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Geothermal energy exploitation in an island-based 100% renewables strategy. Case study of Tenerife (Spain)

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A R T I C L E I N F O

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A B S T R A C T

The large-scale integration of non-dispatchable renewable energy must be carefully planned, especially in poorly robust electrical energy systems. Tenerife is the most populated of the islands in the Canary Archipelago (Spain) and has an isolated electrical system. It is envisaged for the horizon of 2040 that the island will have a high contribution of non-dispatchable renewable energies (fundamentally wind and solar photovoltaic). Tenerife also has exploitable high enthalpy geothermal resources. An energy planning model is implemented in this paper based on which different scenarios with high non-dispatchable renewable energy penetration in the island's electrical system are simulated. Geothermal energy is also incorporated in the simulations as a dispatchable renewable energy source, with the power required sized according to the hypotheses of each scenario. The results are compared according to different technical and economic parameters. An evaluation is also made of the influence that the capacity of the electrical system to take on higher non-dispatchable renewable power and the presence of energy accumulation systems might have on the minimization of losses in the non-dispatchable renewable energy capacity factor. The results of the simulated scenarios show that geothermal energy could meet up to 28.8% of the island's electrical energy demand, increasing the stability, flexibility and supply guarantee of system. A 100% renewable system could be possible through the incorporation of this energy source and the planning of energy accumulation systems. In the case study, the economic saving for Spain's electrical system could exceed 400 €million per year.

1. Introduction

Promoting the integration of electricity from renewable sources is crucial to achieve at least 32% of the European Union's (EU) gross final energy consumption from renewable sources by 2030, which is the overall binding EU target for that year set out in Directive (EU) 2018/2001 of the European Parliament and of the Council (2018). Spain's integrated National Energy and Climate Plan for 2021–2030 (Government of Spain, 2020) proposes the use of different support schemes, such as corporate participation, financing and joint ventures, to promote the development of unique projects involving the use of new renewable technologies, such as high-temperature geothermal energy for large-scale electricity generation, which does not have a market in Spain despite being a mature technology. Measures such as this are necessary to achieve the goal of 74% of Spain's electricity generation coming from renewable sources by 2030. This national plan (Government of Spain, 2020) pays special attention to non-mainland territories such as the Canary Islands, given their high dependence on oil and their special characteristics which include size-limited territory, distance from the mainland, insular nature and the small size of their electricity systems which makes them weak.

Currently, there are several island territories where geothermal energy has been integrated into their corresponding energy systems. Iceland is a clear example of the exploitation of geothermal resources on island territory. According to Iceland's National Energy Authority (Iceland's National Energy Authority, 2021), geothermal resources accounted for 70.4% of Iceland's primary energy use in 2020. Some applications of the direct use of geothermal resources in Iceland are space heating, bathing, industrial uses, greenhouse heating and snow melting. With respect to its electricity mix, Iceland had 755.9 MW of geothermal power installed in 2021 (Iceland's National Energy Authority, 2022a). Geothermal energy accounted for 29.58% of the 19,614.2 MWh (Iceland's National Energy Authority, 2022b) of electricity

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Nomenclature

AHP	analytic hierarchy process
CF	capacity factor
DER	dispatchable energy resource
GIS	geographical information system
IGME	Geological and Mining Institute of Spain
ITC	Canary Islands Technological Institute
NDRE	non-dispatchable renewable energy
NDREP	non-dispatchable renewable energy penetration
NCG	non-condensable gases
ORC	organic Rankine cycle
PHES	pumped hydro energy storage
POEM	Spain's Maritime Space Ordinance Plans
PV	photovoltaic
REE	Spanish electricity system operator
RF	thermal recovery factor
sGs	sequential Gaussian simulation
toe	tonnes of oil equivalent

supplied in that year, with hydropower the largest contributor with a share of 70.38%. Of the remaining 0.04%, 0.03% came from wind power and 0.01% from fuel oil, resulting in an almost 100% decarbonised electricity system, with a tiny share of non-dispatchable renewable energy (NDRE) sources.

Another example is Hawai'i Island (United States), which has a 38 MW geothermal plant that harnesses high enthalpy geothermal resources from underground reservoirs of water heated by the island's volcanic activity. The plant operates with an advanced flash-binary cycle, and met 18% of the island's electricity consumption in 2022 (Hawai'i State Energy Office, 2023). In addition to geothermal, the island also has other dispatchable energy resources (DERs) such as hydro and biofuels, each contributing 4% of electricity demand in 2020. For their part, solar photovoltaic (PV) and wind energy met 19% and 15% of demand, respectively. The island's renewable contribution therefore amounted to 60% in 2022, with a considerable part of this contribution dispatchable.

In the Azores (Portugal), geothermal energy made the greatest contribution in 2022 among the energy sources of renewable origin, reaching 21% of the total electricity generated in the archipelago (823 GWh). This was followed by wind (8.30%), hydro (4.20%), municipal solid waste (1.30%) and solar (0.30%), compared to 64.90% from non-renewable sources (APREN, n.d.), meaning that more than 70% of renewable generation was from DERs. Most of the geothermal generation in the Azores takes place on the island of São Miguel, which has two binary geothermal plants of 13 and 10 MW. Their operation allows 42% of the island's electricity demand to be covered by geothermal energy (Franco and Ponte, 2019).

New Zealand is another island country where geothermal resources are harnessed to produce electricity. Its electricity generation structure is notable for having a high share of renewable energy sources. In 2022, geothermal energy was the second largest energy source in the country, with a share of 18.5%, equivalent to 8060 GWh (Government of New Zealand, 2023). Hydropower was the country's main energy source, supplying 59.8% of total electricity. This means that almost 80% of electricity generation came from renewable DERs. Of the remaining 20%, wind energy contributed 6.5%.

Several studies have analysed the integration of geothermal energy in island electricity systems. Prasad and Raturi (2022) conducted a techno-economic-environmental feasibility study of a 10 MW organic Rankine cycle (ORC) geothermal plant on the island of Fiji. Plant operation was analysed both in terms of exporting the electricity produced to the grid and as a self-consumption facility for the Vatukoula Gold Mine, located on the island. As a result, the geothermal plant would be able to produce 78.9 GWh/year of electricity, thus avoiding the emission of 39,461 $tCO_{2\text{-eq}}$. It would cover 92.5% of the gold mine's electricity demand, which is currently met by a 19 MW diesel generator. In the case of export to the grid, the geothermal plant would have supplied approximately 29% of the island's total domestic demand in 2020.

The aim of the work by Bhagaloo et al. (2022) was to align the geothermal potential of the island of Dominica with the deployment of clean and sustainable energy production in the Lesser Antilles archipelago, located in the Eastern Caribbean Region. All the islands of this archipelago have isolated electricity systems, which explains their high degree of vulnerability. One of the cases proposed by the authors studies the use of part of the geothermal potential existing on the island of Dominica to make its electricity grid 100% renewable. Geothermal energy would cover 67% of local demand, projected to be 27 MW in 2030, while the existing hydroelectric plants would constitute 37% of the grid. However, the case that achieves the most sustainable results was found to be based on harnessing the abundant energy capacity of Dominica's geothermal resources to supply 100% of the electricity demand of both Dominica and its neighbour Martinique. Of a total geothermal capacity of 434 MW, 27 MW would be exported to Dominica's grid, and 407 MW to Martinique's grid through an underwater cable interconnection. In this way, the emission of 2.5 million $tCO_{2\text{-eq}}$/year would be avoided and dispatchable electricity would be generated at a levelized cost of energy (LCOE) 20% lower than current price projections.

Barbaro and Castro (2020) compared different possible configurations of a hybrid renewable islanded energy system on Faial (Azores, Portugal). Of the resulting optimal solutions, the hybrid system, which consisted of a 5.5 MW geothermal plant, a 6.2 MWh battery energy storage system and wind turbines with an installed capacity of 4.25 MW, achieved the highest renewable energy fraction of 75%, significantly higher than the 24.8% of the current system. This makes it the most ambitious design in terms of renewable penetration. For this reason, and considering it has a positive net present value, the authors recommended this configuration despite its not having the highest net present value. The authors highlighted that geothermal energy was the first technology among the optimal solutions. Graça Gomes et al. (2021) carried out a similar study for Corvo, another of the islands in the Azores archipelago. One of the scenarios analysed in their study was based on a renewable microgrid that includes geothermal energy, in addition to wind, solar, ocean and bioenergy, to generate electricity. The results of this scenario always recommend the implementation of geothermal energy due to its high capacity factor (CF), its low operational costs and the availability of dispatchable electricity. In addition, geothermal energy achieved a significantly lower surface area requirement for such a microgrid than the microgrids studied in the other scenarios. However, the renewable microgrid with the lowest LCOE comprised solely wind, solar PV, and hydro pump storage.

Kavadias et al. (2019) proposed implementation of a 40 MW hybrid solar-geothermal plant on the volcanic Greek island of Nisyros. This island is electrically interconnected to eight other Greek islands through the Kos-Kalimnos autonomous grid. The hybrid plant would be able to cover more than 60% of the island complex's electricity demand (350 GWh in 2013). It should be noted that the intention with the plant's solar concentrated array is to heat the geothermal brine prior to its reinjection into the aquifer, with the aim of extending the latter's life and productivity. In addition, the power block is made up of a double flash system.

The archipelago of the Canary Islands (Spain) is made up of eight islands, six of which have an isolated electricity system with no interconnections with other island or continental electricity systems. The islands of Lanzarote and Fuerteventura are electrically interconnected via a high voltage (132 kV) submarine cable. Tenerife and Gran Canaria have transmission lines of 220 kV (Canary Islands Government, 2023), while the other islands have onshore transmission lines of only up to 66 kV. In short, the grid system of all the islands is relatively weak. The conventional dispatchable generation fleet of the islands displays high fragility, given that 31.7% of the 2303.71 MW currently installed does not meet the regulatory conditions in relation to useful life (Canary Islands Government, 2022a). The installed power of this fleet is technologically structured as follows (Canary Islands Government, 2023): combined cycle (35.2%), gas turbine (23.1%), diesel motor (21.7%), and steam turbine (20%). Renewable technologies represent 25.8% of installed power in the generation structure of the islands (REE, n.d.a). Conventional generation using fossil fuels in thermal power plants accounted for 79.9% of the electricity generated in the Canary Islands in 2022 (REE, n.d.a). This high share explains the low diversification of the Canary Islands' electricity systems. In addition, some 98% of the renewable electricity generated in 2022 came from wind and solar PV (REE, n.d.a), both of which are characterised as NDRE resources as they are strictly dependent on weather conditions, which makes it difficult to guarantee electricity supply and increases the likelihood of imbalances in the electricity system. This situation further intensifies the weakness of the Canary Islands' electricity systems. In the scientific literature, several planning research works can be found to aiming maximise in a controlled manner the non-dispatchable renewable power in the isolated electricity systems of the Canary Islands. Velázquez-Medina and Santana-Sarmiento (2021) developed a method based on an analytic hierarchy process (AHP) and geographical information systems (GIS) to identify areas for the self-consumption of wind and PV energy in rural areas, promoting distributed electricity generation. Taking into account the high dependency of islands, such as those in the Canary Archipelago, on desalination processes to obtain drinking water, and the high energy consumption of these processes, Cabrera et al. (2021) developed a method to maximise the contribution of wind and PV energy in the electricity consumption of these processes. To do so, they studied the specific case of the island of Lanzarote. Among other conclusions, the authors deduced that it was necessary to make desalination processes more flexible and to plan water storage systems in order to maximise this integration. Barone et al. (2021) used the island of El Hierro as a case study to test the potential of their novel dynamic simulation tool for the optimization of the islands' energy system configurations, paying special attention to the case of the adoption of renewable energies characterised by their unpredictable behaviour. After simulating various scenarios, they concluded that the wind-power pumped hydro storage plant was the most promising solution for the generation and storage of electrical energy, achieving significant primary energy savings. In addition, the adoption of solar PV fields and solar thermal collectors for domestic hot water production also showed significant energy savings. Díaz et al. (2015) identified the problem in the Canary Islands, and particularly Tenerife, of the potential large-scale integration of NDREs, due to the instability they can cause in the islands' electricity systems. They developed a study of the potential benefit of incorporating the batteries of electric vehicles as a potential distributed load in order to minimise the impact of their integration.

Given the shortcomings identified above, it is evident that the Canary Islands' electricity systems require a structural change. One of the strategic objectives of the Energy Transition Plan of the Canary Islands (Canary Islands Government, 2022a) is to promote the massive incorporation of renewable energies in order to minimise energy dependence on external sources. The Canary Islands is one of the regions in the world with the greatest wind and solar potential. In this sense, one of the objectives of the plan is the large-scale integration of these renewable energy sources. Strategies for such large-scale integration in weak electricity systems, such as isolated systems, require studies to be conducted in the following lines of research: (i) the incorporation of energy storage systems in electrical energy systems; (ii) the stability of electrical energy systems; (iii) the promotion of distributed electricity generation; (iv) the greater use of dispatchable renewable energy sources, etc. Regarding the last line of research mentioned, the Canary Islands Government has published a strategic document to promote the exploitation of geothermal energy in the Canary Islands (Canary Islands Government, 2020a). The volcanic origin of the Canary Islands archipelago and its consequent volcanic activities have led to the execution of various geothermal exploration studies, giving rise to a fairly mature exploration phase on some islands such as Tenerife, La Palma, and Gran Canaria. According to the results of these studies, there is a high geothermal potential in different areas of the islands in comparison with other regions at European level (Canary Islands Government, 2020a), with the expected existence of medium and high enthalpy geothermal resources, and therefore the possibility of generating electricity from them, among other possible energy uses. Geothermal energy is controllable, firm, flexible and reliable (Bhagaloo et al., 2022), making it a DER. Its response to disturbances in contingency situations can reach the standards achieved by conventional generation (Canary Islands Government, 2020a). Moreover, geothermal energy is considered a clean energy source as it has a very high environmental performance compared to other energy conversion technologies (Karlsdottir et al., 2020). These advantageous features justify its presence among the energy alternatives to be incorporated into the Canary Islands' electricity systems in order to achieve decarbonisation by 2040 (Canary Islands Government, 2022a).

To date, five areas of Tenerife have been granted mining permits (expiration date still to be determined) for the exploration and investigation of geothermal resources: Abeque, Garehagua, Garehagua II, Berolo and Guayafanta (Canary Islands Government, 2020a). Around the central volcanic structure of the island there are three rift zones: northwest, south and northeast. The study zone of Abeque is situated in the northwest rift zone, Garehagua and Garehagua II in the south rift zone, and Berolo and Guayafanta in the northeast rift zone.

Diverse geophysical and geochemical studies of geothermal exploration have been undertaken in these areas with mining permits that reveal useful information to obtain a more detailed characterization of the subsoil of the island. A 1060 m deep thermal gradient survey was carried out between 1990 and 1993 in the area of Abeque. A thermal gradient of 94 °C/km was found in the last 160 m (Canary Islands Government, 2020a), a result significantly higher than the mean values, which increases the likelihood of the existence of high enthalpy geothermal resources. In addition, the last metres that were drilled comprised an impermeable layer of ancient highly hydrothermally altered basalts (IDAE, 2011). Piña-Varas et al. (2014) developed a 3-D model of the electrical resistivity of the subsoil of Tenerife based on data provided by 148 of the 233 magnetotelluric surveys carried out by the Geological and Mining Institute of Spain (IGME by its initials in Spanish) (IGME, n.d.), Petratherm (Petratherm, n.d.) and the University of Barcelona (University of Barcelona, n.d.) between 1987 and 2012. The aforementioned study shows two vertical cross-sections of resistivity (one north-south and the other east-west) and horizontal slices at various depths generated using the magnetotelluric model. Piña-Varas et al. (2018) detected shallow phonolitic magma chambers located at a depth of between 1 km above sea level and 2 km below sea level (b.s.l.), and a large-scale mafic reservoir located at depths shallower than 8 km b.s.l., which enable interpretation of the subsoil of Tenerife in a high-temperature geothermal system context. Finally, Rodríguez et al. (2021) undertook a geochemical analysis based on the results of several diffuse carbon dioxide (CO_2) degassing surveys carried out at 2635 sampling sites distributed across the five study areas of Tenerife in the period 2011–2014. Based on a ranking of geochemical indicators, the authors concluded that Garehagua II, Garehagua and Abeque were the study areas with the strongest likelihood of containing geothermal resources. This study includes spatial distribution maps of soil diffuse CO_2 efflux and volcano-hydrothermal contribution constructed using a sequential Gaussian simulation (sGs) algorithm. These maps display surface geothermal manifestations which are not as visible in the Canary Islands as in other active volcanic systems. Based on the results, the authors argue that the island presents several environments with the potential to host volcanic-driven convective hydrothermal systems.

The novel contribution of this paper is based on a study of the incorporation in the electrical energy system of the island of Tenerife of a group of geothermal plants for electricity production and their adaptation within the framework of a strategy of high NDRE penetration (mainly wind and solar PV) that the Canary Islands Government has proposed for the island by 2040. The operating hypothesis for the geothermal plants was developed based on their incorporation as dispatchable generation in the system, replacing current conventional generation, with the aim of increasing the total renewable contribution to the system, while maintaining the guarantee and quality of the electricity supply. To this end, a Matlab-implemented model was developed to simulate different electrical energy system scenarios based on the prediction of renewable generation and electricity demand for the time horizon considered. For each of the scenarios, various technical and economic parameters are evaluated. These include, among others, the required geothermal power, the contribution to demand of each of the renewable energy sources considered, the specific costs of renewable energy, the energy accumulation needs that maximise the CF of the NDREs, and the overall economic saving that the new sustainable energy mix proposed in each simulation entails for the Spanish electrical system.

The model implemented can be used for the simulation of any electrical energy system, especially weak systems, in which the aim is to incorporate a high non-dispatchable renewable power. The generation of electricity through different renewable energy systems contributes to the optimization of distributed and decentralized generation systems that is necessary for the best possible management of weak electrical energy systems, and in this may to ensuring the quality and stability of the supply. The resulting technical and economic parameters of the different simulations can serve as a strategic guide in the development of any energy plan.

2. Method and materials

The method followed for the implementation in Matlab of the developed model is shown in Fig. 1. Following this method, different scenarios are simulated, based on which diverse technical and economic parameters are evaluated and compared.

2.1. Estimation of the electrical energy demand of the island of tenerife

Tenerife is the most populated island in the Canary Archipelago. Its total installed power at the end of 2021 was 1417.6 MW (Canary Islands Government, 2023). Total electrical energy demand in 2022 was 3412.4 GWh (Canary Islands Government, 2023), (REE, n.d.c), equivalent to 40% of the consumption of the entire archipelago.

The energy balances analysed in the different simulations conducted in the present study (Fig. 1) were evaluated with an hourly frequency. For this, an estimation was made of the hourly electricity demand of the island for the horizon of 2040. For this hourly estimation, data on the island's hourly energy demand for 2022 were taken from the website of the Spanish electricity system operator (REE by its initials in Spanish) (REE, n.d.b). For estimation of the hourly demand curve, a distinction was made between two periods: winter and summer. This was based fundamentally on the significant variation between the two periods of the potential of non-dispatchable renewable energy (wind and solar) in the archipelago. The months representing the summer period were taken as those from June to September, with the remaining 8 months corresponding to the winter period. Additionally, in each of the two periods a distinction was made between working days and non-working days due to the considerable variation in electrical energy demand between the two. In summary, hourly demand was determined for 4 types of day. The starting point data consulted for 2022 to calculate the mean hourly

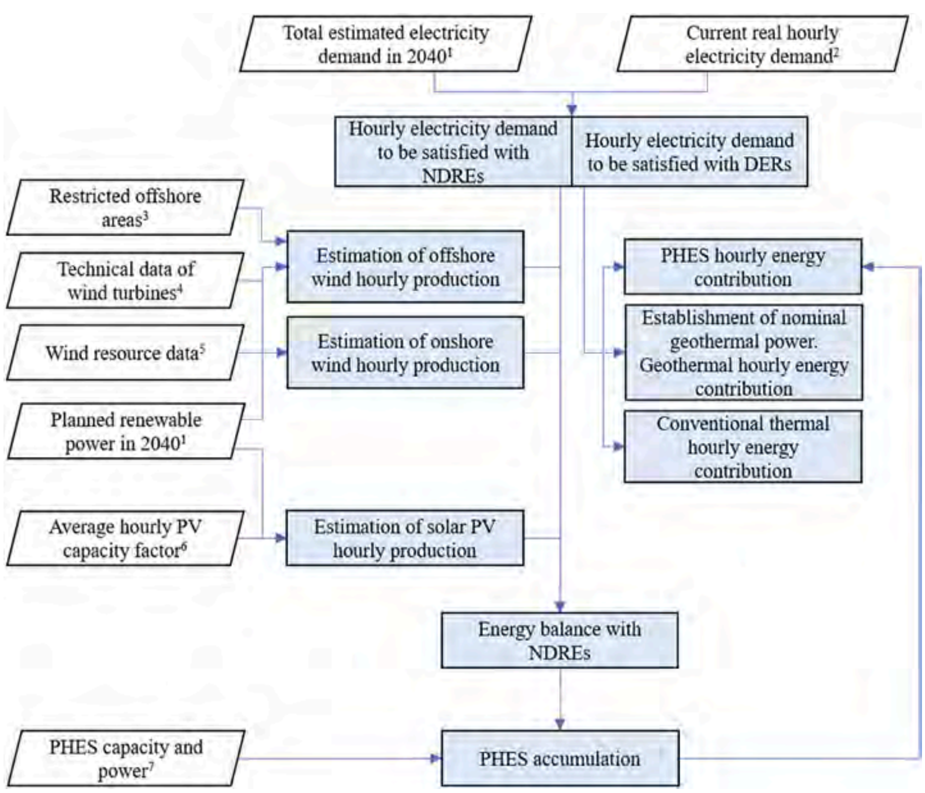

Fig. 1. Developed method.
[1] Canary Islands dispatchable generation strategy (Canary Islands Government, 2022b) [2] Real-time electricity demand (REE, n.d.b) [3] Maritime Spatial Plans (Government of Spain, 2023) [4] Technical data of onshore and offshore wind turbines (Enercon, n.d.; Siemens Gamesa, n.d.a; General Electric, n.d.; Siemens Gamesa, n.d.b) [5] Global Wind Atlas (University of Denmark and the World Bank Group, n.d.) [6] Royal Decree 413/2014, of 6 June (Government of Spain, 2014) [7] Canary Islands Energy Storage Strategy (Canary Islands Government, 2021).

demand for each type of day were as follows.

- 8 winter working days (first Monday of each winter month)
- 4 winter non-working days (first Sunday of January, March, May and November)
- 8 summer working days (first and second Monday of each summer month)
- 4 summer non-working days (first Sunday of each summer month)

Finally, these four types of day were proportionally scaled, maintaining their profiles, to the estimated total electrical energy demand for Tenerife in 2040, which is 3632 GWh (Canary Islands Government, 2022b). In this way, the four types of daily profiles of hourly electrical energy demand for the horizon of 2040 were obtained (Fig. 2).

2.2. Capacity of the geothermal resource

2.2.1. Identification and energy capacity of the geothermal reservoirs

In a previous paper, the authors identified potential areas with high enthalpy geothermal resources on Tenerife and estimated their energy capacity using the volumetric method (Montesdeoca-Martínez and Velázquez-Medina, 2023). With this method, the amount of energy stored in the form of heat in the rocks and fluids contained in the volume of the corresponding geothermal reservoirs can be determined. The mineralogical and electrical resistivity characteristics of the different areas of Tenerife at different depths were used to identify the geothermal reservoirs. Subsoil differentiation was based on a 3-D interpretation of magnetotelluric and seismic topographic models developed for the island of Tenerife by García-Yeguas et al. (2017). Fig. 3 shows the location of the high enthalpy geothermal reservoirs that were identified. These 700 m thick reservoirs are situated at a depth of 2000 m b.s.l. and form part of the central igneous core of Tenerife. They are characterized by the combined effect of shallow aquifers, and sedimentary and volcanoclastic multi-fractured systems. This rock fracturing is due to hydrothermal alteration. These areas also present high permeability and electrical resistivity (36 **Ω** m in this case), and therefore meet the mineralogical and electrical resistivity conditions of high temperature geothermal systems (Cherkose and Mizunaga, 2018). The northernmost reservoir (GR-4) is situated in a Nature Park which forms part of the Canary Islands Network of Protected Natural Spaces (Grafcan, 2008), and therefore exploitation of its geothermal resources had to be discarded. Table 1 shows the resulting surface area and recoverable heat values of the three geothermal reservoirs of interest, with the latter being the product of the heat stored in the geothermal reservoir and the

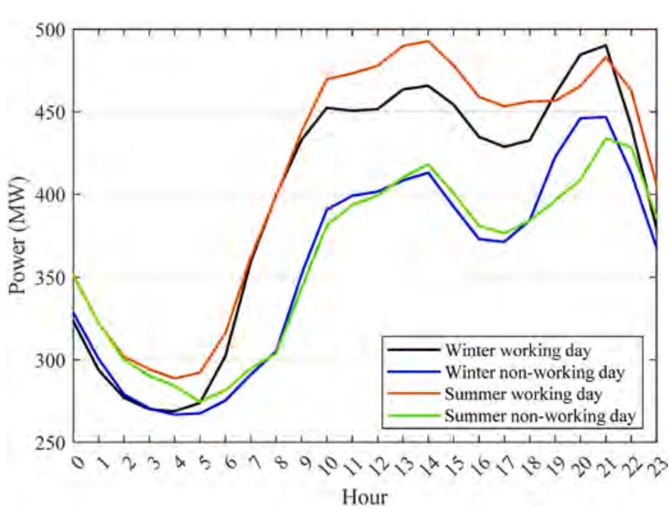

Fig. 2. Daily profiles of the hourly electrical energy demand of Tenerife in 2040.

thermal recovery factor (RF), whose value for the useful life of the geothermal plant is 0.15 (Montesdeoca-Martínez and Velázquez-Medina, 2023). This means that 15% of the heat stored in the reservoirs is recovered at the wellhead. These geothermal energy data obtained from the previous study by Montesdeoca-Martínez and Velázquez-Medina will serve as initial data for the research study undertaken in the present paper. Here, the geothermal energy is integrated in a renewable energy mix in which other non-dispatchable energy sources intervene with the aim being for the island's electrical system to be as close as possible to 100% renewable, while maintaining the stability and quality of the supply.

2.2.2. Technology for geothermal resource exploitation

Various factors are analysed below to determine the most appropriate technology for the exploitation of Tenerife's high enthalpy geothermal resources. The sustainability of a geothermal project is crucial, and this can be affected if the geothermal fluid contains non-condensable gases (NCGs) (Manente et al., 2019a,b). Geothermal fluids from volcanic deposits such as those of Tenerife may contain NCGs (Canary Islands Government, 2020a). For this reason, a technology must be selected which is able to eliminate this environmental hazard. In ORC systems, the geothermal fluid never enters in contact with the atmosphere as it is reinjected into the reservoir as soon as it has given up part of its heat energy to the working fluid of the ORC. However, it should be noted that the action of reinjecting the NCGs of geothermal fluids implies significant power output penalty and water demand (Manente et al., 2019a,b). Given the scarcity of water in the Canary Islands (Rosales-Asensio et al., 2022), the use of dry cooling systems is recommended for heat evacuation. In this regard, air condensation is compatible in ORC systems (Langiu et al., 2022), but is not appropriate for other technologies such as flash cycles (Canary Islands Government, 2020a).

Contributing flexibility to the island's electrical system is another important factor. The electrical system of Tenerife, like those in the rest of the archipelago, is characterised by a high degree of centralization due to the importance of the conventional power plants in the generation structure. This makes it a poorly flexible system which is limited in terms of the integration of renewable energies. The incorporation of smaller-sized generator groups would give greater flexibility to the system, allowing a higher renewable input. In the dispatchable generation strategy of the islands (Canary Islands Government, 2022b), a maximum size of 50 MW is enforced in Tenerife, but the recommendation is for generators not to exceed 25 MW. In this regard, ORC geothermal plants are of interest as their mean and maximum power per unit are currently 13 MW and 35 MW (Wieland et al., 2023), respectively.

Therefore, for the above reasons, the ORC geothermal system was chosen as the most appropriate technology for exploitation of the geothermal resources analysed in the present paper. Fig. 4 shows a flow diagram of the ORC geothermal system which will be employed to generate electrical energy from geothermal energy in the case study of the present paper. The binary system comprises two separate closed loops. Taking place in the first of these closed loops is the extraction, phase separation and reinjection of the geothermal fluid. Phase separation is necessary to extract NCGs (mainly CO_2 and H_2S) form the geothermal fluid, thereby avoiding their intrusion in the heat exchangers. The NCGs are compressed before their reinjection. The organic working fluid flows in the other closed loop and is subjected to the following thermodynamic processes: steam turbine expansion (process 1–2), heat yielding in the recuperator (process 2–3), condensation (process 3–4), compression (process 4–5), heat recovery (process 5–6), preheating (process 6–7), and evaporation (process 7–1). In the expansion process, the working fluid is in vapour state due to prior absorption of the heat given up by the geothermal fluid, and the turbine converts the kinetic energy of its flow into mechanical work, which is subsequently transformed into electrical energy. A heat recuperator is

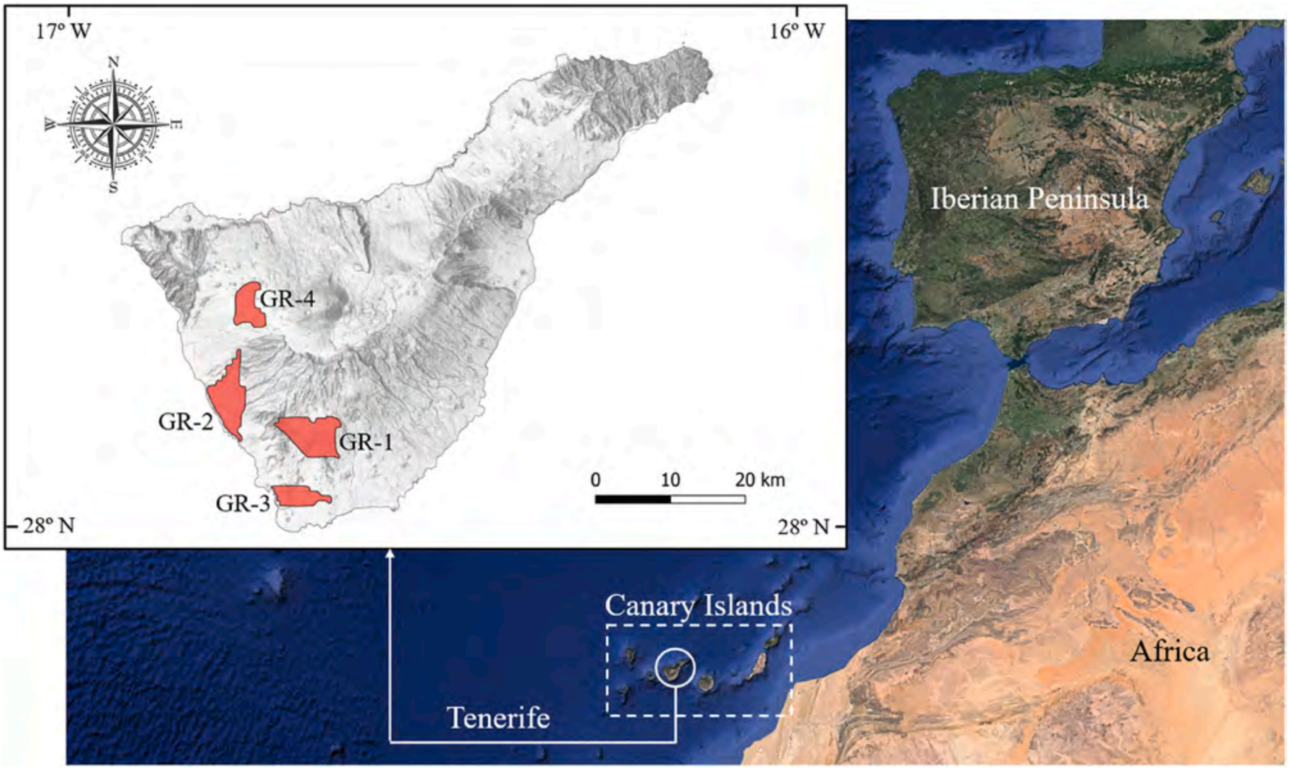

Fig. 3. Geographical location of the island of Tenerife and the respective high enthalpy geothermal reservoirs identified at 2000 m b.s.l.

Table 1
Surface area, stored heat and recoverable heat of the identified geothermal reservoirs with an RF of 0.15 (Montesdeoca-Martínez and Velázquez-Medina, 2023).

Identification	GR-1	GR-2	GR-3
Surface area (km^2)	33.3	30.5	15.5
Stored heat (TJ)	1,921,475	1,759,696	893,771
Recoverable heat (TJ)	288,221.2	263,954.4	134,065.6

incorporated with the aim of reducing the heat load on the dry cooling system. Regarding the condensation process, as a dry cooling system is used based on an induced draft air cooled condenser, the minimum temperature at which the working fluid can be condensed will depend on the ambient dry temperature, with a normal margin between the two temperatures of 15 °C (IDAE, 2007).

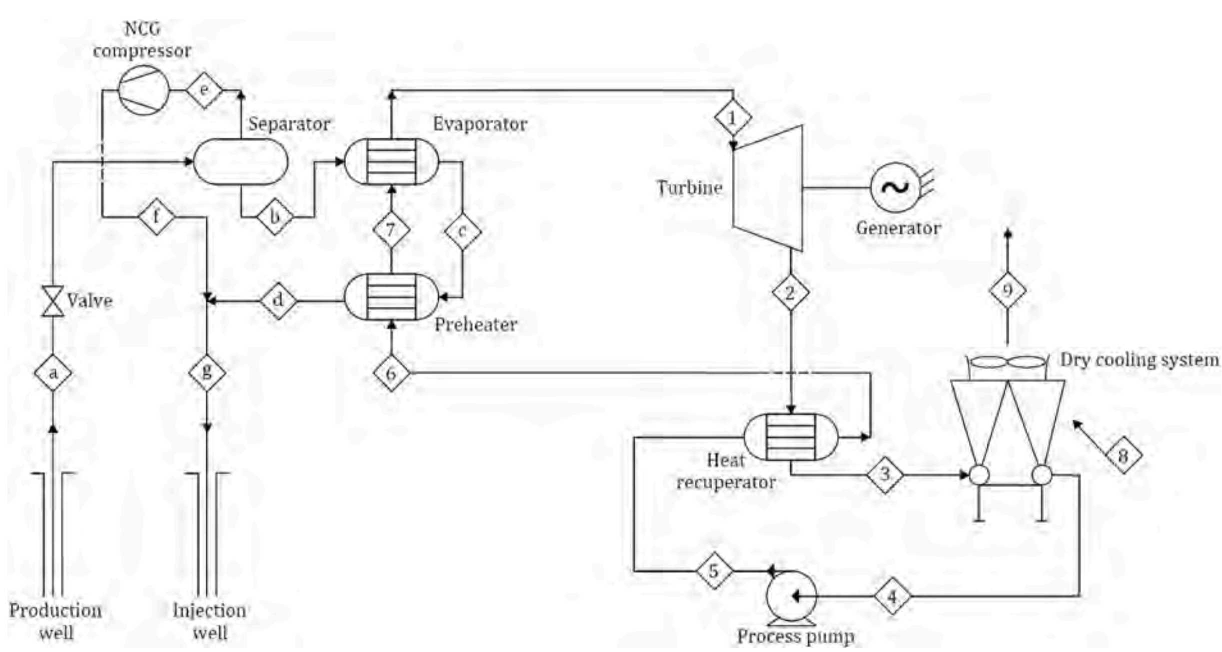

Fig. 4. Flow diagram of the ORC geothermal system. States 1–7, 8–9, and a-g correspond to the working fluid, air, and geothermal fluid, respectively.

2.3. Energy balance with NDREs

As described in section 2.1., the analysis of the energy balances was carried out according to two different periods of the year: winter and summer. An estimation was therefore made of the electrical energy generation of the NDREs for each period separately.

2.3.1. Estimation of onshore and offshore wind hourly production

In the dispatchable generation strategy of the Canary Islands (Canary Islands Government, 2022b), modelling has been developed for the 2022–2040 period through which the optimal annual evolution is estimated of the power to be installed in Tenerife for each type of electrical energy generation technology based on the ideal configuration for the island's electrical system. In 2022, the installed onshore and offshore wind powers were 195.65 and 0 MW, respectively. The optimal installable powers for 2040, following the evolution set out in the corresponding document are 1568 and 505.3 MW, respectively. Comparing the powers in the two years and taking into consideration the time periods required for the execution of these types of projects (including administrative procedures), we consider that this ideal hypothesis is unrealistic. Therefore, for the present study, we have taken as installed actual powers for the year 2040 those presented in the corresponding document for 2030, namely 568.5 MW and 130 MW, respectively (Canary Islands Government, 2022b).

Estimation of the daily profile of wind generation was made based on estimation of the wind CF, with this being the ratio of actual yearly production over the theoretical maximum that would be achieved if perfect wind conditions lasted all year long (both in MWh) (Boccard, 2013).

For this purpose, use was made of the free web-based application Global Wind Atlas (University of Denmark and the World Bank Group, n.d.) to generate high resolution raster maps in 'tif' format with the CF distribution in different areas of the island. To generate these maps, it is necessary to select a wind turbine model and its power curve as input data. Thus, CF maps were generated for each area of Tenerife corresponding to each selected wind turbine. The different onshore wind turbines selected were the 4.2 MW Enercon E−115 EP3 E3 (Enercon, n.d.) and the 5 MW S Gamesa SG 5.0–132 (Siemens Gamesa, n.d.a). The selected offshore wind turbines were the 13 MW General Electric Haliade-X (General Electric, n.d.) and the 8 MW S Gamesa SG 8.0–167 DD (Siemens Gamesa, n.d.b), with both of these included among the potential offshore wind turbines to be installed in the archipelago according to the marine energies strategy of the archipelago (Canary Islands Government, 2022c).

The wind CF maps that were obtained were subsequently introduced as a raster layer in QGIS (OSGeo, n.d.), a free and open source GIS, to

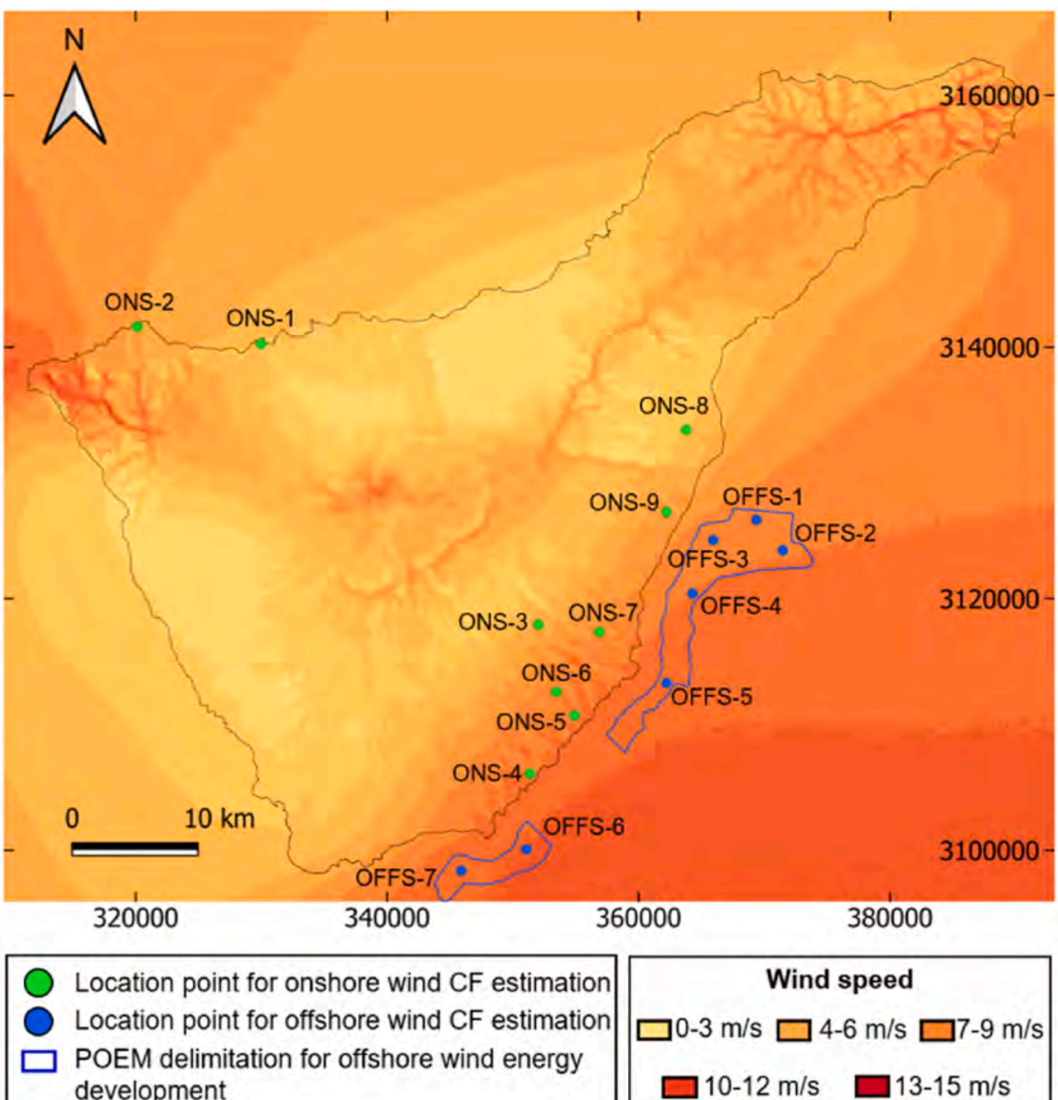

Fig. 5. Location of the onshore and offshore points for mean wind CF estimation. Wind speed data at 100 m above ground level (agl).

which a delimited text layer was also added with the UTM geographic coordinates of a series of strategically selected points in both the onshore and offshore zones for which the intention is to calculate the annual wind CF. The points selected in the onshore zone are situated in areas of high wind potential (see Fig. 5) according to the Canary Islands Wind Map (Canary Islands Government and ITC, 2016), where most of the wind farms presently in operation are found (Canary Islands Government, 2023) and where use of the island's territory is compatible with this type of installation (Grafcan, 2023). The selected offshore strategic points are situated within those areas defined in the Maritime Space Ordinance Plans (POEM by its initials in Spanish) (Government of Spain, 2023) (see Fig. 5) for the development of offshore wind energy.

In this way, it was possible to estimate the annual wind CF obtained by the different selected wind turbine models in each of the specified points, with the mean CF of the point being the mean value of those obtained for each wind turbine model. Finally, as a representative value for the island's onshore and offshore wind CF, the mean value of those obtained for the different strategic points was chosen. For the onshore case, the mean was calculated assigning a weight of 95% to those points situated in the eastern area of the island (ONS-3 to ONS-9), with the remaining 5% assigned to those corresponding to the northwest area (ONS-1 and ONS-2). This was done considering the current distribution of installed wind power on the island and the future distribution envisaged for the two areas. The resulting mean onshore and offshore wind CF values were 0.435 and 0.537, respectively.

Finally, the daily profiles were estimated of the hourly onshore and offshore wind CFs representative of the island of Tenerife for the seasonal cases of winter and summer (see Table 2). For this, the mean calculated CF values were distributed for both seasons based on official data of monthly wind energy production for Tenerife in 2019–2021 (Canary Islands Government, 2020b, 2022d, 2023), a three-year period in which the installed wind power remained at 195.65 MW. Based on these winter and summer mean CF values, estimation was then made of the hourly distribution of both cases using real hourly wind production values for strongly representative winter and summer days in Tenerife's electrical energy system (REE, n.d.b).

2.3.2. Solar PV generation

In the Spanish Technical Building Code (Government of Spain, 2013) a climate zoning of the national territory is performed based on the annual mean daily global solar radiation. Five climate zones are generated, ranging from "I" to "V" or lowest to highest solar radiation. The Canary Archipelago (and therefore Tenerife) are in the V climate zone, with a global mean daily solar radiation of 5.40 kWh/m^2 (AEMET, 2012).

In Royal Decree 413/2014 (Government of Spain, 2014), a daily profile of the hourly solar PV CF is provided for each month and climate zone. Using these data, the mean hourly CFs were calculated for a typical winter and summer day (see Table 3). The hourly electricity produced by the solar PV farms will be equal to these mean hourly CFs multiplied by the total installed solar PV power in 2040. As with the onshore and offshore wind powers, the solar PV power in 2040 is taken as that contemplated in the dispatchable generation strategy of the Canary Islands (Canary Islands Government, 2022b) for 2030, namely 354 MW.

2.3.3. Energy storage system

The planning of energy storage systems is a key aspect within the framework of a strategy of high penetration of NDREs in isolated electrical energy systems. In this regard, the Canary Islands Government has included in its document on the energy strategy of the Canary Islands (Canary Islands Government, 2021) pumped hydro energy storage (PHES) systems as one of the most promising future alternatives with respect to large-scale energy storage in Tenerife. A potential PHES system for future installation, called in this document the "Tanque-Sibora" system, has an estimated storage capacity of 2479 MWh and a maximum power in turbine and pumping cycles of 150 MW. In the studies carried out in the present paper, it is assumed that this PHES installation will be fully integrated in the island's electrical energy system and operation in the 2040 horizon. One-way efficiencies of 85% are assumed for the charging and discharging of this hydraulic system.

2.3.4. Energy scenarios considered

After the model was implemented in Matlab, different scenarios of the electrical energy system of Tenerife were simulated, differentiated according to the contribution of the different energy sources to satisfying demand (see Table 4). For electrical energy systems in Spain, the maximum injection of NDREs is limited to 50% of the capacity of the transmission line in which the connection point is situated (Government of Spain, 2021a) in order to guarantee the quality and stability of the electricity supply. For the specific case of distribution lines with a voltage below 36 kV, this maximum penetration is limited to 70% (Government of Spain, 2021a; Government of Spain, 2021b). In this regard, the scenarios considered in this paper were differentiated for NDRE penetration (NDREP) values of 50% and 70%. That is, the NDREP represents the maximum percentage of the electrical energy demand of the island that can be met by NDREs. If the latter do not reach the limit set for NDREP, the model considers the possible contribution of

Table 2
Mean onshore and offshore hourly wind CF in winter and summer.

Hour	Onshore		Offshore	
	Winter	Summer	Winter	Summer
0:00	0.290	0.469	0.358	0.579
1:00	0.360	0.340	0.445	0.420
2:00	0.321	0.469	0.396	0.579
3:00	0.329	0.363	0.406	0.448
4:00	0.321	0.346	0.396	0.427
5:00	0.345	0.312	0.425	0.386
6:00	0.298	0.285	0.367	0.351
7:00	0.321	0.201	0.396	0.248
8:00	0.329	0.234	0.406	0.289
9:00	0.353	0.469	0.435	0.579
10:00	0.533	0.720	0.658	0.889
11:00	0.392	0.653	0.484	0.806
12:00	0.298	0.653	0.367	0.806
13:00	0.298	0.792	0.367	0.978
14:00	0.251	0.831	0.309	1.000
15:00	0.290	0.692	0.358	0.854
16:00	0.439	0.753	0.542	0.930
17:00	0.674	0.697	0.832	0.861
18:00	0.564	0.725	0.696	0.895
19:00	0.407	0.803	0.503	0.992
20:00	0.486	0.792	0.600	0.978
21:00	0.400	0.625	0.493	0.771
22:00	0.282	0.368	0.348	0.455
23:00	0.501	0.491	0.619	0.606

Table 3
Mean hourly solar PV CF in winter and summer.

Hour	Winter	Summer
5:00	0.000	0.005
6:00	0.020	0.095
7:00	0.098	0.263
8:00	0.240	0.455
9:00	0.393	0.640
10:00	0.526	0.803
11:00	0.616	0.908
12:00	0.651	0.938
13:00	0.616	0.908
14:00	0.526	0.803
15:00	0.393	0.640
16:00	0.240	0.455
17:00	0.098	0.263
18:00	0.020	0.095
19:00	0.000	0.005

Table 4
Scenarios with the initial conditions of contribution to demand of the different electrical energy generation sources.

Scenario	NDREP	Contribution of the DERs to demand		
		Conventional thermal	Geothermal	PHES
1	50%	35%	7.5%	7.5%
2	50%	20%	15%	15%
3	50%	0%	25%	25%
4	70%	35%	7.5%	7.5%
5	70%	20%	15%	15%
6	70%	0%	25%	25%

geothermal resources. If the electricity generation of the NDREs exceeds the limit, this energy surplus will be pumped to the accumulation system through the PHES facility. The rest of demand, up to 100%, will be covered with DERs such as conventional thermal generation, hydraulic energy, through the PHES system, and geothermal plants. These will participate in accordance with certain percentages established for each scenario (see Table 4).

Each scenario is simulated in an initial situation in which it is assumed that the PHES system and the geothermal plants contribute equitably to the demand to be satisfied with DERs and that the geothermal power is unlimited. In this way, the hourly geothermal generation is obtained that is required for there to be no energy deficits at any moment during the year. After the initial simulation, a frequency distribution of the hourly data of geothermal generation is made in order to determine the rated geothermal power that can meet the geothermal power requirements observed in at least 80% of the data obtained in the initial simulation. The aim is to avoid oversizing of the facilities and, therefore, overestimation of the economic costs, ensuring that the geothermal facility would operate in ranges closer to its rated power. After determination of the rated geothermal power appropriate for each scenario, a resimulation is performed for each scenario in which a technical minimum is established, as an operating condition of the geothermal plant, equal to 25% of the rated potential. In this case, the aim is to optimize plant performance during its operation. It should be noted that flexible operation of the geothermal plants is achieved through advanced flow control of the geothermal fluid.

2.4. Maximum installable geothermal power

The geothermal CF is obtained as a result in the resimulation of each scenario. This CF is incorporated in Eq. (1) to calculate the maximum installable geothermal power. The conversion efficiency is the ratio between the useful electrical energy and the heat recovered at the wellhead. It is envisaged that ORC geothermal plants will have a conversion efficiency of 14.7% in 2040 (European Commission, 2014). The installable electrical power will then be the ratio between the electrical energy and the equivalent operating time of the geothermal plants throughout their working life. The envisaged technical lifetime of ORC geothermal plants in 2040 is 30 years (European Commission, 2014).

$$P = \frac{H \cdot RF \cdot \eta}{Lt \cdot CF} \quad (1)$$

where.

- P: installable electrical power (in kW)
- H: heat stored in geothermal reservoirs (in kJ)
- RF: thermal recovery factor (dimensionless)
- η: conversion efficiency (dimensionless)
- Lt: technical lifetime of the geothermal plants (in seconds)
- CF: geothermal capacity factor (dimensionless)

3. Results and discussion

3.1. Energy scenarios

Fig. 6 shows how the electrical energy generation of the NDREs is higher than the corresponding part of demand to be satisfied with an NDREP of 50% and 70% during a large part of the day both in winter and in summer. It should be noted that with an NDREP of 50% energy surpluses are generated in all the hours of a typical summer day and in 23 of the 24 h of a typical winter day, maximizing the production of energy surpluses. These surpluses decrease if the corresponding part of demand is satisfied with an NDREP of 70%. Given that the technical limitations of the PHES system do not allow accumulation of all this excess NDRE, energy curtailment (an enforced reduction in power output (Chen et al., 2021)) is required. In consequence, energy curtailment gives rise to a significant loss of the CF of the NDREs, with scenarios 1 and 2 being those in which more NDRE is not exploited (see Table 5). In contrast, scenario 6 sees the lowest energy curtailment, therefore maximizing exploitation of the NDREs.

Table 6 shows the values of the rated geothermal power adopted in each resimulated scenario, which would be the total power of the group of ORC geothermal plants, the resulting geothermal CF and the maximum installable geothermal power according to Eq. (1). This final parameter was calculated initially based on an RF of 0.15, with the exception of scenario 3 where it is 0.17, a value that remains below the maximum credible value of 0.20 based on world-wide experience (Garg and Combs, 2015). It should be noted that the present study does not aim to determine the number of geothermal plants or their distribution. Future technical projects are required for such determinations.

By way of example, Fig. 7 represents the geothermal generation profile of a typical winter and summer day for scenarios 2 and 5 in the initial simulation, while Fig. 8 shows the annual distribution of geothermal power requirements for the same scenarios. Based on these results, the rated geothermal power is established, as commented in section 2.4, and the scenarios are then resimulated.

As for the final contribution of the different energy sources to meeting the electrical energy demand in Tenerife in 2040 (see Table 7), the NDREs cover almost half in the first three scenarios and 68% in the other three. Scenario 3 sees the greatest contribution of geothermal energy (28.8%) and of the PHES system (20%) and is also the scenario least dependant on conventional thermal generation, whose contribution to demand is reduced to 1.4%. The contribution of geothermal energy in this scenario would be similar to that observed in Iceland in 2021 (Iceland's National Energy Authority, 2022a), and higher than the current contribution of other island territories such as Hawaii (Hawai'i State Energy Office, 2023), the Azores (APREN, n.d.) or New Zealand (Government of New Zealand, 2023), all with recognized high geothermal resource potential. Importantly, unlike these other island territories, the resulting NDRE contribution for the island of Tenerife is much higher. For this reason, the integration of geothermal energy with the PHES systems will have greater importance for regulation of the insular electrical system and its stability.

Despite the fact that in the initial simulation conditions a null participation of conventional thermal energy was considered, both scenarios 3 and 6 show in the resimulation results a small contribution of conventional thermal energy to demand. This is because, when limiting the rated geothermal power, energy deficits are generated at certain moments of the year (mostly in winter (see Fig. 6)) when the PHES system does not have in storage the amount of energy required to eliminate them and so there is a need to make up these deficits using this energy source. Scenarios 1 and 4 have the highest conventional thermal generation, and hence more pollutants. Nonetheless, these scenarios also achieve significant improvements in terms of cleaner and sustainable production thanks to the incorporation of these more sustainable technologies in the island's energy mix. More specifically, it is possible to reduce the energy that is generated in conventional thermal power

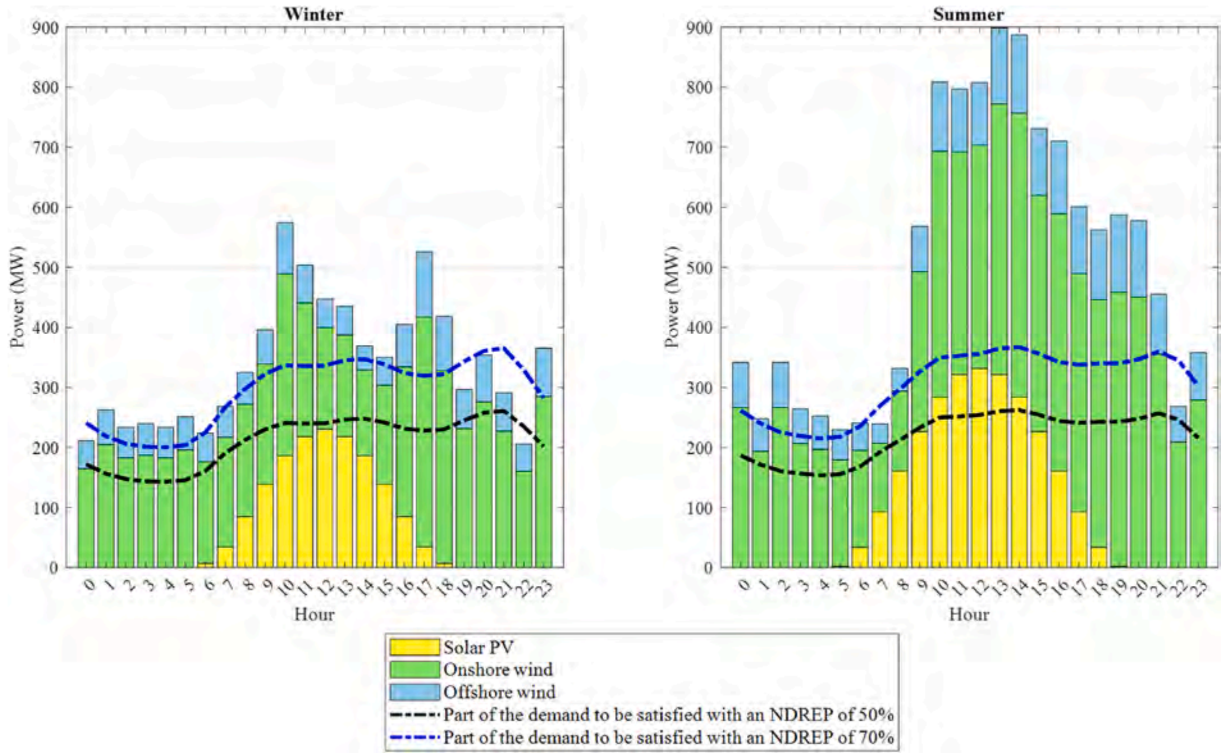

Fig. 6. Hourly generation of the NDREs and corresponding part of the demand to be satisfied with an NDREP of 50% and 70% for a typical winter and summer working day.

Table 5
NDRE lost in each scenario.

Scenario	Curtailed NDRE (GWh)	NDRE CF not exploited	NDRE CF not exploited/ maximum exploitable NDRE CF (in %)
1	1284.19	0.139	37%
2	908.58	0.099	26.2%
3	659.98	0.072	19%
4	777.63	0.084	22.4%
5	552.32	0.060	15.9%
6	412.22	0.045	11.9%

Table 6
Parameter values of geothermal facilities for each scenario.

Scenario	Rated geothermal power (MW)	Resulting geothermal CF	Maximum installable geothermal power (MW) (from Eq. (1))
1	45	0.695	153.4
2	75	0.826	129.1
3	170	0.700	172.6
4	35	0.593	179.8
5	50	0.772	138.1
6	120	0.663	160.8

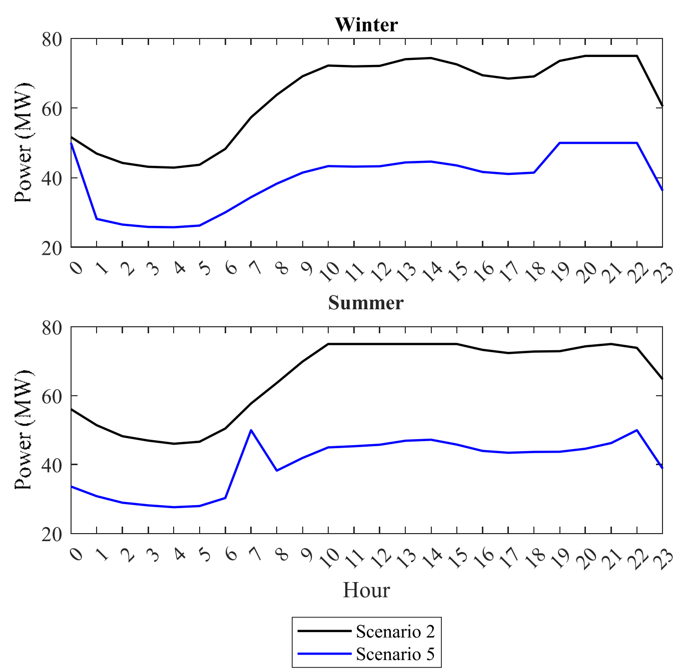

Fig. 7. Geothermal generation profile for a typical winter and summer day. Scenarios 2 and 5.

plants from 2,357,168 MWh/year in scenario 1 to 3,581,152 MWh/year in scenario 3. Considering the latest official conversion factors corresponding to the electrical system of Tenerife (Canary Islands Government, 2023), these energy reductions would correspond to a mitigation of emissions of between 1,499,159 $tCO_{2\text{-eq}}$/year and 2,277,613 $tCO_{2\text{-eq}}$/year, respectively. In terms of primary energy, they would be equivalent to a saving of between 525,648 toe/year and 798,597 toe/year, respectively.

If scenarios 2 and 5 are compared, it can be seen that geothermal energy satisfies a greater part of demand, like PHES and conventional thermal energy, in the former than in the latter. In contrast, the contribution of the NDREs is lower in scenario 2 than in scenario 5, with the former characterized by a higher participation of DERs though making greater use of contaminating fossil fuels.

Fig. 9 represents the energy accumulation of the PHES over the course of a year for scenarios 2 and 5. The PHES system discharges more in scenario 5 than in scenario 2 given that there are more instants when

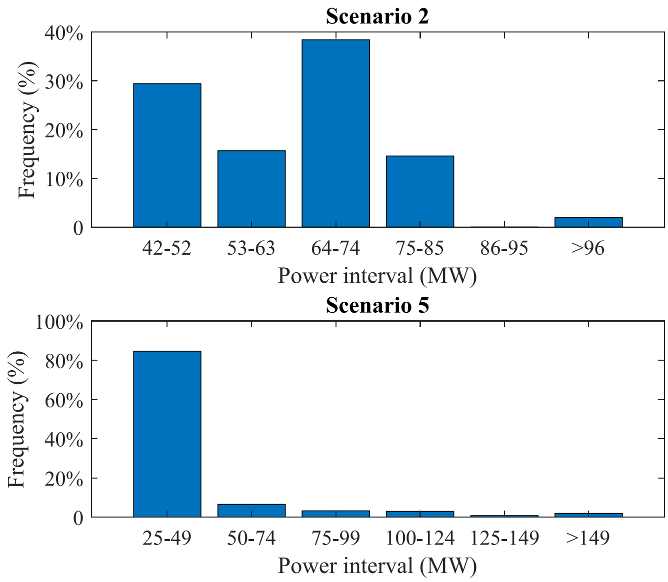

Fig. 8. Annual distribution of geothermal power requirements corresponding to the initial simulation of scenarios 2 and 5.

Table 7
Contribution of the different energy sources to electrical energy demand by scenarios.

Scenario	NDREs	Geothermal	PHES	Conventional thermal
1	49.8%	7.6%	7.5%	35.1%
2	49.8%	15%	15%	20.2%
3	49.8%	28.8%	20%	1.4%
4	68%	5%	4.5%	22.5%
5	68%	9.3%	9%	13.7%
6	68%	18.4%	11.8%	1.8%

the NDREs are unable to cover the corresponding part of demand (see Fig. 6). These energy deficits have to be covered through geothermal energy, which means that geothermal energy contributes to a lower extent to the part of demand that is satisfied through DERs and that, therefore, the energy contribution of the PHES system increases.

It was also decided to analyse three further variants of scenario 6, as this scenario had the highest NDREP with a minimal conventional thermal energy generation.

- The first variant is based on not limiting the capacity of the accumulation system, so that the CF not exploited by the NDREs is minimized to 0%. The required accumulation capacity in this case rises to 311.66 GWh, 125 times the capacity of the accumulation system planned initially by the Canary Islands Government and taken as a reference for scenarios 1 to 6.
- The second variant involves analysing the CF not exploited for the NDREs, taking as installed power that planned for the island in the 2040 horizon (Canary Islands Government, 2022b) instead of that for 2030, and maintaining the initial technical limitations of the PHES system. In this case, the non-exploited CF amounts to 0.260, equivalent to a 72.9% loss of the NDRE CF.
- The third simulated variant is the same as the first but taking as NDRE power that planned for 2040. In this scenario, the energy accumulation requirements rise to 7517.55 GWh, 3000 times the capacity of the accumulation system initially planned by the Canary Islands Government.

As a general conclusion for the results of the different simulated scenarios, it can be deduced that in order to achieve a 100% renewable contribution to the island's electrical energy system.

i. The exploitation of dispatchable renewable energy resources, such as geothermal energy, is vital.
ii. A high energy accumulation capacity is required. In this regard, research lines need to be incorporated in energy planning for the identification of potential accumulation systems and the evaluation of their capacities.

3.2. Analysis of economic aspects

The LCOE for each of the renewable electrical energy generation sources was calculated through Eq. (2):

$$LCOE = \frac{CAPEX \cdot CRF + C_{O\&M}}{\sum_{i=1}^{T} E_i} \tag{2}$$

where.

- CAPEX: initial investment cost of the facility (€)
- CRF: capital recovery factor, Eq (3).
- $C_{O\&M}$: annual operating and maintenance costs of the facility (in €/year)
- T: total number of annual hours (8760 h)
- E_i: electrical energy generated in the instant "i"

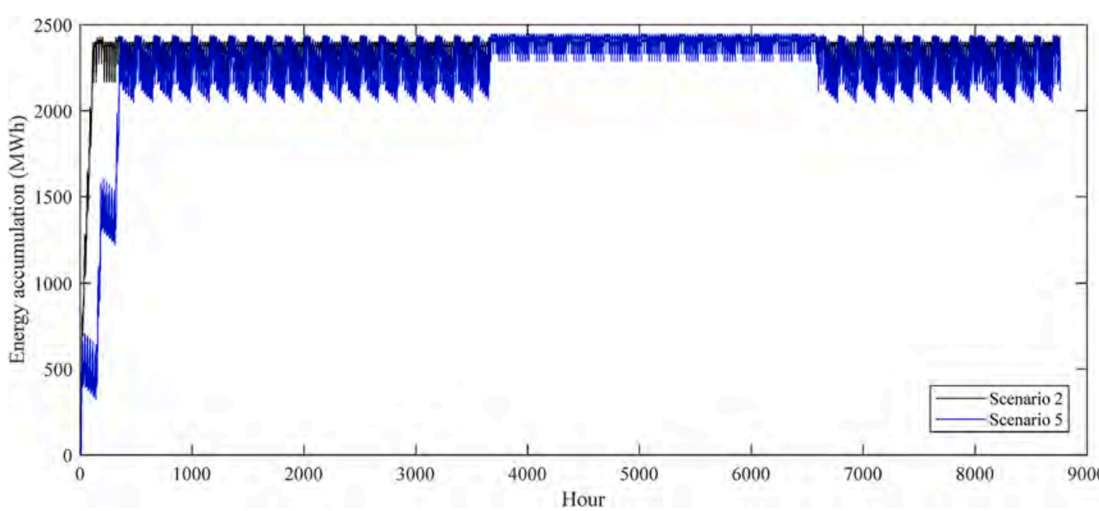

Fig. 9. Variation of energy accumulation of the PHES system in scenarios 2 and 5.

$$CRF = \frac{r(1+r)^{Lt}}{(1+r)^{Lt} - 1} \quad (3)$$

where.

- r: discount rate (a discount rate of 3% is considered a realistic value in stable macroeconomic circumstances)
- Lt: technical lifetime of the facility (in years) (see Table 8)

To determine the mean investments costs (CAPEX), operating and maintenance costs and the technical lifetime of the different energy injection systems into the island's electrical system, the Energy Technology Reference Indicator projections (European Commission, 2014) were consulted for 2040 (see Table 8). It should be noted that the geothermal energy reference indicators specifically refer to ORC systems and those of the PHES system include the incorporation of both reservoirs, the penstock and electrical equipment.

Table 9 shows the resulting LCOE of the different sources that contribute renewable electrical energy to the island's energy system. In particular, the LCOE of the NDREs is the mean annual weighted cost, for which the extent of the contribution of solar PV, onshore wind and offshore wind differs depending on the instant in the year. The resulting LCOE values of the NDREs implicitly include the increase due to the amount of non-exploited NDRE in each scenario. The geothermal and PHES LCOEs are lower in scenario 2 than in scenario 5. In contrast, the mean weighted LCOE of the NDREs is higher in scenario 2 than in scenario 5, given that in the latter it is possible to exploit a larger amount of the NDRE that is produced (see Table 5). It should be noted that the low energy contribution to demand of geothermal energy and the PHES system in scenario 4 (see Table 7) explains the resulting high value of their corresponding LCOEs.

Using the LCOEs of the NDREs, geothermal energy and the PHES system, the weighted mean LCOE of renewable energy can be determined for each instant of the year. In general, the LCOE is lower in summer, given that it in this period that higher generation of the NDREs takes place, whose costs are lower than those of geothermal energy and the PHES system. In any case, the resulting weighted mean LCOE of renewable energy for the six simulated scenarios is significantly lower than the last official value for the mean annual electrical energy generation cost in Tenerife, which amounted to 159.16 €/MWh (Canary Islands Government, 2023). Given this cost datum and those obtained as mean weighted values in each scenario, the annual economic saving that the Spanish electrical system could obtain ranges between 272.69 and 417.70 €million per year for scenarios 1 and 6, respectively (see Table 7).

4. Conclusions

A model was implemented for the simulation of weak electrical systems with a high non-dispatchable renewable energy contribution (wind and solar PV). Different scenarios were implemented in which, as network regulator elements, geothermal facilities were additionally incorporated as a dispatchable renewable resource along with energy accumulation systems. The model was applied to the case study of the isolated electrical grid system of the island of Tenerife (Canary Islands, Spain).

For each scenario, the results obtained for different technical and economic parameters were evaluated with the aim of comparing them and determining the proposal of strategies for large-scale renewable power integration while maintaining safety and quality in the energy supply.

Based on the results obtained, scenarios were found with a high renewable contribution to the island's electrical energy demand. For this, it is necessary to include in future energy planning the integration of dispatchable renewable energy sources, such as geothermal energy, to improve the regulation and control capacity of the electrical grids, and to incorporate energy accumulation systems with appropriate capacities to serve as a base and complement to the island's electrical energy generation structure. These elements will add stability and flexibility to the electrical grid, minimizing the weaknesses caused by its low robustness in scenarios with a high participation of non-dispatchable renewable energy sources.

Bearing in mind the capacity of the geothermal resource, this energy source could satisfy up to 28.8% of demand. However, the low dispatchable capacity of the other renewable energy sources (wind and solar PV) means that energy planning on the island must consider an energy storage capacity increase to improve the management and exploitation of these energy resources. According to the results obtained, if this latter aspect is not considered the loss in the non-dispatchable renewable energy capacity factor could be as high as 37%.

For the present study, the identification of the high enthalpy geothermal reservoirs was done solely on the basis of geophysical data, given that this was the result of an interpretation of magnetotelluric and seismic topographic models. In this regard, further research studies are required for the interpretation of both geophysical and geochemical data in order to know in greater detail the particular properties of the hydrothermal systems of Tenerife including, for example, the extent of their spatial variability. In this way, it would be possible to evaluate with greater precision the energy capacity of the island's geothermal resources.

The specific costs of current electrical energy generation are very high. This is fundamentally due to the high dependence on conventional energy resources, the small size of the electrical energy system and its insular nature. According to the results obtained in this study, large-scale exploitation of the existing renewable energy resources could entail an economic saving for the system operator of up to 417.70 €million per year.

The model that has been implemented can be employed for the simulation of any electrical system, preferentially in weak electrical energy systems with low control and dispatchability capacity where the aim is to incorporate non-dispatchable renewable power on a large scale. Through the additional incorporation in the model of energy accumulation systems, energy storage needs can be calculated with a view to minimizing losses in the non-dispatchable renewable energy capacity factor and, consequently, economic losses in the generation of electricity.

It can also be concluded from the results that further research studies are required to identify alternative large-scale energy accumulation

Table 8
Energy Technology Reference Indicator projections (European Commission, 2014) for 2040 of the different technologies employed in the case study of the present paper.

Technology	CAPEX (€/kW)	$C_{O\&M}$ (€/kW·year)	Technical lifetime (years)
Onshore wind	1200	22.8	25
Offshore wind	2380	66.64	30
Solar PV	790	11.85	25
Geothermal ORC	5870	146.75	30
PHES	3000	45	60

Table 9
LCOE (in €/MWh) of the different renewable electrical energy contribution technologies and the weighted mean LCOE of the insular renewable generation.

Scenario	NDREs	Geothermal	PHES	Weighted mean
1	32.45	73.26	83.64	43.13
2	30.98	61.68	41.85	38.79
3	30.08	72.78	31.75	42.88
4	30.50	85.87	106.20	38.49
5	29.71	65.97	60.35	36.83
6	29.24	80.48	52.95	41.69

systems for the island and quantify their capacities.

CRediT authorship contribution statement

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

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.

Data availability

Data will be made available on request.

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