temperature variation [63]. Consequently, the variation of the dry-bulb temperature is considered in this study in order to evaluate its effect on the power

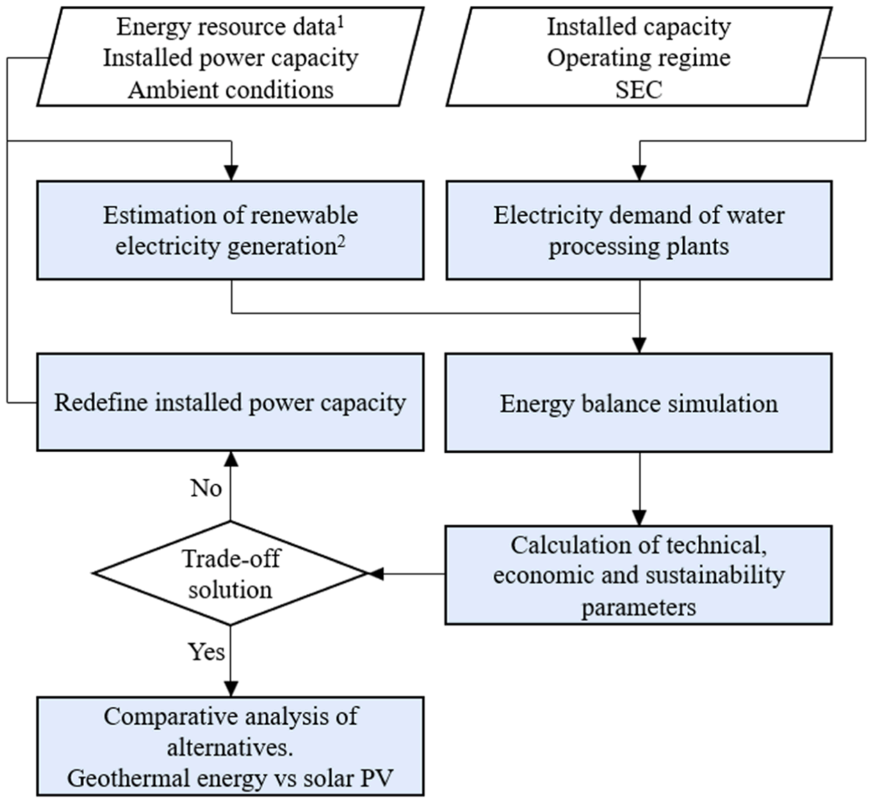

Fig. 7. Developed method.
[1] Extractable heat and solar radiation. [2] Geothermal and PV facilities.

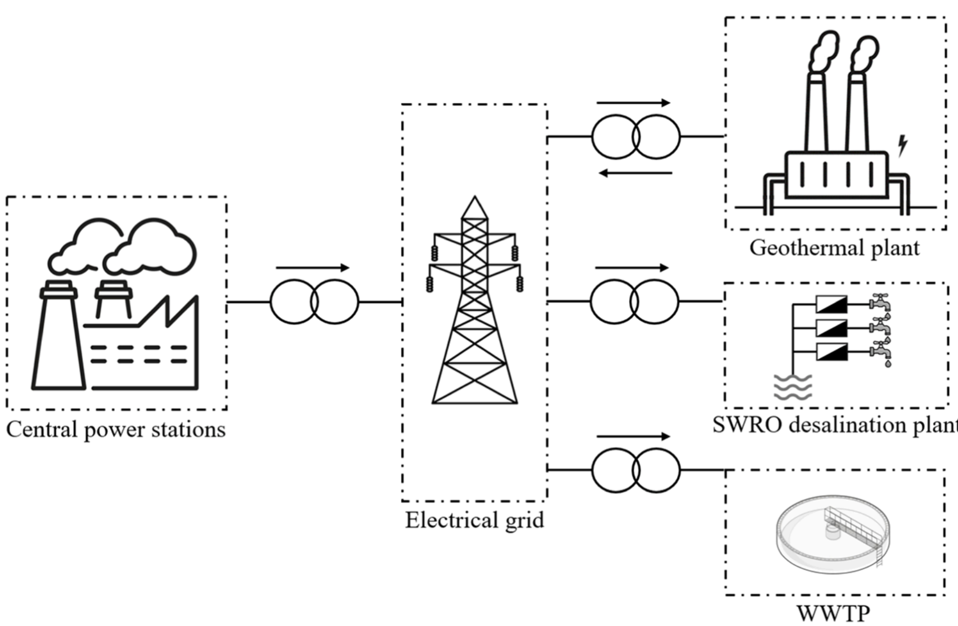

Fig. 8. On-grid geothermal plant and water processing plants.

produced by the geothermal plant on both a diurnal and seasonal basis [64]. For this purpose, average hourly temperature data reported by a meteorological station located in the south of Tenerife are used [65]. The ambient temperature range is from 15 to 30 °C, with 15 °C the average low temperature in the coldest month of the year and 30 °C the average high temperature in the hottest month of the year. The local dry-bulb temperature at instant 't' is an input parameter of the model, while the net electrical energy produced at that instant, $E_{net,t}$, is calculated and obtained as an output parameter.

The fluctuations of geothermal generation influence the capacity factor (CF) for a period of time *Tp* (Eq. (5) [66]). For an annual period, *Tp* would be equal to 8760 h. Another important factor on which the geothermal CF depends is the maintenance of the power plant [67]. The operating hours are defined on a monthly basis to accommodate maintenance activities [68]. Considering a standard 8500 annual operating hours [68], a shutdown is included in the model of 65 consecutive hours each quarter, which is equivalent to 260 h of downtime per year. The duration of each shutdown was established taking into account that certain maintenance activities usually require between two and three days [69].

$$CF = \frac{\sum_{t=1}^{Tp} E_{net,t}}{P_n \cdot Tp} \quad (5)$$

In the study, it is considered that the installed capacity of the geothermal plant, P_n, will be equal to its running capacity at the design dead-state temperature, considered to be 15 °C in the case study of the present paper. It will be verified that the installed capacity is always equal to or lower than the access capacity to the island grid. Given that synchronous generators are used in geothermal power plants [70], the assumed access capacity will be the capacity available at the node for synchronous generation modules with direct connection to the transmission or distribution grid.

3.1.2. Estimation of solar PV generation

The second mode of energy supply is the use of non-dispatchable RES such as solar PV. This renewable generation technology can be directly connected to water processing plants to cover their energy demand instantaneously [57]. Therefore, the PV farms are geographically distributed, located in areas close to energy consumers, resulting in decentralised generation within the study area. The PV farms must be connected to the conventional grid to enable discharging of the surplus renewable energy produced.

The model includes estimation of the mean production of the PV facilities at time 't', $E_{PV,t}$, through Eq. (6) [71]:

$$E_{PV,t} = P_{PV} \cdot PSH_t \quad (6)$$

where P_{PV} is the total installed PV capacity (in kW) and PSH_t is the magnitude of peak solar hours for the instant 't' (in kWh/kW), which is obtained by dividing solar radiation (in kWh/m^2), see Table 2, by the reference irradiance per peak solar hour (equivalent to 1 kW/m^2) [72].

3.2. Definition of parameters for the comparison of solutions

An evaluation of technical, economic and sustainability aspects is necessary to compare solutions in order to find a trade-off solution that guarantees a balance between different objectives, such as: (i) maximisation of RES share in total electricity demand (SED) or, which is the same, of the degree of self-sufficiency (DSS); (ii) competitive specific generation costs; and (iii) minimisation of demand meeting effort (DME), Eq. (7). A lower DME means a lower renewable energy effort needed to supply the demand in question, in this case water processing systems. The nature of each type of RES determines whether its behaviour is more or less consistent.

$$DME = \frac{P_{RES}}{P_{d,peak} \cdot SED} \quad (7)$$

where P_{RES} is the installed renewable capacity and $P_{d,peak}$ the peak power load.

Evaluation of the levelized cost of energy (LCOE) (in €/MWh) of the RES was calculated through Eq. (8):

$$LCOE = \frac{CAPEX \cdot CRF + OPEX}{\sum_{t=1}^{Tp} E_{RES,t}} \quad (8)$$

where capital expenditures (CAPEX) and operational expenditures (OPEX) represent the initial investment cost of the facility (in €) and the operating and maintenance costs (in €/year), respectively, CRF is the capital recovery factor (Eq. (9)), $E_{RES,i}$ is the electrical energy generated in the instant 't' (in MWh), and Tp is the total number of annual hours.

$$CRF = \frac{i \cdot (1+i)^L}{(1+i)^L - 1} \quad (9)$$

where i is the discount rate and L the useful life of the facility (in years).

The specific land occupation (in m^2/MW) is another parameter used for the comparison of results. This parameter must be taken into account especially in territories where the available surface area for renewable energy exploitation is limited. In the particular case of the Canary Islands, the PV installations currently in operation have a mean specific occupation of approximately 12,000 m^2/MW [73]. According to the data collected in [74], this specific occupancy is among the lowest percentiles of PV farms installed worldwide. Geothermal binary plants have a generalised value of 2700 m^2/MW [75]. These data were used to obtain the results of the case study in the present paper.

3.2.1. Data assumed for LCOE calculation

The low deployment rate of geothermal energy explains why its average CAPEX varies significantly from year to year, with these costs being determined by a small number of geothermal plants. In the period 2018–2022, the average CAPEX of geothermal plants was 3891 €/kW [76] (applying the US dollar to euro exchange rate as of 30 December 2022 [77]). However, the costs of geothermal energy are strongly influenced by the type of technology to be implemented. The vast majority of geothermal plants with binary technology commissioned in this period had total installed costs ranging between 3750 and 5625 €/kW [76]. The latter value was taken as a reference for the case study of the present paper, taking into account the lack of implementation of this technology in the Canary Islands. For its part, it is assumed that the geothermal plant has operating and maintenance costs of 108 €/kW per year [76].

The global mean CAPEX of solar PV parks experienced a significant decrease of 83 % in the period 2010–2022 [76]. There is a wide disparity between the mean CAPEX values for this technology depending on the country in Europe. Spain was the only one of the major European markets whose CAPEX decreased between 2021 and 2022. More specifically, it decreased by 11 %, resulting in a solar PV CAPEX of 729 €/kW [76]. Operating and maintenance costs also decreased for solar PV in 2022, averaging 12.4 €/kW per year.

For calculation of the LCOE, a technical lifetime of 25 years was considered for both the geothermal plant and the PV farms [76], along with a discount rate of 3 %. In addition, the land lease cost was also taken into account. In this regard, the standard price for land rental for solar purposes is 2400 €/(ha·year) [78]. This coincides with the indicative maximum value of the land rental price for solar PV in climate zone V of Spain, which receives the highest global annual mean daily solar radiation (5 kWh/m^2 or more) [79]. The Canary Islands are in this climate zone [80]. For its part, geothermal power presents many similar characteristics to those of the oil and gas sector, including access to subsurface resources, the use of similar technologies, and having similar development timelines and types of environmental impact [81]. Consequently, leases in both sectors also display similarities. Generally, both have similar lease terms and require a nomination fee, as well as the payment of bids, rents, and royalties [81]. The annual rent for a lease for this type of facility is typically 8 % of the land value [82]. Bearing in mind the price for land in the Canary Islands (83,299 €/ha in 2022 [83]), a price for land rental for geothermal purposes of 6664 €/(ha·year) is assumed.

4. Results and discussion

4.1. Supply of electricity with geothermal energy

4.1.1. Results of the sensitivity analysis

Fig. 9(a) shows the specific exergy of the geothermal fluid as a function of reservoir temperature at different dead-state temperatures. It

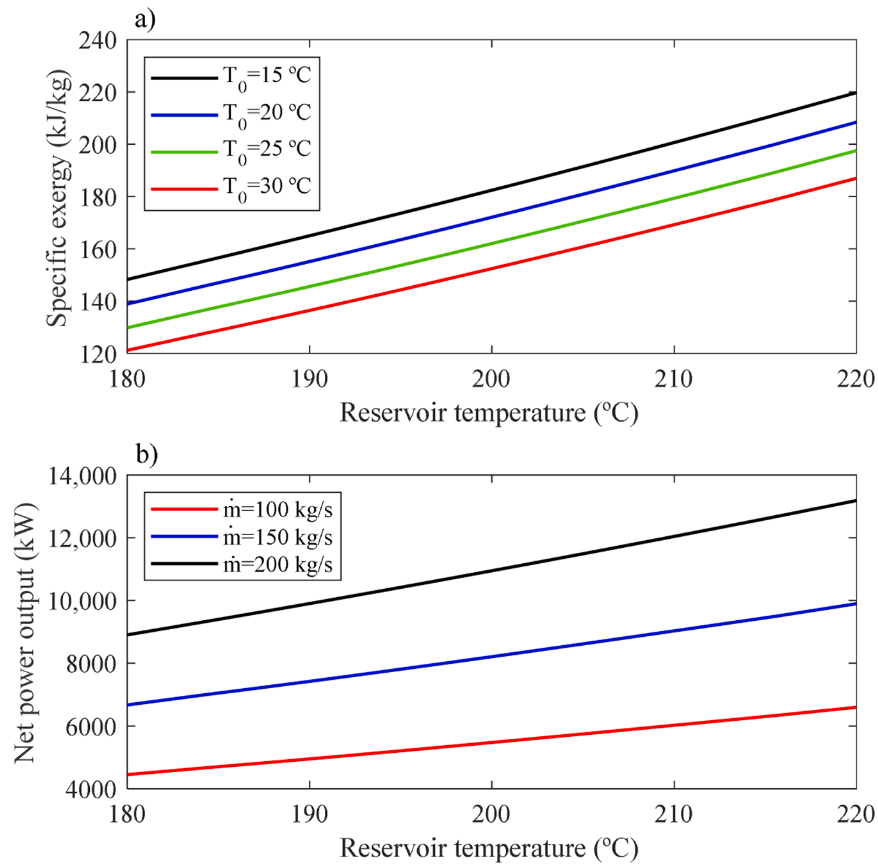

Fig. 9. a) Specific exergy of the geothermal fluid vs. reservoir temperature for the dead-state temperatures of 15, 20, 25 and 30 °C. b) Net power output vs. reservoir temperature for total mass flow rates of 100, 150 and 200 kg/s and the dead-state temperature of 15 °C.

can be seen that the specific exergy of the geothermal fluid increases as the reservoir temperature increases and the dead-state temperature decreases. Fig. 9(b) shows the net power output as a function of reservoir temperature for the total mass flow rates of 100, 150 and 200 kg/s and the design dead-state temperature of 15 °C. The maximum net power output (13,188 kW) is obtained with the total mass flow rate of 200 kg/s of geothermal fluid and the reservoir temperature of 220 °C. In these conditions, the total rate of exergy produced is 43,960 kW. At lower reservoir temperatures and the same value of geothermal fluid mass flow rate, both the total rate of exergy production and the net power output of the plant decrease.

4.1.2. Results of the energy balance with geothermal energy

The annual energy balance was simulated for each of the installable capacities according to the sensitivity analysis developed. Table 3 shows the results of geothermal SED, DME, EEP relative to total energy production, and land occupation, for capacities between 8 and 13 MW. This power range is achievable within the considered ranges of reservoir temperature, mass flow rate of the geothermal fluid, and dead-state temperature (see Fig. 9(b)).

The installed capacity of 11 MW was selected as a trade-off solution because, compared to lower capacities, it allows a significant increase in the degree of self-sufficiency without requiring a significantly higher energy effort. In addition, this option has advantages over higher capacities, such as lower surplus energy production and less land use. For these reasons, the 11 MW capacity is considered to be the one that optimises the joint combination of energy self-sufficiency and territorial sustainability.

Table 3
Results of the on-grid geothermal energy system.

Power (MW)	SED	DME	EEP/Total production	Land occupation (m^2)
8	71.4 %	1.10	0.0 %	21,600
9	80.3 %	1.10	0.0 %	24,300
10	89.2 %	1.10	0.0 %	27,000
11	95.5 %	1.13	2.7 %	29,700
12	97.0 %	1.21	9.4 %	32,400
13	97.0 %	1.31	16.4 %	35,100

It can be seen how from 12 MW onwards the geothermal SED remains constant, which leads to an increase in the DME, and consequently to a decrease in the energy efficiency of the renewable system. In this sense, it is necessary to find a trade-off solution that reduces the effects of oversizing the plant, such as EEP, excessive land occupation, and increased economic costs, while still contributing significantly to the energy demand of the water processing plants. The trade-off solution results in a geothermal SED of 95.5 %. The unsatisfied part of the energy demand is mostly due to the four shutdowns per year due to maintenance activities.

The effect of the local dry-bulb temperature on the net power output of the plant is shown in Fig. 10. It can be seen how the increase in ambient temperature results in a considerable decrease in the power output of the plant. The average monthly net power output of the 11 MW geothermal plant is shown in Fig. 11(a), where the variability of generation due to fluctuating ambient temperature can be seen. The highest average net power outputs are achieved in the winter months. In contrast, the net power outputs are minimised in the summer months. As an example, Fig. 11(b) shows the net power generation profile of the 11 MW plant on a typical day in July. The profile shows that net electricity production is highest during the night, reaching peak values between 6:00 and 8:00, and falls during the day, with the lowest values between 14:00 and 17:00. The variation in weather conditions results in a noticeable fluctuation of the net electricity production of the geothermal

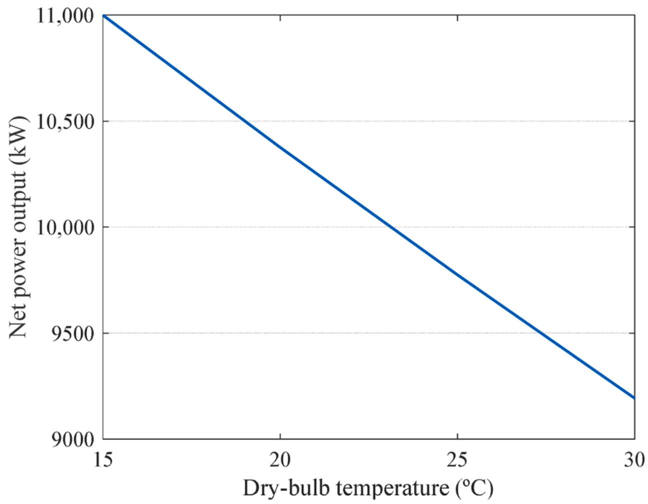

Fig. 10. Net power output of the 11 MW plant vs. the local dry-bulb temperature.

plant. However, this is not as significant as in the case of other intermittent RES.

The plant has a geothermal CF of 0.908. This value was achieved by several real geothermal plants with binary, flash, direct steam and hybrid technologies in the period 2008–2022 [76]. The plant achieves a low DME (1.13) thanks to its high contribution to energy demand and its low production of surplus energy. Specifically, the EEP is 2406.6 MWh/year, which is <5 % of the plant's total production, with the latter considered ideal in terms of energy efficiency according to the literature [84]. This surplus energy covers other parts of the electricity demand not related to the water sector. These results justify the high performance of the geothermal plant configured according to the trade-off solution.

4.2. Energy supply with solar PV

For the solar PV energy supply mode, the energy balance was simulated by varying the total installed capacity from 8 MW to 24 MW. Fig. 12 shows the DSS obtained and the EEP relative to the total production of the PV farms according to the total installed capacity. It can be seen that, for total capacities below 12 MW, the production of surplus energy is practically zero and, therefore, all the energy produced by the PV parks directly covers the energy demand of the water processing plants. However, the degree of demand coverage is <30 %, resulting in an DME of above 4 (see Table 4). The demand coverage increases for higher total installed capacities, but the production of surplus energy also increases (see Fig. 13). Consequently, the share of energy self-consumed by the water processing plants in the total energy produced by PV parks decreases, resulting in a higher DME, which is almost 6 for the total installed capacity of 24 MW. As with geothermal energy, the selection of the trade-off solution for solar PV was based on a compromise between maximising the SED and minimising the negative effects of oversizing the renewable generation system. It can be seen in Fig. 12 that the solar PV SED has a large slope in the power range between 8 and 16 MW. From 16 MW onwards, the slope starts to decrease, resulting in an increase in solar PV SED of <1 % for each MW added. Moreover, for the installed PV capacity of 16 MW, the EEP does not exceed 10 % of the total production of the PV farms, which indicates an optimal energy efficiency according to the literature [84]. In this regard, a total installed capacity of 16 MW was selected as the trade-off solution for solar PV.

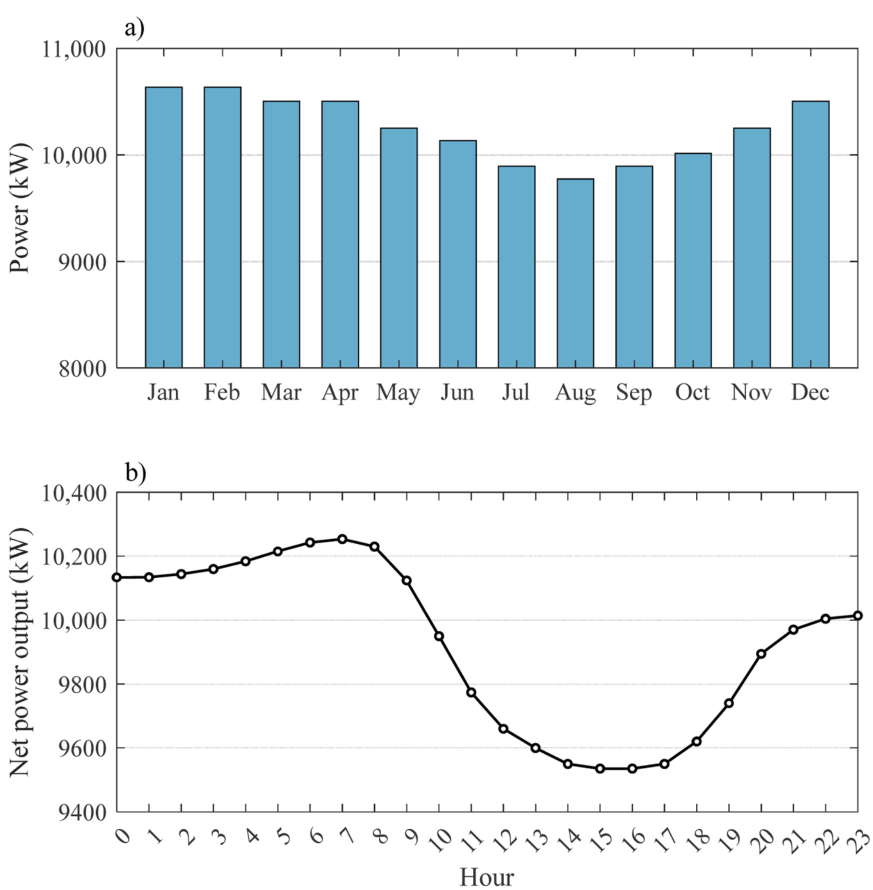

Fig. 11. a) Mean monthly net power output of the 11 MW plant. b) Net electricity generation profile of the 11 MW plant on a typical July day.

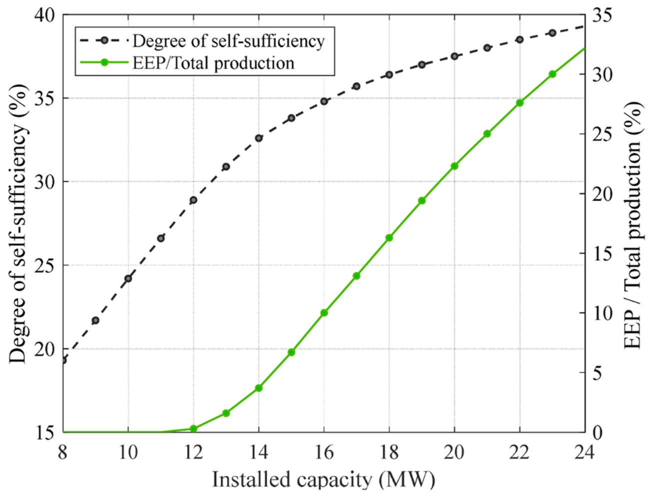

Fig. 12. DSS obtained with solar PV and relative production of surplus energy as a function of total installed capacity.

Table 4
Results of energy supply with solar PV.

Power (MW)	SED	DME	EEP/Total production	Land occupation (m^2)
8	19.3 %	4.05	0.0 %	96,000
12	28.9 %	4.06	0.3 %	144,000
16	34.8 %	4.49	10.0 %	192,000
20	37.5 %	5.21	22.3 %	240,000
24	39.3 %	5.97	32.3 %	288,000

4.3. Comparative analysis

The results of the trade-off solutions for geothermal and solar PV indicate that geothermal is able to increase the degree of demand coverage achieved by solar PV by up to 2.7 times with a land area requirement 6.5 times lower. On the other hand, the DME of solar PV (4.49) is significantly higher than that of geothermal energy (1.13). This is due to the high consistency of geothermal energy, which is able to operate at high output during most hours of the year, easily adapting to demand, which is not possible with solar PV. This is reflected in the CF results, with 0.908 and 0.246 obtained for geothermal and solar PV, respectively.

The CO_2 emission savings were calculated to determine which of the two trade-off solutions is cleaner. Considering the latest official data on the emission factor of the final electricity distributed through the electricity grids of the island of Tenerife, 631 $gCO_{2\text{-eq}}$/kWh [43], the energy consumption of the water processing plants without renewable self-consumption systems represents emissions of 55,616 $tCO_{2\text{-eq}}$/year. Geothermal energy manages to reduce these emissions by 93.8 %, while the savings achieved by solar PV are 31.5 %. The assumed emission factors are 11.3 $gCO_{2\text{-eq}}$/kWh for geothermal energy with binary technology [85] and 60 $gCO_{2\text{-eq}}$/kWh for solar PV [86]. It should be noted that the operational CO_2 emission is near zero in closed-loop binary power plants [87], which minimizes life cycle greenhouse gas emissions. There are several sustainable practices in geothermal energy development that help protect the environment, such as air cooling to minimise water use and targeted injection to mitigate ground subsidence effects [87]. By reinjecting the geothermal fluid back into the reservoir, the damage that the various toxic gases present could cause to ecosystems is avoided.

With regard to the specific generation costs, and for the particular case of the trade-off solutions, the results were 54.38 €/MWh and 26.54 €/MWh for the geothermal and PV installations, respectively. The high CAPEX and OPEX of geothermal energy explain why its LCOE is almost double that of solar PV. However, the LCOE of geothermal is 75.3 % lower than the last official annual data of the average generation cost of the Tenerife electricity system, which amounted to 220.07 €/MWh [32]. This high value is due, among other factors, to the high dependence on imported fossil fuels and the isolated nature of the island's electricity system. Consequently, it is concluded that geothermal energy achieves very competitive specific generation costs.

The integration of geothermal energy into national energy systems is a strategic objective set out in Spanish government planning documents, such as the integrated National Energy and Climate Plan [88]. In the particular case of the Canary Islands' electricity systems, the regional government has developed the Canary Islands Energy Transition Plan [89]. Within the framework of this Plan, specific strategic documents have been drawn up, including one on geothermal energy [16] and another on dispatchable generation in the islands [33]. The results of the present study are intended to contribute to meeting the strategic objectives set at national level and, in particular, those established by the Government of the Canary Islands, within the general framework of energy system decarbonization strategies.

Following publication of the Canary Islands Geothermal Strategy in 2020, this energy alternative has acquired a greater presence in the energy panorama of the archipelago, positioning itself as an economic opportunity for public and private organisations. It is currently at a crucial moment, given that the Ministry for Ecological Transition and the Demographic Challenge has recently opened the first call for grants to perform feasibility studies of deep geothermal energy in Spain [90]. The subsidies include 106 million euros for the Autonomous Community of the Canary Islands.

Others EU countries, such as Ireland, Netherlands, Poland, Croatia, France and Germany, have created national geothermal roadmaps with ambitious targets to make investment in geothermal projects more attractive and encourage their development [91].

All these strategic initiatives in different countries are aimed at removing potential barriers and risks to investment in geothermal energy projects. In addition, the dynamization of this sector will further reduce the CAPEX and OPEX of this type of installation and, consequently, the LCOE of this dispatchable RES.

Fig. 14 presents a summary of DME values obtained by the trade-off solutions of this study and by various hybrid systems proposed in the scientific literature. The latter were calculated from the installed capacity, the peak power load, and the resulting renewable SED for each case. The lowest DME value corresponds to that obtained for geothermal energy in the trade-off solution of this paper. The hybrid systems proposed in other papers present higher DME values, since they require an oversizing of the renewable power capacity to increase the SED, as in the case presented by Dallavalle et al. [11], in which a total capacity of 17, 670 kW is installed through wave energy and solar PV, with which 85 % of the energy needs of a desalination plant with a peak power load of barely 2000 kW are satisfied, resulting in a DME of 10.4 (see Fig. 14). The hybrid wind/PV system studied in [4] achieves a relatively low DME (3.20) but requires a certain water storage capacity to increase the RES contribution. Fig. 14 shows how another hybrid PV/wind system, without energy storage systems, has a higher DME. From this comparative analysis it is concluded that the constant and efficient operation of geothermal energy allows coverage of a large part of the energy demand without having to significantly oversize the installed capacity, which is necessary when non-dispatchable RES are employed.

5. Conclusions

Industrial processes for large-scale desalination and water treatment have quite high energy consumptions. Their overall energy demand is usually significant for the electrical systems. The case study of this paper focuses on the Canary Islands. Like other regions, the Canary Archipelago, due to its climatic conditions, is characterised by a high dependence on water production from desalination processes. For this reason, and

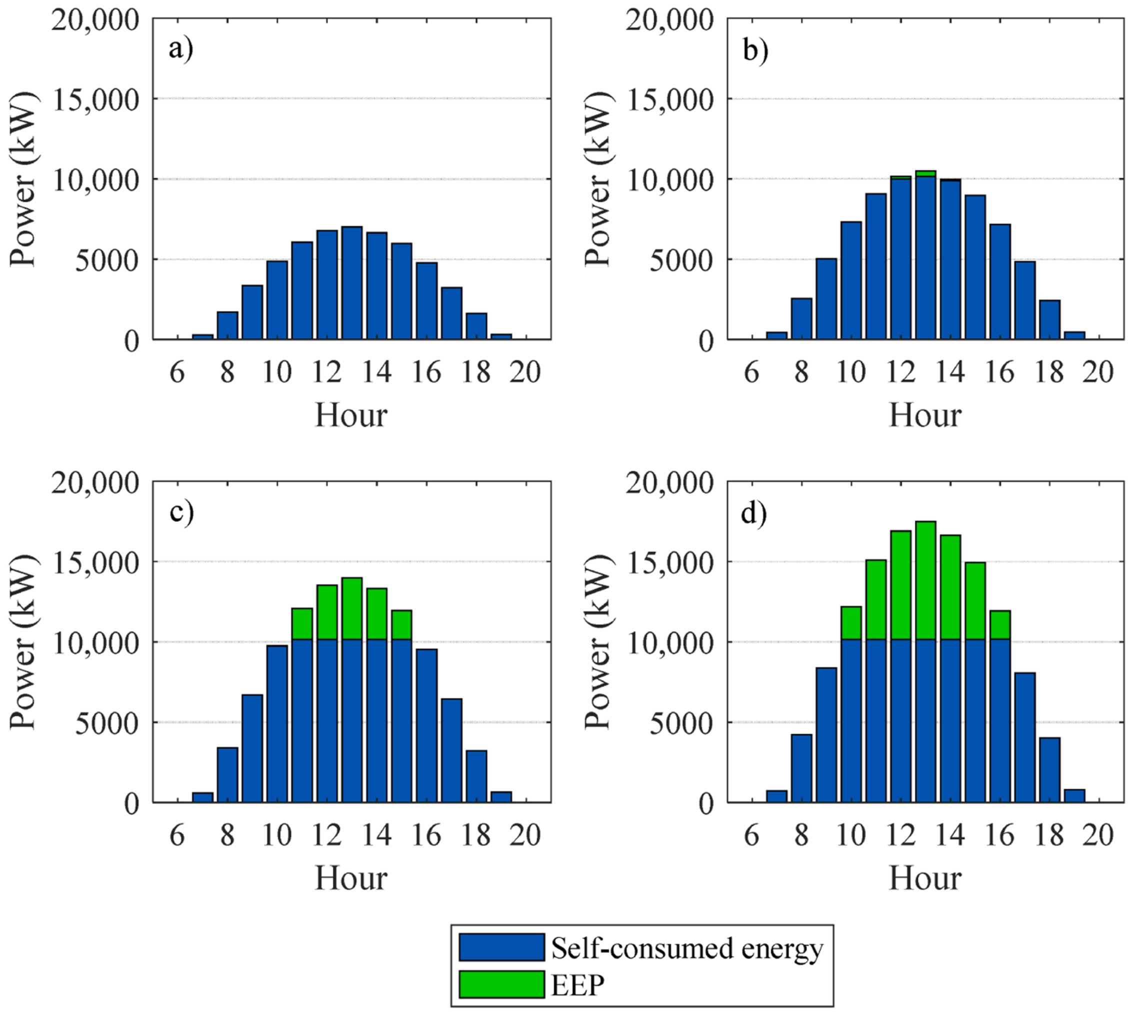

Fig. 13. Profile of solar PV generation for a typical summer day with installed capacities of: a) 8 MW; b) 12 MW; c) 16 MW; and d) 20 MW.

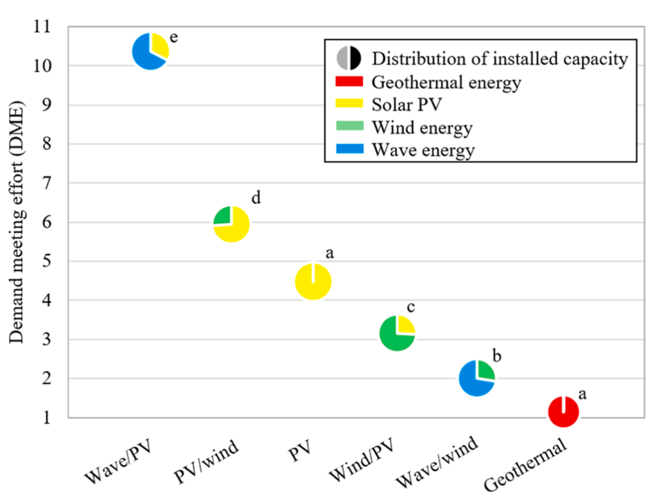

Fig. 14. Comparison of the DME of the trade-off solution obtained in this study with other hybrid renewable systems proposed in the scientific literature: [a] This study; [b] Ref. [92] (case 2); [c] Ref. [4] (Pareto optimal solution); [d] Ref. [10] (system A_2); [e] Ref. [11].

because water is a fundamental and critical commodity, the large water production facilities on the islands are publicly owned. They tend to operate continuously throughout the year, with little fluctuation in production. In support of the sustainability of water treatment processes, numerous research studies found in the scientific literature have analysed the use of non-dispatchable renewable energy sources, such as wind, wave and solar PV, as a means of supplying the electricity needs of this type of process.

In the study carried out in this paper, a method was developed to analyse the effects of the incorporation of geothermal power in the water-energy nexus, comparing the results with those obtained for an alternative system consisting of a non-dispatchable renewable installation. The method was applied to a case study of an island electricity system, in which the results obtained when supplying the energy requirements of a set of seawater desalination and wastewater treatment plants by means of a geothermal installation were compared with those obtained for a PV installation. Different simulations were carried out for each of the two renewable energy sources, from which the trade-off solutions for each of these were identified and finally compared.

Specifically, the method was applied to an area of the island of Tenerife which most likely contains high-temperature geothermal resources. To estimate the geothermal power generation, the reservoir and ambient temperatures were used as input parameters of the model, while solar radiation data were used to estimate the solar PV production. The results obtained in this particular application confirm the following advantages of geothermal energy with respect to the alternative non-dispatchable RES (solar PV):

i) Lower renewable energy effort to cover the electricity demand of water processing plants. In the case of trade-off solutions, the PV facility requires 4.0 times more installed capacity to achieve the same degree of demand coverage as the geothermal installation.

ii) More constant and stable electricity supply. Geothermal installations have a much more regular coverage of demand, both in the different seasonal periods and in the hourly period of a typical day.

iii) Lower land occupation. This indicator is of great interest for territorial sustainability, especially in regions with limited land. In this sense, from the results obtained for the trade-off solutions, the degree of demand coverage achieved with geothermal energy was 2.7 times higher than that of solar PV, requiring 6.5 times less land.

iv) Higher greenhouse gas mitigation. Binary geothermal technology has a lower emission factor and higher demand coverage, with the latter reducing dependence on conventional fossil fuel generation which significantly reduces CO_2 emissions.

Additionally, the result obtained for the demand meeting effort of the resulting trade-off solution with the geothermal installation was compared with other reference studies in the scientific literature, in which hybrid renewable systems have been employed using a combination of solar energy, wind energy and/or wave energy. From this comparative analysis it was deduced that the hybrid systems proposed in other papers present higher DME values, since they require an oversizing of the renewable power capacity to increase the SED.

There are some disadvantages with respect to the geothermal energy that should be recognised, including a lack of knowledge of the various properties of the geothermal resource, greater restrictions on the location of the resource and greater distance from consumption points, as well as higher economic costs in electricity generation. In this sense, further studies are needed to update knowledge about the characteristics of the geothermal resource, as well as support policies for the promotion of this type of dispatchable and consistent renewable facility with the aim of boosting their economic activity to thereby achieve a reduction in the specific installation costs.

CRediT authorship contribution statement

Fernando Montesdeoca-Martínez: Writing – original draft, Visualization, Software, Investigation, Data curation, Conceptualization. **Sergio Velázquez-Medina:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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