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Enabling synergies among hydrogen, desalination, and flywheel storage for sustainable island energy systems

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ABSTRACT

The reliance of Lanzarote (Spain) on imported fossil fuels and its complete dependence on energy-intensive desalination underscore the need for an integrated approach to sustainability. This study proposes and evaluates multiple scenarios that combine wind and solar power with hydrogen-based storage, desalination (power-to-water), and flywheel technology, highlighting the synergies among these elements. By leveraging scenario modelling, we show how surplus wind electricity can be converted into hydrogen (power-to-hydrogen), used to drive desalination processes, and buffered by flywheels to stabilize short-term fluctuations.

Key findings from the study show that renewables can supply 87% of the overall electricity demand of Lanzarote with a competitive levelized cost of energy (LCOE), substantially reducing carbon emissions. However, raising the renewables share from 87% to 100% increases the LCOE considerably. When focusing exclusively on desalination, fully renewable configurations also prove feasible, although they produce notable excess electricity that can be redirected to additional uses or stored as hydrogen. The integration of hydrogen storage helps mitigate the intermittent nature of wind and photovoltaic generation, while flywheels provide rapid-response frequency regulation.

Overall, this synergy-focused strategy demonstrates a practical pathway toward large-scale decarbonization and water-security enhancement on islands with similar constraints. By aligning water and energy objectives through power-to-X solutions, Lanzarote's case study offers valuable insights into achieving a more sustainable and resilient future.

1. Introduction

Most of the world's islands rely principally on conventional fossil fuel energy sources to meet their electricity demand [1]. Such dependence on external energy sources (e.g., imported oil or gas) renders them vulnerable to price volatility and potential supply disruptions [2,3]. At the same time, current global efforts to reduce greenhouse gas emissions and achieve full energy decarbonization by 2050 [4,5] require islands to integrate higher percentages of renewable energy sources (RES) [6,7]. However, the geographic isolation of many islands, their limited interconnection capacity, and their constrained land availability make this transition particularly challenging in practice.

Numerous studies have investigated pathways to increase renewable energy penetration in island energy systems using modelling and simulation tools. For instance, Feio et al. [8] evaluated the feasibility of combining wind, solar photovoltaic (PV), and reversible hydropower on a small remote island in Brazil. Alves et al. [9] simulated scenarios to attain nearly 100% renewable penetration for two islands in the Azores (Portugal), comparing interconnected and isolated configurations. Other works employed Geographic Information Systems (GIS) to identify global renewable potential for small islands [10] or used specialized software such as HOMER [11] to model different demands on a small island in northern Norway. Roy [12] also used the HOMER program, creating six different scenarios in which three different technologies (wind power, solar PV and diesel generators) were varied to optimise a hybrid off-grid system on Ghoramara Island, India. In Ref. [13], the authors used the Calliope tool to generate a 100% renewable system by 2050. In Ref. [14], an analysis was carried out to generate hybrid

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systems on non-interconnected islands, with 90% renewable penetration achieved. A similar case can be found in Ref. [15], where the authors sought to optimise a 100% hybrid renewable system in an isolated region without electrification. Renewable pumped-hydro energy storage has also been successfully implemented in some of the Canary Islands (Spain) where suitable orographic conditions exist, demonstrating its effectiveness in isolated systems but also highlighting its strong dependence on local topography and land availability [16].

Given the intensified push to replace conventional generation with renewables, hydrogen has emerged as a key vector for future energy plans. The European Union (EU) [17], along with its local governments [18], have established short- and long-term strategies for a greater participation of hydrogen in the push towards the energy transition it proposes [17]. Several studies have highlighted the potential of hydrogen to enhance renewable-penetration rates, either importing it or producing it locally via electrolysis. In Ref. [19], for example, the aim was to import or generate hydrogen, complementarily with other renewable energy sources, to achieve a transition to a 100% renewable system. In Ref. [20], the authors focused on the role of hydrogen and batteries for integration in a 100% renewable system located on the island of Pantelleria, Italy, concluding that the most cost-effective scenarios included hydrogen. Although the focus of such studies is on high renewable-penetration levels—potentially 100%—many of them only consider mainland grids or broad energy sectors and generally overlook pressing island-specific challenges such as water scarcity.

In regions where potable water is derived entirely from desalination—a process demanding significant electricity—studies such as [21] and [22] proposed covering the energy demand of a reverse osmosis (RO) desalination plant with a 100% renewable system. In Ref. [23], the authors proposed a hybrid renewable system with diesel generators to optimise the demand of small autonomous desalination systems located on two islands of the Canary Archipelago, Lanzarote and Fuerteventura. In this sense, the Canary Islands is a pioneering region, as pointed out in Ref. [24]. Hybrid wind–diesel systems supplying RO desalination plants have already been implemented in Fuerteventura, providing practical evidence of the technical feasibility of coupling energy generation and desalination in island environments [25].

In [26], Jacobson et al. analysed the impact of integrating electrolytic hydrogen in 100% renewable wind water solar systems. While, in this case, hydrogen was not used for grid energy, the authors consider it can serve other purposes including helping to reduce the costs of maintaining grid stability. In a further study, Jacobson [27] undertook a comparison of hydrogen and batteries for grid electricity storage modelling a 100% renewable grid using wind, water and solar energy in 145 different countries. The author investigated the most cost-effective alternative to meet the need for the integration of energy storage in power grids.

Although in Ref. [28] the authors explored the power-to-water concept and considered the optimal sizing of all the desalination plants on an island, their proposal was not to cover the demand of the entire desalination system with renewables but rather only most of the demand of specific plants. Recent reviews of renewable-powered desalination systems further confirm that most existing studies focus on plant-level solutions rather than fully integrated, island-scale energy–-water systems [29]. Electricity generation and desalination are either addressed separately or at the level of individual facilities, rather than through an integrated, island-wide perspective. As a result, holistic solutions capable of jointly assessing total electricity demand, high renewable penetration, and secure water supply at island scale remain limited. The aim of the present study is to cover this gap, proposing a unified power-to-X approach for an entire island's electricity and desalination needs, incorporating large-scale wind, PV, hydrogen, and flywheel storage.

The present study focuses on leveraging synergies among hydrogen production, desalination (power-to-water), and flywheel storage to advance a sustainable energy transition on islands facing water scarcity. Flywheel energy storage has already been deployed in the Canary Islands to enhance grid stability in isolated power systems, demonstrating its suitability for short-term frequency regulation and fast-response support in island grids [30]. Using the island of Lanzarote (Canary Archipelago, Spain) as a case study, we examine multiple integration scenarios in which surplus wind electricity is converted to hydrogen or used to produce potable water. After evaluating different integration scenarios, solutions are proposed that maximize the participation of renewable energies both in the total energy system of the island and in the desalination sector of the island. The selected island is ideal for this study as it currently relies almost entirely on fossil fuels imported from other countries [31]. Although the population of the island is not excessively high, the large number of tourists it receives annually aggravates the energy-water situation [32]. The freshwater demand of Lanzarote (846 km^2) is driven by its permanent population (156,189 inhabitants in 2021) [33] and around 3 million annual tourists [32]. In 2022, the island's public plants produced over 28 million m^3 of desalinated water, requiring 89.5 GWh of electricity [34]. The fact that practically all of the island's water is generated through desalination, which is an energy-intensive process, has exacerbated its external energy dependence. However, Lanzarote has significant solar and wind potential, providing an excellent opportunity to implement these renewable energies.

This research advances two main pathways toward near-100% renewable coverage on Lanzarote: one addressing the entire island's electricity demand and the other focusing solely on its desalination sector, a critical issue for water-scarce island systems. Our approach centres on channelling surplus wind energy into hydrogen production (power-to-hydrogen) or potable water generation (power-to-water) to reduce fossil fuel reliance. Additionally, flywheel storage is employed to manage short-term power fluctuations, complementing hydrogen's longer-term capacity. Unlike previous studies that examined isolated facilities or partial loads [28], the present work offers a holistic, island-wide framework—analysing the technical and economic viability of near or fully 100% renewable power systems under various cost and emission constraints.

Although Lanzarote is used as a representative case study, the proposed framework is applicable to other island systems facing similar energy and water challenges.

The rest of the article is structured as follows: Section 2 describes the proposed method. Section 3 shows the results obtained from the case study after applying the method to it. Section 4 provides a discussion of the results of the case study. Finally, Section 5 presents the main conclusions of the study.

2. Method

This section describes the methodological framework adopted in this study, including the underlying principles, the modelling tool used, and the sequential stages applied to optimise island-scale energy systems with high shares of renewable energy.

2.1. Basic principles of the method

The procedure follows a series of basic principles when choosing the most valid option in each scenario. These are as follows.

1. The procedure focuses on two different types of scenarios: (1) meeting the island's entire electricity demand; and (2) meeting solely the island's desalination electricity demand.
2. The criteria used to evaluate and select feasible solutions depend on whether conventional energy sources are retained in the system configuration. For grid-connected scenarios retaining conventional generation, the evaluation criteria include the levelized cost of energy (LCOE), CO_2 emissions, and the share of RES. For scenarios without conventional generation, LCOE remains a primary criterion,

while excess electricity is introduced as a key indicator of system oversizing and inefficiency.

3. The analysis is conducted with hourly demand, wind and sun data. This is because the renewable technologies used (wind and solar PV) have a highly variable generation trend.
4. The method proposed in this study is designed for islands in general, meaning that it can be implemented on other islands with similar needs.
5. The case study is the island of Lanzarote, and the system modelled corresponds to the island's electrical grid using hourly demand and resource data from the year 2022. This single-year representation captures short-term variability but does not explicitly account for interannual climate or demand variability, which is acknowledged to be a limitation of the study.
6. The analysis assumes a simplified representation of the island electricity grid, without explicit modelling of transmission line sizing, nodal network constraints, or power flow limitations. This assumption allows the study to focus on system-level generation, storage, and sector-coupling trade-offs within an integrated electricity–water framework. Aggregate losses associated with renewable generation and electricity transport are accounted for through reduction factors applied to renewable energy production, while network-related costs are implicitly included within the operation and maintenance (O&M) cost assumptions. Nevertheless, the absence of an explicit grid model may lead to optimistic estimates of cost and renewable penetration in real-world applications. Previous studies have shown that high wind penetration in weak or isolated power systems can exacerbate frequency stability and power quality issues, underscoring the importance of grid-support measures and fast-response technologies in practical implementations [35]. In addition, carbon dioxide removal technologies are not considered, and CO_2 emissions are therefore limited to those associated with conventional electricity generation.
7. In the different simulated scenarios, wind power can be either offshore or onshore, depending on the specific case. PV generation includes both rooftop and utility-scale systems, with costs represented by a weighted average. Detailed spatial siting constraints, including environmental protection areas, infrastructure exclusion zones, bathymetric limitations, visual impact considerations, and permitting restrictions, are not explicitly modelled in this study. Such constraints are known to significantly affect the practical deployment of renewable energy systems on islands, particularly in the Canary Islands, as demonstrated by detailed spatial planning analyses reported in the literature [36,37]. These aspects are therefore treated as methodological limitations rather than explicit decision variables within the present system-level assessment.

These simplifying assumptions are applied consistently across all scenarios and stages of the method, ensuring that the comparative assessment of alternative system configurations is not biased by differential treatment of network-related effects.

2.2. HOMER simulation tool

Several tools/software programs are available that can be used to analyse and simulate different renewable integration configurations in energy systems. The HOMER tool [38,39] was selected due to its adaptability in terms of the generation of different scenarios. With this tool, it is possible to select the types of wind turbine deployed on the island in question, as these are included in the HOMER database along with their characteristics (power curve, etc.). The programme also allows the addition of any energy demand recorded in a database, as well as the data of various energy resources or satellite-based data. HOMER is flexible, allowing the setting of a series of energy factors and the variability of others. In other words, the demand and one or more energy sources of the system can be set, with HOMER calculating the remaining sources based on the initial data. In the automatic choice of results, the programme generates different options which are ordered in terms of LCOE-based economic feasibility. LCOE is calculated as shown in Eq. (1). However, the programme leaves the user free to choose the most suitable option according to the selected criteria. HOMER can calculate all types of results, showing the emissions that would be produced in each of the alternatives it offers. HOMER was selected over other energy-system modelling tools, such as EnergyPLAN, due to its flexibility in generating and comparing a large number of discrete techno-economic configurations, its integrated treatment of generation and storage technologies, and its suitability for scenario-based optimisation as opposed to long-term transition pathway analyses.

$$LCOE = \frac{\left(\frac{i(1+i)^N}{(1+i)^N-1}\right) * \sum (Capital\ costs + O\&M\ costs)}{Electric\ load\ served} \quad (1)$$

where i is the annual real discount rate (%) and N is the project lifetime (yr).

2.3. Stages of the method

The procedure is based on various stages which are shown in Fig. 1.

2.3.1. Stage 1: Identifying, modelling and validating the reference scenario

The demands and resources of the island are identified in the first stage. The collected data were extracted from the following sources: the Canary Islands Energy Yearbook [31], REE (Spain's transmission system operator) [40] and AEMET (State Meteorological Agency) [41]. These data were introduced into HOMER to model the reference system of the island and simulated to obtain the first results. All electricity demand and renewable resource inputs were treated at hourly resolution. Electricity demand data obtained from REE correspond to complete hourly records for the year 2022, and no gap-filling or interpolation was required. Wind and solar resource data were likewise available as continuous hourly time series, and no explicit statistical filtering or outlier removal was applied beyond the standard preprocessing embedded within the HOMER environment. The cost data compiled in Table 1 are based on previous techno-economic analyses carried out in the Canary Islands, thereby providing methodological consistency and regional relevance. While this choice may lead to optimistic absolute cost estimates, it ensures internal consistency and enables transparent

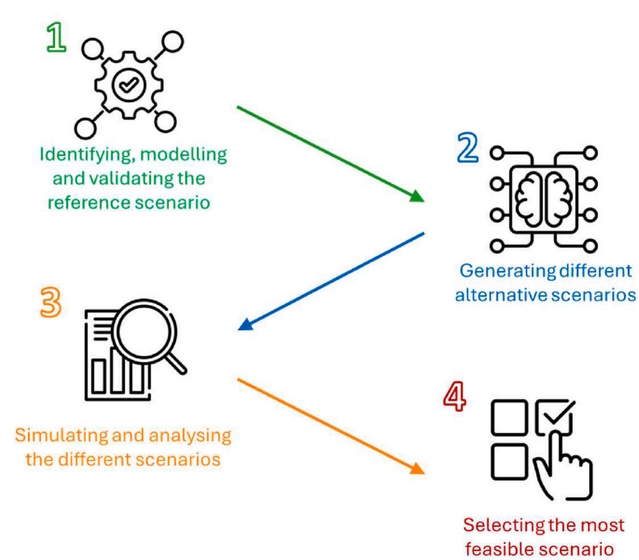

Fig. 1. General method followed in this study.
Source: own elaboration.

Table 1
Costs of the most important components.

Equipment	Capital cost	Replacement cost	O&M cost	Lifetime	Reference
Wind power (onshore)	1140 €/kW	1000 €/kW	24 €/kW year	30 years	[43,44]
Wind power (offshore)	1760 €/kW	1760 €/kW	55 €/kW year	30 years	[43,44]
PV power	530 €/kW	530 €/kW	8 €/kW year	40 years	[43,44]
Converter	100 €/kW	100 €/kW	-	15 years	[45–48]
Electrolyser	560 €/kW	560 €/kW	33 €/kW year	25 years	[44]
Hydrogen tank + compression O&M	669 €/kg	669 €/kg	6.69 €/kg year	30 years	[45–48]
Fuel cell	1800 €/kW	1800 €/kW	0.01 €/op. hr	25000 h	[45–48]
Li-ion battery	297 €/kWh	297 €/kWh	6.625 €/kWh year	10 years	[49]
Flywheel	1000 €/kW	900 €/kW	1 €/kW year	25 years	[45–48]
Diesel power plant	800 €/kW	800 €/kW	0.03 €/op. hr	20 years	[45–48]

comparison across scenarios within the same modelling framework. Wind resource data were obtained from ERA5 reanalysis products, which are widely used in offshore and onshore wind energy assessments. However, previous studies have reported systematic biases between ERA5 wind data and measured observations, particularly for offshore locations. In this study, no bias correction could be applied to the offshore wind data due to the lack of available local measurements, which is acknowledged as a source of uncertainty in the resource representation [42].

To validate the reference system, the results obtained by HOMER were compared with known real results. Deviations between simulated and observed values were quantified, and model parameters were iteratively adjusted to minimise the error and ensure consistency with real system operation. The purpose here was to know the error generated in the simulation and to present accurate results.

2.3.2. Stage 2: Generating different alternative scenarios

The second stage comprises the generation of alternative scenarios based on the two categories differentiated in section 2.1. This is the most extensive stage of the procedure as different possibilities are simulated in which various power generation technologies and their capacities are modified.

In the modelling of the scenarios, the aim is to eliminate conventional generation systems. For this reason, the scenarios are created with and without conventional generation systems without varying the types of renewable technologies in the system, although the quantity of these technologies does vary. In other words, the scenarios are duplicated only eliminating the conventional generation system. For each scenario the values will differ from those of the previous one and are adjusted according to the demand to be covered.

2.3.3. Stage 3: Simulating and analysing the different scenarios

In the third stage, the results obtained for each scenario are analysed and the most relevant data selected. In the scenarios that retain the conventional grid, we first simulate using the grid option in HOMER as conventional generation and select the highest value for both case studies. Once this is done, the scenarios with conventional generation are simulated again, replacing the grid option with conventional generation plants in HOMER with the maximum values obtained. The most relevant results for the Pareto multi-objective optimisation model are extracted from the program and implemented in tables.

2.3.4. Stage 4: Selecting the most feasible solution

In this last stage, all feasible solutions for each scenario are obtained and compared in order to identify representative system configurations. For the selection of the most suitable scenario for each case study, the Pareto multi-objective optimisation model is used. This model allows the calculation of a series of possible optimal solutions called the Pareto front [28] [50–56]. These solutions are obtained according to a series of criteria chosen for the evaluation of the energy system of the target island. The Pareto front that is obtained serves to give a better view of the overall system and thus to see all the consequences of each decision based on the choice of criteria. To identify the most suitable system configurations, a Pareto-based multi-objective optimisation approach is applied. This approach allows the simultaneous evaluation of conflicting objectives without aggregating them into a single weighted metric, thereby preserving transparency in the trade-offs among economic, environmental, and operational criteria. Each point on the Pareto front represents a non-dominated solution, meaning that no objective can be improved without worsening at least one other objective. This enables a comprehensive comparison of alternative configurations and supports the selection of compromise solutions aligned with the specific priorities of island energy systems.

To compare the set of feasible system configurations obtained from the HOMER simulations, a Pareto-based multi-objective approach is adopted. Let $\boldsymbol{x} = [x_1, x_2, \ldots, x_8]$ denote the decision vector, where $x_1 - x_8$ represent the installed capacities of wind, PV, battery, fuel cell, hydrogen tank, electrolyser, flywheel, and converter, respectively (some variables may be zero depending on the scenario). For each configuration, HOMER provides the corresponding performance indicators, and the multi-objective problem is formulated as:

$$\textit{minimise}\, f(x) = [f_1(x), f_2(x), f_3(x)]\,, \text{subject to } l_i \le x_i \le u_i, i = 1, \ldots, n \quad (2)$$

A solution x is Pareto-optimal if no other feasible solution x' exists such that $f(x') \le f(x)$ for all objectives and $f(x') < f(x)$ for at least one objective. The resulting non-dominated set constitutes the Pareto front.

Two objective sets are considered, one without conventional generation (Eq. (3)) and one retaining conventional generation (Eq. (4)):

Renewable-only (off-grid) configurations:

$$\begin{aligned} f_1(x) &= \text{LCOE } (€/\text{kWh}), \\ f_2(x) &= \text{Excess electricity } (\%), \\ f_3(x) &= \text{Total annual consumption } (\%) \end{aligned} \quad (3)$$

Configurations retaining conventional generation (grid-connected):

$$\begin{aligned} f_1(x) &= \text{LCOE } (€/\text{kWh}), \\ f_2(x) &= CO_2 \text{ emissions } (\text{kg/yr}), \\ f_3(x) &= 100\% - \text{RES share of production } (\%) \end{aligned} \quad (4)$$

In both cases, the bounds l_i and u_i are defined from the current installed capacities and the maximum feasible values explored in HOMER for each technology.

In this context, the term “optimal” is used to refer to representative compromise solutions within the Pareto front rather than to a unique mathematically optimal configuration. These compromise solutions balance economic, environmental, and operational objectives by avoiding extreme points located at the edges of the Pareto front, which strongly optimise a single objective at the expense of others.

3. Results after applying the method to the lanzarote case studies

This section presents the results obtained after applying the method to the energy system of the island of Lanzarote. The results are presented step by step.

3.1. Identifying, modelling and validating the reference scenario

In this first step, all the resources, costs, infrastructures and demands of the island are identified and the current reference scenario then validated using the HOMER programme.

3.1.1. Identifying the reference scenario

The island of Lanzarote is located in the Canary archipelago of Spain, some 125 km off the northwest coast of Africa [57] (see Fig. 2).

The easternmost island of the archipelago, its climate is significantly influenced by its proximity to the African continent. Most notably, the desert climate of the West African coast extends to Lanzarote, making water scarcity a characteristic of the island.

Its geographical location (28-29°N, 13°W) also places Lanzarote in the pathway of the trade winds. These winds, loaded with humidity from the Atlantic, collide with the Canary archipelago from the N-NE and deposit their load of water on the more mountainous regions of the islands. Lanzarote, a highly eroded island with a maximum altitude of just 700 m, is unable to retain the humidity of these winds.

However, the trade winds are an excellent resource to obtain wind energy. In addition, the PV energy that can be obtained is more constant throughout the year than at higher latitudes due to the island's geographical location close to the tropics.

3.1.2. Identifying the energy resources and demand of the island

The island's energy resources and demands were taken from different reports published by the Canary Islands Government [31,34,40,41]. According to these reports, Lanzarote is 90% dependent on fossil fuels for energy [31]. Installed wind power meets 8.8% of the total demand and PV just 1.2%. This means that out of a total of 839 GWh, only 74 GWh is covered by wind power and 10 GWh by solar power. The remaining 755 GWh are covered by conventional fossil fuel-sourced energy (Fig. 3).

The wind data used in the study were obtained from ERA5 [59], as used in Ref. [49]. ERA5 is a global climate reanalysis product from the European Centre for Medium-Range Weather Forecasts (ECMWF) which allows precise selection of the required year and location and is especially useful when no historical data are available for the location, as in this case study. Upon request, mean hourly wind speeds are available for free download at two different heights (10 m and 100 m). Two precise locations were used for the wind data, one corresponding to the onshore Los Valles wind farm (UTM coordinates 29°05′44.27"N, 13°30′25.31"W) and the other to the potential offshore wind farm in the area identified in the Ocean Winds project [60] (UTM coordinates 28°56′11.3"N, 13°29′54.3"W). HOMER automatically extrapolates the data to the selected wind turbine hub height.

In 2022, Lanzarote had 4 wind farms [31]. The Los Valles wind farm has 10 × 850 kW Gamesa wind turbines in operation, while those at Punta Grande, Teguise and Arrecife have, respectively 2, 4 and 4 Enercon wind turbines with a rated power of 2.3 MW. The total number of installed wind turbines is therefore 20, with a total installed power of 31.5 MW.

The installed PV power on the island amounts to 16.89 MW [31] and is scattered across the island, with the largest plants, including three with capacities above 300 kW, found on the eastern slope.

HOMER assumes that carbon dioxide emissions are generated exclusively by conventional power generation, while renewable energy technologies are considered emission free. This assumption is adopted in the present study. However, it is well established that although RES do not produce direct carbon emissions during operation they are nevertheless associated with carbon footprints arising from construction, manufacturing, and end-of-life recycling processes [49].

The freshwater demand of this 846 km^2 island is influenced by two main factors, its permanent population, which in 2021 comprised 156,189 inhabitants [33], and the approximately 3 million tourists who visit the island each year [32].

In 2022, over 28,000,000 m^3 of desalinated water were produced by the island's public plants [34]. The island's electricity demand for desalination purposes in that year amounted to 89.5 GWh with a specific cost of desalination of 3.2 kWh/m^3 [34]. Of this demand, 84.7% corresponded to the plants named Lanzarote III, IV and V, and the remaining 15.3% to the Janubio plant (Fig. 4).

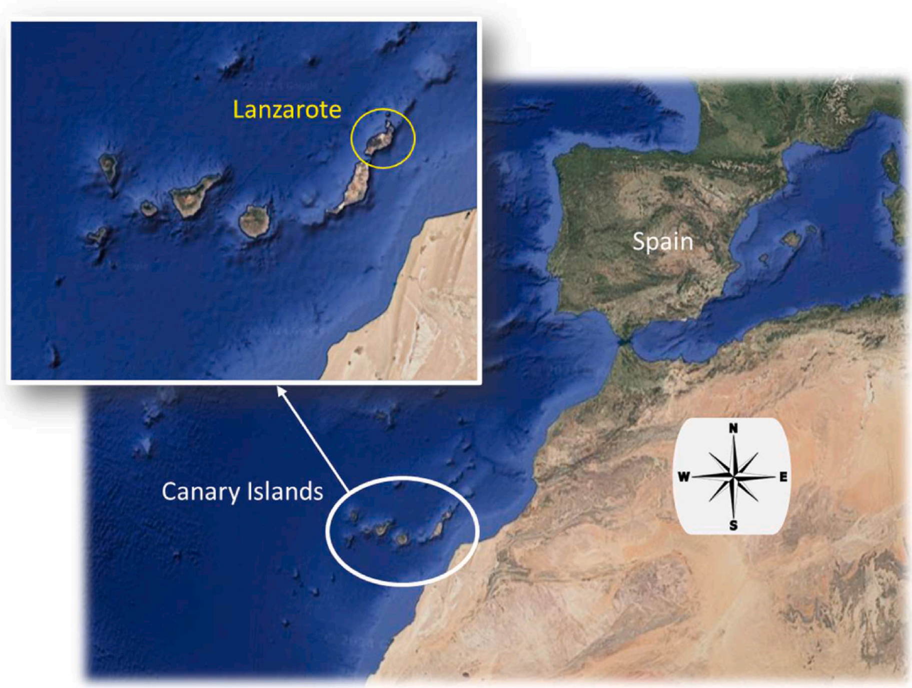

Fig. 2. Map of the island of Lanzarote.
Source [58]:

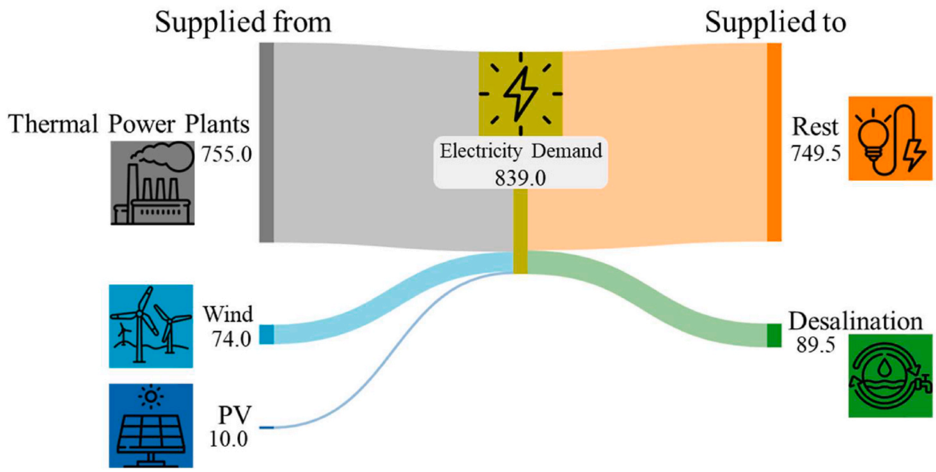

Fig. 3. Sankey diagram of the current Lanzarote 2022 energy system (all units in GWh/yr).
Data sources [31,34,40,41]:

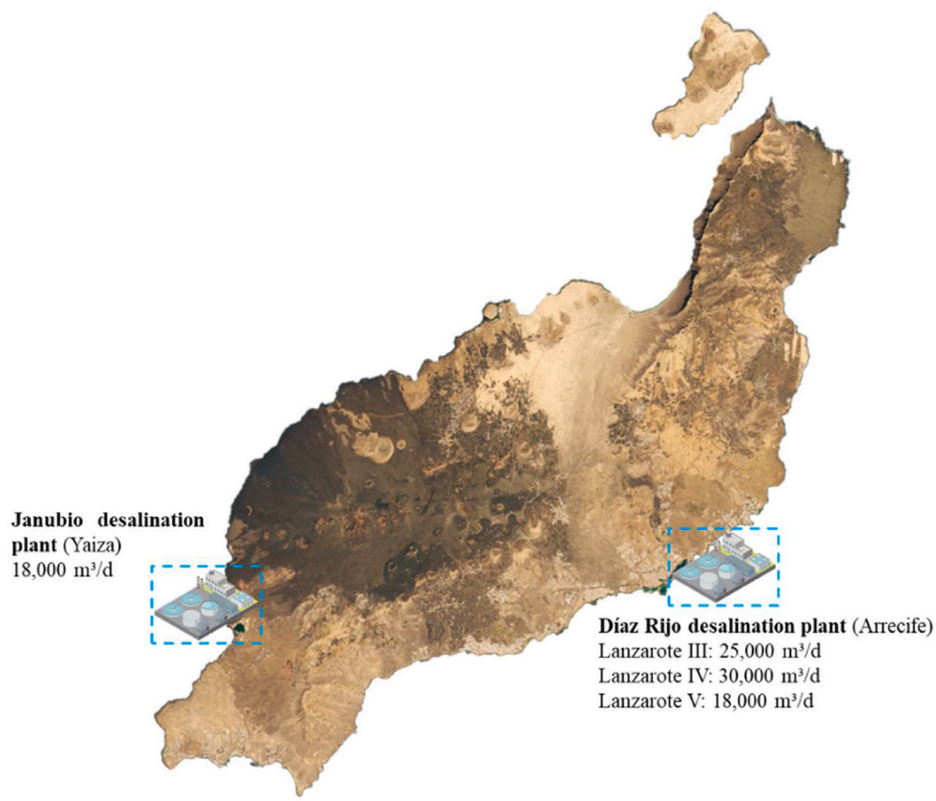

Fig. 4. Location of Lanzarote desalination plants and their maximum water production.
Source [61]:

3.1.3. Existing infrastructures and definition of the water-related scope of the study

The water is collected through wells on the coast and taken to the processing plants. In these processing plants the seawater is treated and two flows obtained. The product water (fresh water) flow enters the Lanzarote water distribution system while the reject water (water enriched in salt) flow is returned to the sea, as far from the coast as possible, through the outfalls of the water processing plants.

Among the different technology alternatives available for seawater desalination, RO has recently gained a certain advantage. This is because, in the absence of heat sources that favour thermal technologies, the optimal technology (economically speaking) for desalination using electricity is RO. It has been established that around 20-30% of the cost of desalinated water corresponds to the electricity consumed [62]. In this context, RO is the optimal technology.

Producing the water is only the first step in the water cycle. The desalinated water then has to be transported to the consumption centres without interruptions to the supply, which is done through a main and secondary networks using a series of pumps, pipes and tanks for its distribution. After its use, the water is collected through the drainage system and taken to wastewater treatment plants where it is treated and piped into the sea. There is also an additional tertiary system which collects part of the water that emerges from the treatment plants and converts it into reclaimed water which can then be used for applications such as irrigation. These infrastructures are outside the scope of this study, and their associated electricity consumption is not included in the 89.5 GWh considered for water production.

3.1.4. Cost assumptions

In this step, the costs employed for this study are based on actual data obtained from different sources [49,43–48]. These data are shown in Table 1. Some of the cost references employed in this study, notably [49] and [46], were selected because they were developed by the same research group and are based on previous techno-economic analyses carried out in the Canary Islands. In particular, cost and system information specific to Lanzarote were taken from Ref. [46], while previously validated values for island energy systems in the archipelago were obtained from Ref. [49]. The use of these sources ensures methodological consistency and regional relevance. Additional international references are included to maintain comparability with the broader literature. All cost parameters were adopted as reported in the original sources and were not further adjusted.

The price of the energy purchased from the grid (0.225 €/kWh) was taken as the PVPC 2.0 TD (Voluntary Price for the Small Consumer) tariff, which is regulated by the Spanish Government [63,64]. The data used for the reference scenario were taken from the REE website [65]. The O&M cost parameters implicitly account for system-level expenses associated with electricity transport and grid operation, following a simplified representation consistent with island-scale techno-economic studies. In addition, aggregate losses related to renewable energy generation, wake effects, and electricity transport within the island grid are accounted for through reduction factors applied to renewable energy production. Specifically, the losses amount to a total of 14.8%, while transmission losses to the grid are 4.7% [49]. A flat electricity tariff was adopted for grid electricity, rather than a time-varying price structure, to ensure consistency across scenarios and to focus the analysis on comparative system-level performance rather than market-driven operational optimisation. The tariffs used were €0.025941/kW for power and €0.118419/kWh for energy [49].

In addition to adopting these cost assumptions, a dedicated sensitivity analysis was performed to assess the influence of uncertainties in investment and O&M costs on the economic performance of the system. This analysis allows the robustness of the LCOE results to be evaluated under plausible variations of key techno-economic parameters, rather than relying exclusively on fixed point estimates.

3.1.5. Validating the reference scenario modelled in HOMER

After identifying the components of the energy system and their corresponding costs, the real-life demand data for Lanzarote were introduced into HOMER [40], along with the data corresponding to the number and type of wind turbines employed on the island [31]. The PV power capacity was also introduced as well as the grid option in HOMER that would correspond to the other sources used in the island's energy system [31].

To validate the system, an iterative adjustment was made in HOMER until the errors were less than 5% in each of the generations. This is shown in Table 2.

The reference scenario was modelled, as seen in Fig. 5, with the different renewable energy sources described in Table 3.

Table 2
Sampling error between HOMER data and real-life data.

Energy type	Real (GWh)	HOMER (GWh)	Error
Wind	74	73.92	0.10%
Solar	10	10.005	0.005%
Other	755	760.7	0.75%
Total	839	844.6	0.66%

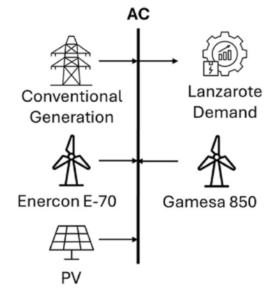

Fig. 5. Diagram for the reference scenario.
Source: own elaboration.

Table 3
Renewable energy sources installed capacity and quantity.

Energy source	Installed capacity	Quantity
Wind Turbine Enercon E−70	23 MW	10
Wind Turbine Gamesa G-52/850	8.5 MW	10
PV Power	16.8 MWp	-

3.2. Generating different alternative scenarios

Fig. 6 shows the 12 alternative scenarios which were developed to cover the entire electricity demand of the island. Of these, 6 retain the conventional generation systems and 6 comprise solely renewable sources. The scenarios are described in Table 4 along with their feasibility.

To cover the island's electricity demand for desalination, a total of 10 scenarios were developed, six with conventional generation systems and four with 100% renewable systems (Fig. 7). The selection of two different wind turbine types is motivated by the technical distinctions between offshore and onshore technologies, with offshore turbines typically exhibiting substantially higher rated capacities. The choice of the 7.5 MW wind turbine is intended to maximize the installed capacity within the spatial constraints of the island. The inclusion of both flywheel and battery energy storage systems reflects their treatment as complementary rather than interchangeable technologies, each addressing distinct operational requirements. Battery storage primarily provides short-to medium-duration energy balancing, enabling load shifting and the smoothing of renewable generation over hourly timescales. In contrast, flywheels are characterized by their capability to deliver very fast response and high power over short durations, thereby providing frequency regulation, inertial support, and grid stability services that are particularly relevant in weak, non-interconnected island power systems. The simultaneous deployment of both technologies enables an assessment of their combined contribution to system stability and operational flexibility. The development of fewer scenarios in this case was due to a prior analysis of the results for total electricity demand in which the omitted scenarios did not give any relevant results. The scenarios are described in Table 5, together with an indication of whether they are feasible.

3.3. Simulating and analysing the different scenarios

Tables A1-A4 show a selection of results obtained with the HOMER programme. Tables A1 and A2 show the results of 100% renewable scenarios to meet both total energy needs and desalinated water energy needs only, in which the data required to apply the Pareto method are shown as Total consumption, AC primary load, Excess electricity (%), and the LCOE (€/kWh).

Tables A3 and A4 show the results of the scenarios that maintain conventional generation, also to meet both total energy needs and desalinated water energy needs only. In this case, the data shown are

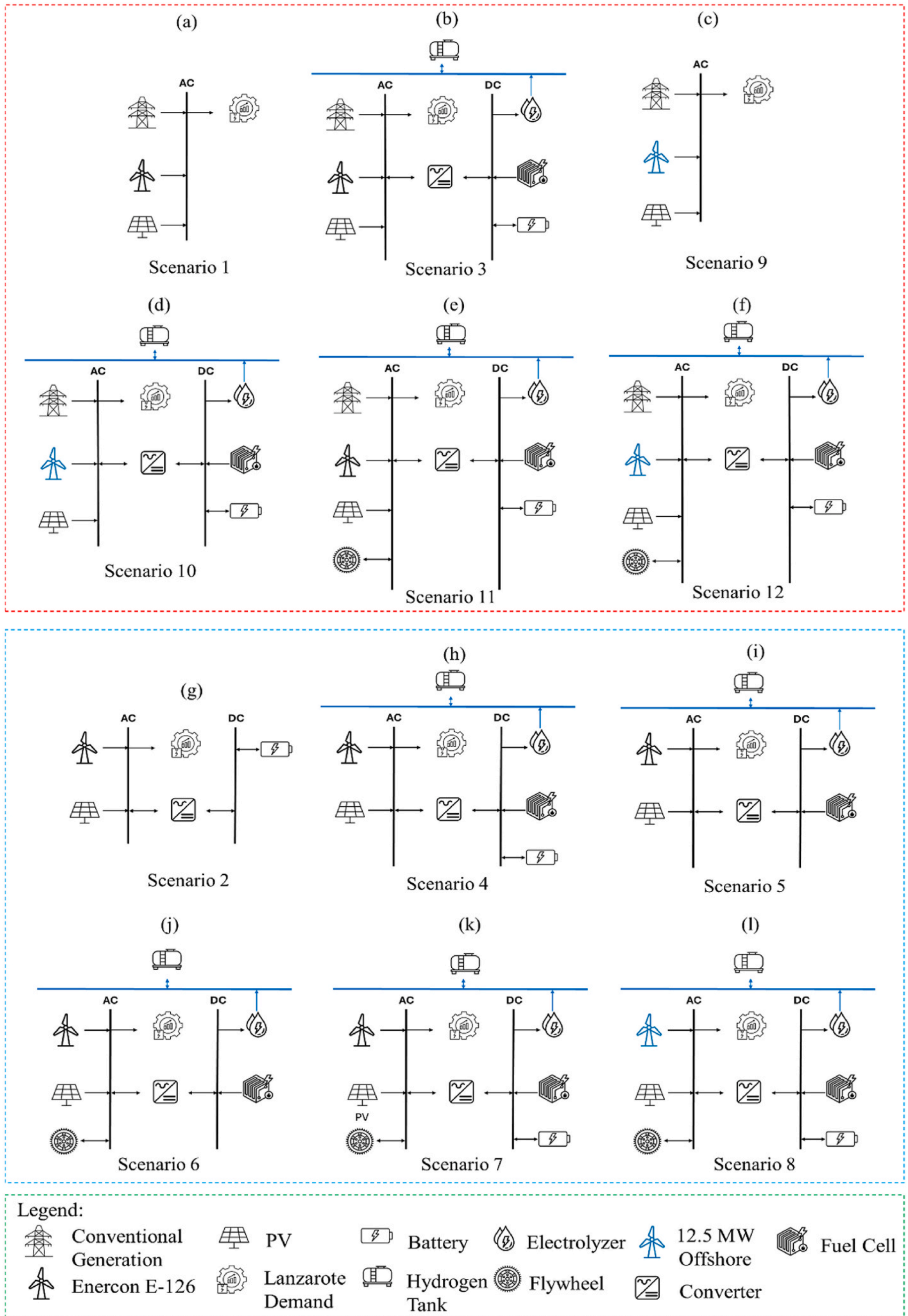

Fig. 6. Scenarios to cover the entirety of Lanzarote's electricity demand. Scenarios (a), (b), (c), (d), (e) and (f) retain the conventional energy sources. Scenarios (g), (h), (i), (j), (k) and (l) are powered with 100% renewable energy sources.

more numerous and include Total consumption (MWh/yr), Wind, PV and Conventional energy production (MWh/yr), the LCOE (€/kWh) and both the RES percentage and the 1-RES percentage. The latter datum is important to obtain an appropriate Pareto plot.

3.4. Selecting the most feasible scenario

In the following analysis, the term "optimal" refers to representative compromise solutions selected from the Pareto front, rather than to a unique mathematically optimal configuration. Various scenarios were defined as unfeasible due to the enormous number of wind turbines that would have to be installed onshore (around 10,000 in some cases), and which is impossible on an island where a maximum number of 138 Enercon E−126 wind turbines is allowed [66]. This number was calculated considering the maximum area of 89.3 km^2 for wind energy in Lanzarote according to the Canary Islands Energy Transition Plan (PTECan) [67]. This area was then divided by the area that would be occupied by one of the wind turbines in question, taking into account the optimal spacing of 8 times the rotor diameter in the upwind direction and 5 times the rotor diameter in the downwind direction. Given an Enercon E−126 rotor diameter of 127 m [66], the area obtained is 0.645 km^2. Therefore:

$$\textit{number of WT} = \frac{89.3}{0.645} = 138\ \textit{WT} \tag{5}$$

Due to the unfeasibility of almost all the 100% renewable scenarios, the results of the scenarios with conventional generation were analysed first, followed by the sole feasible 100% renewable scenario.

Table 4
Description of simulated scenarios to cover Lanzarote's electricity demand.

Scenario	Characteristics	Objectives	Feasibility
Scenarios with conventional energy sources			
Scenario 1	Contains the same elements as the reference scenario, but replacing the current wind turbines with 7.5 MW Enercon E−126 ones	To use the current scenario, while allowing in HOMER maximization of the percentage of renewables penetration	Feasible
Scenario 3	A hydrogen tank, electrolyser, batteries and a fuel cell powered by the hydrogen produced are added	To obtain a higher percentage of renewables penetration by adding energy storage systems and clean energy production	Feasible
Scenario 9	Identical to Scenario 1, but replacing the wind turbines with 12.5 MW offshore ones	To try to reduce the number of wind turbines through offshore installation	Feasible
Scenario 10	Identical to Scenario 3, but replacing the wind turbines with 12.5 MW offshore ones	To try to reduce the number of wind turbines through offshore installation	Feasible
Scenario 11	Identical to Scenario 3, but adding flywheels	To pursue a higher percentage of renewables integration	Feasible
Scenario 12	Identical to Scenario 10, but adding flywheels	To pursue a higher percentage of renewables integration	Feasible
Scenarios 100% renewable			
Scenario 2	Contains the same elements as Scenario 1, but eliminating conventional generation and adding batteries	To use the main scenario, but adding the minimum number of elements possible for it to be fully off grid	Unfeasible
Scenario 4	Identical to Scenario 3, but eliminating conventional generation	To study the feasibility of Scenario 3 without conventional generation	Unfeasible
Scenario 5	Identical to Scenario 4, but eliminating the batteries	To study the feasibility of Scenario 4 only with hydrogen generation	Unfeasible
Scenario 6	Identical to Scenario 5, but adding flywheels	To replace the batteries with flywheels	Unfeasible
Scenario 7	Identical to Scenario 6, but adding batteries	To seek greater balance through the most complete scenario, with all the elements used in the previous scenarios	Unfeasible
Scenario 8	Identical to Scenario 7, but replacing the wind turbines with 12.5 MW offshore ones	To seek a reduction in the number of wind turbines and greater feasibility	Unfeasible

The solutions shown in Tables A3-A4 and in Figs. 8 and 9 for the second Pareto optimisation correspond to the scenarios that maintain conventional generation.

It can be seen in both Figs. 8a and 9a that the LCOE increases with CO_2 emissions. Something similar can also be seen in Figs. 8b and 9b, where the LCOE increases as the RES percentage falls. This increase in LCOE becomes evident as renewable energy integration is reduced from 80% (represented as 20% in Figs. 8b and 9b, where the term is inverted to allow proper visualization of the Pareto front), with the LCOE nearly doubling when a 0% renewable energy share is reached in both figures (corresponding to 100% in the inverted representation). The most favourable scenarios are those which are around 0.2 €/kWh in Fig. 8a and around 0.6 €/kWh in Fig. 9a, with the more expensive ones those at or above 0.4 €/kWh in Figs. 8a and 1 €/kWh in Fig. 9a, where the participation of renewables is below 40% and, in some cases, even falls to 0%. In addition, in Figs. 8a and 9a some cases can be seen with a very high LCOE (1.6 and 3.2 €/kWh, respectively), with a renewable participation of close to 100% but a high degree of economic infeasibility. In the most unfavourable cases, emissions rise to values above 500,000 tCO_2/year in Fig. 8a and over 50,000 tCO_2/year in Fig. 9a.

In Fig. 9, the selected compromise solution gives an LCOE of 0.251 €/kWh and a RES participation of 87.01%. These data were obtained from the following parameters of the system.

- An installed wind power of 525 MW. This corresponds to 70 × 7.5 MW wind turbines which cover 73.68% of the demand.
- An installed PV power of 349.13 MW. This covers 11.88% of the demand.
- A 500,000 kg hydrogen tank.
- A 90 MW electrolyser.
- A 14 MW fuel cell which covers 1.45% of the demand.
- A 500 MW system converter.
- An installed power of 133 MW of conventional generation, covering 12.99% of the demand.

Fig. 10 shows the average monthly production of the different production technologies in the optimal scenario. It can be seen how wind energy is predominant, with excess energy being produced. This is because the graph represents a monthly average and does not capture the peaks of wind energy production accurately. For its part, solar PV produces less energy but generally remains stable over time. The hydrogen fuel cell is the smallest percentage contributor to the system. Finally, conventional energy production remains stable over time, with a drop in production in the central months of the year, coinciding with a higher production of wind energy. It can also be seen how emissions increase and decrease with more or less conventional production.

In Fig. 9, the selected compromise solution gives an LCOE of 0.601 €/kWh and a RES participation of 91.65%. These data were obtained from the following parameters of the system.

- An installed wind power of 25 MW. This corresponds to 2 × 12.5 MW offshore wind turbines which cover 59.13% of the demand.
- An installed PV power of 82.47 MW. This covers 31.73% of the demand.
- A 500,000 kg hydrogen tank.
- A 90 MW electrolyser.
- A 0.52 MW fuel cell which covers 0.78% of the demand.
- A 100 MW system converter.
- A maximum installed power of 15 MW of conventional generation which covers 8.35% of the demand.
- Batteries with a capacity of 6.213 MWh.
- 5 × 10 MW flywheels.

Fig. 11 shows the average monthly production of the different production technologies in the conventional optimal scenario to cover the island's desalination demand. As in the previous scenario, wind energy is predominant, producing the excess energy seen in Fig. 10. In this case, solar PV energy plays a more significant role with higher percentages of participation. It remains generally stable throughout the year, falling slightly in the winter months. The hydrogen fuel cell in this scenario has a low share and is appreciable in January and in December. Finally, conventional energy production tends to reduce in the summer months of the year, coinciding with a higher production of wind and PV energy. As in the previous case, it can be seen how emissions are linked to conventional production.

Table 6 shows the most relevant data from the optimal solutions in both case studies (total demand and desalination demand), as well as the lower and upper Pareto front solutions.

In the case of the 100% renewable scenarios, the only feasible one is that intended to cover the island's desalination demand. The results shown in Fig. 12 reveal an increasing LCOE trend as excess electricity increases. In other words, the inefficiency of the system leads to a higher LCOE. It can also be seen that an excessive reduction in excess electricity requires a larger amount of equipment, thus considerably increasing the cost. Due to the non-consideration of the unfeasible cases, the LCOE only

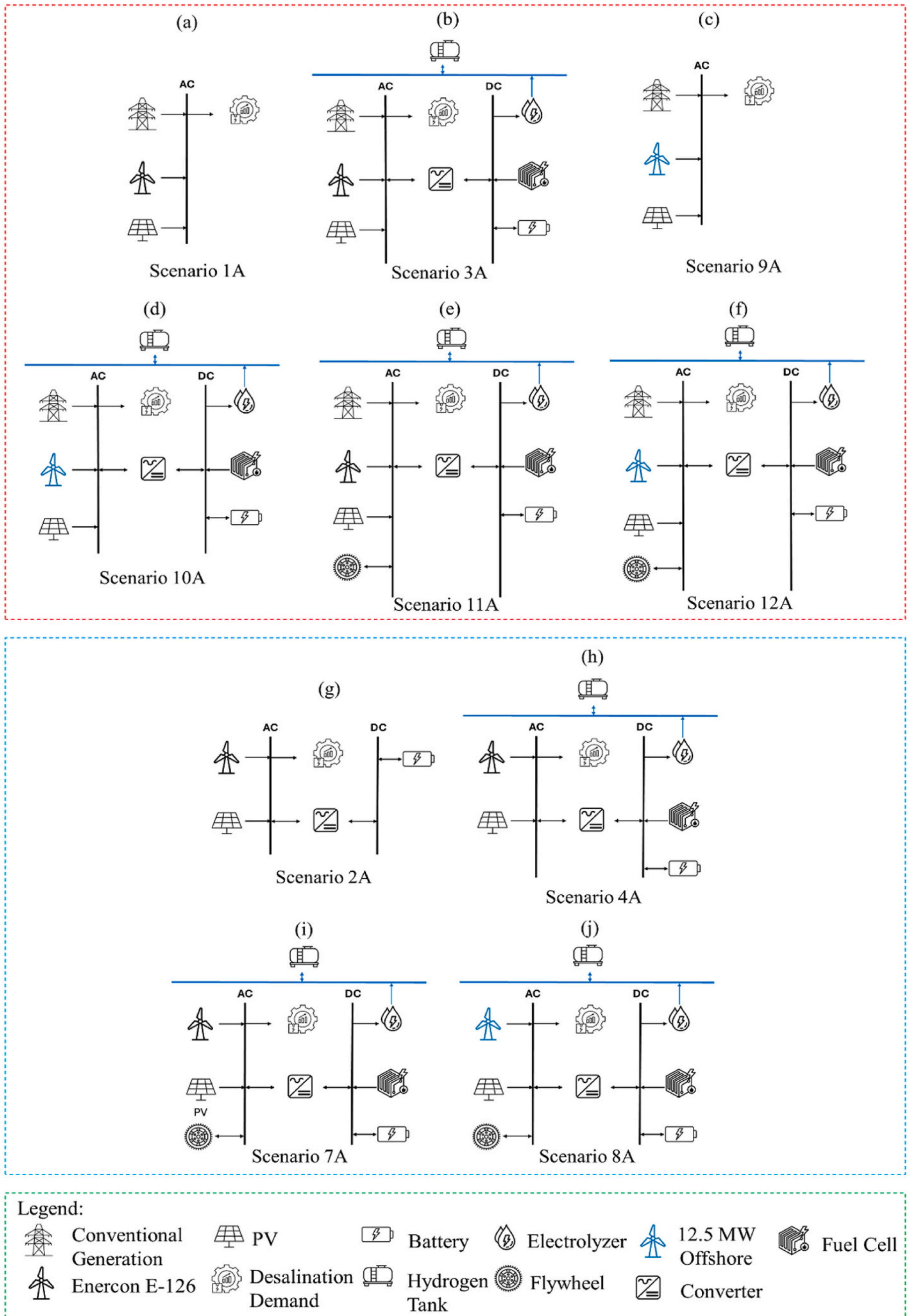

Fig. 7. Scenarios to cover Lanzarote's desalination electricity demand. Scenarios (a), (b), (c), (d), (e) and (f) retain the conventional energy sources. Scenarios (g), (h), (i) and (j) are powered with 100% renewable energy sources.

reaches a value close to 1 €/kWh when excess electricity is greater than 60%. The unfeasible cases have a much higher LCOE and excess electricity values of above 90%, as can be seen in Tables A1-A2. In contrast, in Fig. 12, the selected compromise solution gives an LCOE of 0.625 €/kWh and an excess electricity of 27.3%. These data were obtained from the following parameters of the system.

- An installed wind power of 52.5 MW. This corresponds to 7 × 7.5 MW wind turbines which cover 63.84% of the demand.
- An installed PV power of 114.41 MW. This covers 33.73% of the demand.
- Batteries with a capacity of 96.72 MWh.
- A 17 MW hydrogen fuel cell which covers 2.43% of the demand.
- A 500,000 kg hydrogen tank.
- A 90 MW electrolyser.
- A 300 MW system converter.

Fig. 13 shows the average monthly production of the different production technologies in the optimal 100% renewable scenario to cover the island's desalination demand. As in the previous two cases, wind energy is the main energy source for the system, with some excess electricity produced due to the nature of the 100% renewable system especially in the summer months. Solar PV power is relatively constant throughout the year, with a slight reduction in the winter months. The hydrogen fuel cell meets more demand in the winter months, coinciding with a reduction in wind and PV production. In contrast, the opposite effect occurs in the middle months of the year, corresponding to the summer.

Table 5
Description of simulated scenarios to cover Lanzarote's desalination electricity demand.

Scenario	Characteristics	Objectives	Feasibility
Scenarios with conventional energy sources			
Scenario 1A	Contains the same elements as the reference scenario, but replacing the current wind turbines with 7.5 MW Enercon E−126 ones	To use the current scenario, while allowing in HOMER maximization of the percentage of renewables penetration	Feasible
Scenario 3A	A hydrogen tank, electrolyser, batteries and a fuel cell powered by the hydrogen produced are added	To obtain a higher percentage of renewables penetration by adding energy storage systems and clean energy production	Feasible
Scenario 9A	Identical to Scenario 1A, but replacing the wind turbines with 12.5 MW offshore ones	To try to reduce the number of wind turbines through offshore installation	Feasible
Scenario 10A	Identical to Scenario 3A, but replacing the wind turbines with 12.5 MW offshore ones	To try to reduce the number of wind turbines through offshore installation	Feasible
Scenario 11A	Identical to Scenario 3A, but adding flywheels	To pursue a higher percentage of renewables integration	Feasible
Scenario 12A	Identical to Scenario 10A, but adding flywheels	To pursue a higher percentage of renewables integration	Feasible
Scenarios 100% renewable			
Scenario 2A	Contains the same elements as Scenario 1A, but eliminating conventional generation and adding batteries	To use the main scenario, but adding the minimum number of elements possible for it to be fully off grid	Unfeasible
Scenario 4A	Identical to Scenario 3A, but eliminating conventional generation	To study the feasibility of Scenario 3A without conventional generation	Feasible
Scenario 7A	Identical to Scenario, but adding flywheels	To obtain greater response capacity in the face of energy fluctuations with a lower cost	Unfeasible
Scenario 8A	Identical to Scenario 7A, but replacing the wind turbines with 12.5 MW offshore ones	To seek a reduction in the number of wind turbines and greater feasibility	Unfeasible

Table 7 shows the most relevant data from the 100% renewable optimal solution that would cover the desalination demand as well as the lower and upper Pareto front solutions.

3.5. Sensitivity analysis of techno-economic assumptions

To assess the robustness of the economic results, a sensitivity analysis was performed on key techno-economic parameters affecting the LCOE. The analysis focused on two representative configurations selected from the Pareto-optimal solutions: (i) the system supplying the total electricity demand of the island; and (ii) the system supplying the electricity demand associated with seawater desalination.

A one-at-a-time sensitivity approach was adopted in which individual parameters were varied while all others were kept at their baseline values. The parameters analysed include the discount rate, capital investment costs, O&M costs, and component lifetimes of the main technologies. Each parameter was varied within ±20% of its baseline value.

Figs. 14 and 15 present the resulting variations in LCOE for the total island system and the desalination system, respectively.

For both cases, the discount rate has the strongest influence on LCOE. Among technology-specific parameters, the capital investment costs of wind and PV generation have the largest impact. The capital costs and lifetimes of electrolysers and battery storage exhibit a moderate influence, while the cost parameters of hydrogen storage tanks and flywheel storage have a comparatively limited effect on LCOE.

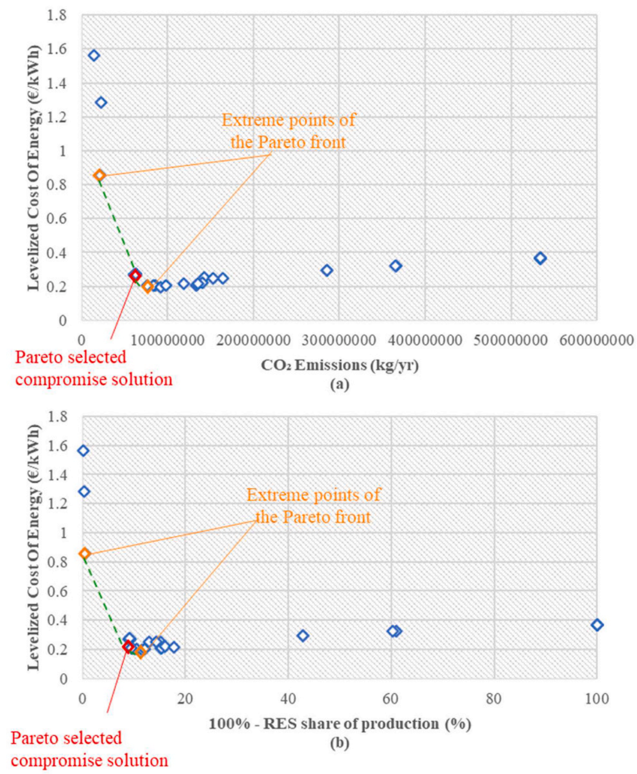

Fig. 8. Pareto fronts from Pareto-optimal solutions retaining conventional energy sources for total electricity consumption of the island.
Source: own elaboration.

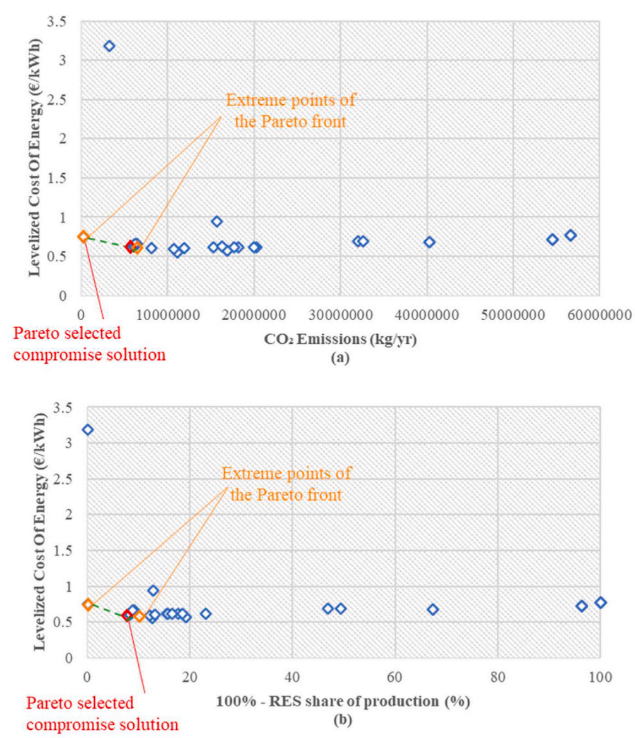

Fig. 9. Pareto fronts from optimal solutions which retain the conventional energy sources for desalination electricity consumption of the island.
Source: own elaboration.

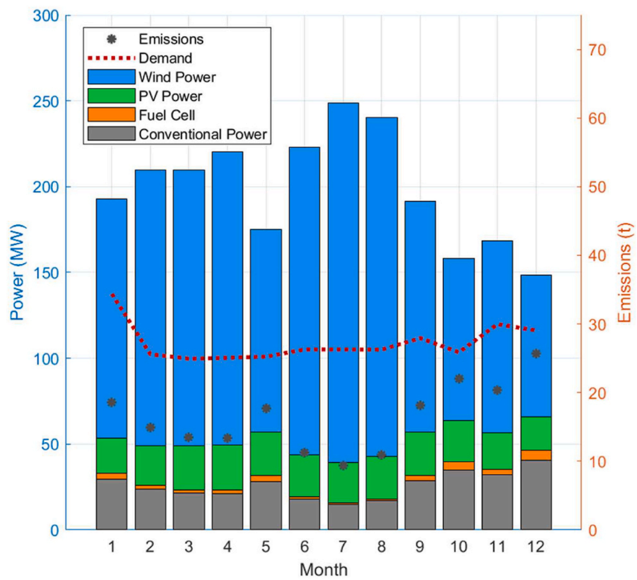

Fig. 10. Monthly average power productions of the different technologies to cover total demand.
Source: own elaboration.

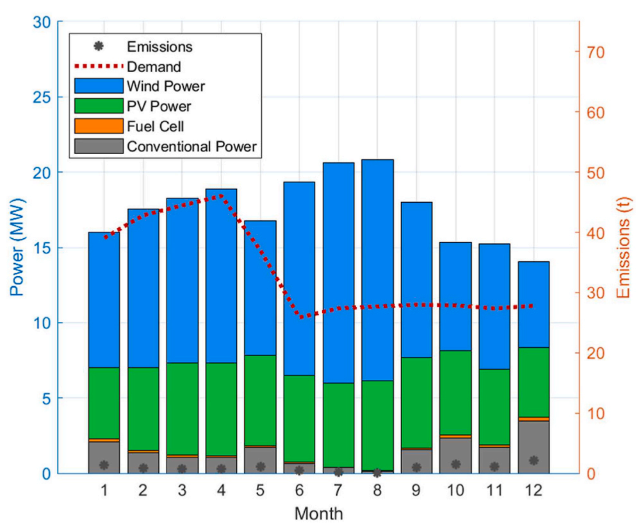

Fig. 11. Monthly average power productions of the different technologies to cover desalination demand while maintaining conventional energy sources.
Source: own elaboration.

4. Discussion

This study analysed the feasibility of an energy system based on renewable sources for the island of Lanzarote.

4.1. Covering total electricity demand while retaining conventional energy sources

In the scenarios that retain conventional generation, relatively low LCOE values are achieved. For instance, the selected Pareto-optimal scenario to cover the total electricity demand of the island yields an LCOE of 0.251 €/kWh, which is lower than in the fully renewable scenarios as it does not require large battery capacities that significantly increase system costs (Table 6). In addition, the high penetration of wind power (73.68%) plays a dominant role in maintaining low generation costs. PV energy contributes 11.88% of total generation, complemented by hydrogen fuel cells, resulting in a high renewable share of 87.01% (Table 6). This configuration also leads to substantially reduced CO_2 emissions (142,957 t/yr) (Table 6). The renewable penetration achieved exceeds that reported in previous island studies such as [11] and [9], which considered considerably smaller populations and therefore lower absolute demand levels.

The number of wind turbines required (70 units; Table 6) is compatible with the available surface area of the island and does not constitute a limiting factor, as discussed in Section 3.4.

The inclusion of a hydrogen storage subsystem allows surplus wind electricity to be stored, thereby improving overall system efficiency and operational flexibility. Although the installed fuel cell covers only 1.45% of total demand, it enhances system resilience by providing dispatchable renewable power during periods of low wind and solar availability. Excess hydrogen could also be redirected to other end uses, such as transport. A further advantage of hydrogen storage lies in the relatively low cost of storage tanks, which has been identified as a key factor in reducing system costs in similar configurations [20]. Even when conventional backup generation is retained, hydrogen production offers multiple benefits: it reduces renewable curtailment, offsets fossil-based generation during shortfalls, and supports longer-term decarbonization pathways by enabling sector coupling beyond electricity supply. Although hydrogen storage can also present drawbacks, including low volumetric energy density, energy losses, safety concerns, and potential leakage, its use as an alternative energy storage solution is increasingly prevalent in most recent studies [68,69].

From an economic robustness perspective, the sensitivity analysis presented in Section 3.5 indicates that the relatively low LCOE values obtained in scenarios retaining conventional generation are preserved under plausible variations in investment costs, O&M costs, component lifetimes, and discount rates. Although absolute LCOE values vary, the dominant influence of wind power penetration and financing conditions remains unchanged. Although absolute LCOE values vary across the sensitivity ranges analysed, the relative importance of the main cost drivers remains unchanged, with wind power penetration and the discount rate consistently dominating the economic performance of the system. From an implementation perspective, the large-scale deployment of renewable generation and storage technologies on Lanzarote would be subject to significant territorial, environmental, and regulatory constraints. According to the Strategic Environmental Assessment in PTECan [70] the siting of onshore and offshore wind, PV installations, and associated infrastructures must comply with multiple criteria, including protected natural areas, landscape sensitivity, proximity to population centres, aeronautical and maritime servitudes, existing land uses, and grid accessibility. The PTECan explicitly acknowledges that, while overall renewable deployment targets are achievable at archipelago scale, certain technologies, particularly onshore wind, approach territorial feasibility limits on specific islands, including Lanzarote. Consequently, the technically feasible configurations identified in this study should be interpreted as upper-bound system-level scenarios, whose real-world implementation would require detailed project-level environmental impact assessments, permitting procedures, and coordination with territorial planning instruments. These aspects fall outside the scope of the present techno-economic modelling but are essential to translate system-level feasibility into implementable projects [70].

It should be noted that transmission losses and grid operation costs are represented in an aggregated manner in this study. While a more detailed grid model with spatial resolution and time-varying tariffs could affect absolute cost estimates, such refinements are unlikely to alter the relative performance trends observed among the analysed scenarios. Similar system-level studies using scenario-based energy system models often adopt simplified grid representations when the focus is on comparative system design rather than detailed network operation.

Table 6
Most relevant data from selected Pareto-optimal solutions retaining conventional energy sources.

Selected Pareto-optimal solution	LCOE (€/kWh)	RES (%)	Emissions (t/yr)	Wind power (MW)	PV power (MW)	Batteries (MWh)	Hydrogen tank (t)	Fuel cell (MW)	Flywheel (MW)	Conventional power (MW)
Selected Pareto-optimal scenario for total demand	0.251	87.01	142957	525 (70x7.5)	349.13	-	500	14	-	133
Upper Pareto front for total demand	0.856	99.73	20192	637.5 (51x12.5)	927.27	-	500	14	50x10	133
Lower Pareto front for total demand	0.206	90.46	85382	277.5 (37x7.5)	951.77	126.77	500	14	-	133
Selected Pareto-optimal scenario for desalination demand	0.601	91.65	8123	25 (2x12.5)	82.47	6.213	500	0.52	5x10	15
Upper Pareto front for desalination demand	0.741	99.88	281.9	75 6x12.5)	165.34	168.23	500	0.52	-	15
Lower Pareto front for desalination demand	0.626	91.33	6065	-	166.02	169.21	500	0.52	-	15

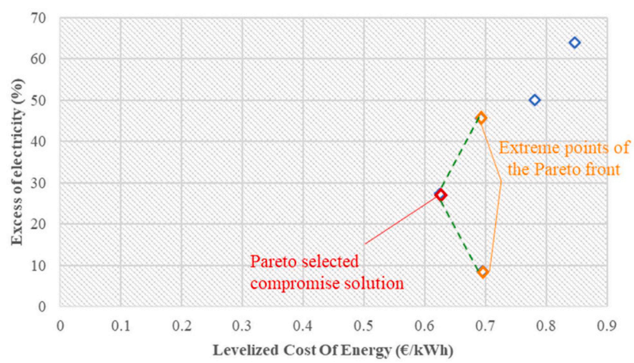

Fig. 12. Pareto front from 100% renewable optimal solutions with the desalination consumption of the island.
Source: own elaboration.

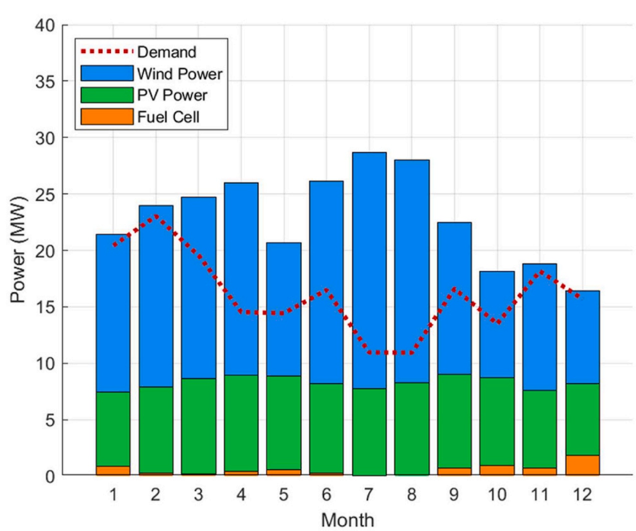

Fig. 13. Monthly average power productions of the different technologies to cover desalination demand (100% renewable scenario).
Source: own elaboration.

4.2. *Covering desalination demand while retaining conventional energy sources*

In the second case study, scenarios dedicated exclusively to covering the island's desalination electricity demand while retaining conventional energy sources are analysed. The optimal solution uses wind and PV generation, complemented by a small contribution from a hydrogen fuel cell.

Wind energy accounts for a large share of renewable generation (59.13%), which, as in previous cases, contributes to maintaining a relatively low LCOE. The number of wind turbines required is relatively small (two units; Table 6), and, being offshore installations, land availability on the island is not a limiting factor. The optimal offshore wind turbine location corresponds to the area identified in Ref. [71], off the southeast coast of the island. A similar configuration was reported by Hoseinzadeh et al. [11] for the Norwegian region of Hinnøya. This high share of wind energy is also consistent with previous studies highlighting the strong performance of wind-powered desalination systems [24].

When solar PV generation is included (31.73%), the overall renewable share exceeds 90% and reaches 91.65% with the contribution of the hydrogen fuel cell (Table 6).

Battery storage ensures supply reliability and reduces the need for additional conventional generation. By absorbing surplus electricity (primarily from wind and, to a lesser extent, from PV generation) batteries contribute to lower CO_2 emissions and improved system efficiency.

The deployment of five 10-MW flywheel units enhances system stability and provides a rapid response to power fluctuations (Table 6). In this context, flywheels support frequency regulation and contribute to smoother power delivery.

The system also includes hydrogen storage with a tank capacity of 500,000 kg (Table 6). Given the relatively small fuel cell capacity (0.52 MW), hydrogen contributes a limited share of the overall energy supply.

Finally, the resulting LCOE is 0.601 €/kWh (Table 6), which is slightly higher than that obtained for the optimal fully renewable configuration.

The sensitivity analysis indicates that the economic performance of the desalination-focused system is primarily driven by the capital costs of wind and PV generation and by the discount rate, while storage-related components play a secondary role. This confirms that the conclusions drawn for the desalination case remain robust under reasonable techno-economic uncertainty.

4.3. *Covering total electricity demand only with renewables*

With respect to the 100% renewable scenarios, none of those intended to cover the entire electricity demand of the island were found to be feasible. This is mainly due to the enormous number of wind turbines required, much higher than the permitted maximum of 138, and, consequently, to the excessively high LCOE values, many of which were above 10 €/kWh.

Table 7
Most relevant data from selected Pareto-optimal solutions for the 100% renewable case.

Pareto-optimal scenario for desalination demand	LCOE (€/kWh)	Excess electricity (%)	Wind power (MW)	PV power (MW)	Batteries (MWh)	Fuel cell (MW)	Hydrogen tank (t)	Electrolyser (MW)	Converter (MW)
Selected Pareto-optimal scenario for desalination demand	0.625	27.3	52.5 (7x7.5)	114.41	96.72	17	500	90	300
Upper Pareto front for desalination demand	0.692	45.7	157.5 (21 x 7.5)	-	79.82	17	500	90	300
Lower Pareto front for desalination demand	0.694	8.46	-	291.91	180.94	17	500	90	300

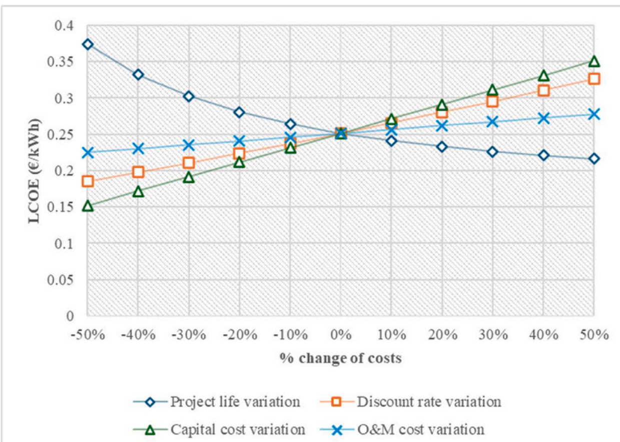

Fig. 14. Sensitivity of LCOE to key techno-economic parameters for the total island electricity system.
Source: own elaboration.

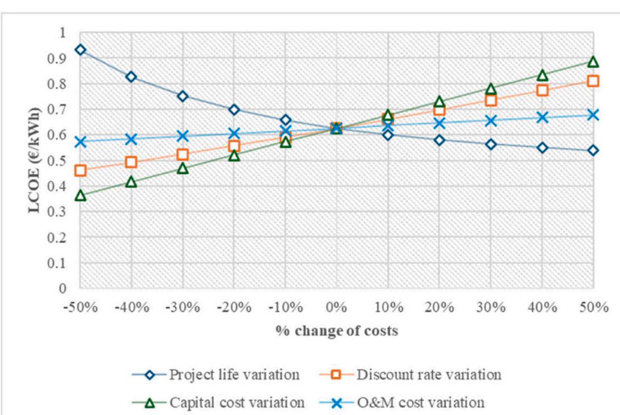

Fig. 15. Sensitivity of LCOE to key techno-economic parameters for the desalination electricity system.
Source: own elaboration.

4.4. Covering desalination demand only with renewables

In the case of the scenarios intended exclusively to cover the island's desalination demand, all but one of the simulated scenarios had to be discarded for the same reasons as above. Therefore, the results analysed in this case correspond to the only feasible scenario.

It has been seen that, in the optimal result, most of the desalination electricity consumption is covered by wind energy (63.84%) (Table 7). This high wind power penetration means that the LCOE is kept relatively low (0.625 €/kWh) (Table 7), slightly higher than its counterpart for conventional generation but very similar in comparison. This is because wind energy has low operational costs, as also discussed in Refs. [14] and [21]. This high wind participation is also a reflection of the significant wind resource that the Canary Islands possess [22]. Covering the desalination demand alone requires a much lower energy production and is a simpler scenario to implement.

The number of wind turbines required (7) (Table 7) is not a limiting factor, as it is below the estimated limit (138).

Solar PV energy covers practically the rest of the demand (33.73%) (Table 7), but in a greater proportion than in Ref. [15] where the largest percentage is produced by hydroelectric energy rather than wind energy. Maintaining at least two types of RES is key to ensure greater system flexibility.

The inclusion of batteries in the system ensures that there are no power outages at times when there is insufficient solar radiation or wind. The batteries are charged with surplus electricity produced by the system and reduce system losses. While more batteries could be installed or excess electricity sold, as proposed in Ref. [28], the relatively high percentage of excess electricity (27.3%) needs to be reduced to increase the efficiency of the system (Fig. 13).

According to the sensitivity analysis (Section 3.5), the relatively high LCOE observed in fully renewable desalination scenarios is mainly influenced by financing conditions and the capital cost of renewable generation technologies. Variations in hydrogen storage tank size and flywheel-related costs have a limited impact on the overall LCOE, confirming that excess electricity and system oversizing, rather than storage costs alone, are the main drivers of economic performance in these scenarios.

Excess electricity could be used to heat the feedwater of the SWRO modules and increase the product water flow. As mentioned in Ref. [22], operating with warmer feed water decreases seawater viscosity, enhancing membrane permeability and, consequently, increasing permeate flux. As a general guideline, permeate production rises by approximately 3% for each 1 °C increase in temperature. While higher temperatures also lead to increased osmotic pressure and may promote greater salt passage (thereby reducing permeate quality due to thermally induced changes in membrane structure), heating seawater within acceptable temperature limits results in lower viscosity, improved membrane permeability, and ultimately higher product water output.

The rest of the electricity demand (2.43%) is covered by a hydrogen-powered fuel cell (Table 7). Although it does not cover a large percentage of the demand, the 500,000 kg capacity offers the system the possibility of storing excess energy in the form of hydrogen. Another possible use for the hydrogen generated could be in land transport. This contrasts with a previous study by Roy [12] in which, in the scenarios simulated in HOMER in that study, only batteries were used to cover the storage needs of the isolated system proposed for the island of Ghoramara in India.

The two storage systems included in the system (hydrogen and batteries) help to reduce oversizing of the system in this type of renewable scenario, as indicated in Ref. [20].

4.5. Limitations and future work

Although this study presents a comprehensive analysis of renewable energy integration and desalination on Lanzarote, some limitations must be noted. First, the simulations assume large-scale deployment of wind turbines and PV arrays, yet real-world land-use and regulatory constraints may reduce the available space or impose additional environmental requirements. Second, the capital and operating costs used here rely on current market data, which may shift over time due to policy changes (such as feed-in tariffs or carbon taxes). Third, while hourly demand profiles were considered, seasonal variations in both desalination and tourism-driven electricity consumption might necessitate multi-year datasets for more accurate modelling.

In addition, the island electricity grid is represented at a system level, without explicit modelling of transmission line sizing, nodal constraints, or power-flow dynamics. Transmission and distribution losses, as well as wake and generation losses, are accounted for in an aggregated manner through reduction factors applied to renewable generation, and network-related costs are implicitly included in O&M assumptions. While this approach is consistent with many scenario-based island energy system studies, the absence of a spatially resolved grid model may affect absolute LCOE values, particularly in scenarios with very high installed renewable capacities.

Finally, the research employs HOMER's default system-dispatch logic, which may overlook aspects such as turbine inertia, minimum loading levels for conventional plants, and real-time frequency regulation complexities that could influence system stability in practice. Moreover, the treatment of uncertainty in this study is necessarily simplified. Although a deterministic sensitivity analysis was performed to assess the influence of key techno-economic parameters, uncertainties were addressed by varying individual inputs independently. This approach does not fully capture the combined effects of multiple uncertain parameters or their potential statistical dependence, which may be relevant in complex, highly integrated energy–water systems.

Future research could address these limitations in several ways. Techno-economic validation through pilot-scale demonstrations or more detailed power-flow simulations would refine the economic viability of hydrogen and flywheel integration under real operational conditions. More advanced uncertainty quantification approaches could also be explored, including global sensitivity analysis frameworks that explicitly account for probability distributions and statistical dependencies among multiple input parameters. Recent methodological developments have demonstrated the use of multivariate copula-based techniques to represent correlated uncertainties and to propagate them through complex energy system models. Applying such approaches to the techno-economic variables considered in this study would allow a more comprehensive assessment of uncertainty and robustness in island-scale energy–water system planning [72].

A life-cycle assessment is also warranted to gauge the broader environmental impact of the manufacture and disposal of system components such as batteries, electrolysers, and wind turbines. In parallel, policy and regulatory analysis, including the design of incentives and tariffs, could facilitate the adoption of renewables for island communities and encourage both hydrogen production and desalination. Extending the methodology to other archipelagos with distinct wind, solar, and tourism patterns would further confirm the broader applicability of this approach.

4.6. Policy and practical implementation

From a policy and regulatory perspective, the authorities in the Canary Islands have established several strategic initiatives to encourage renewable energy adoption, including the Estrategia Canaria del Hidrógeno Verde [18] ("Canary Green Hydrogen Strategy"). These frameworks, supported by Spain's national decarbonization commitments and broader EU targets [17], can help expedite permitting processes for new wind and PV installations and incentivize hydrogen production. Additionally, island authorities could consider dedicated tariffs or subsidies to promote power-to-water desalination systems and flywheel storage, thereby reducing project risk for investors. By integrating policy incentives into the technical scenarios proposed here, the Canary Islands could more quickly adopt these solutions, paving the way for other archipelagos and remote regions facing similar water and energy challenges.

5. Conclusions

In this article, a method is proposed with the aim of integrating as many renewable energies as possible into an island's energy system. Given that island resources are generally limited and are highly dependent on external sources, especially for energy and water, two specific case studies are proposed, one covering the total energy system of the island and the other only the part which meets the island's desalination demand. For this purpose, a balance between the LCOE, excess electricity and CO_2 emissions is sought.

The method developed is applied to the island of Lanzarote (Canary Archipelago, Spain). The analyses undertaken show that it is possible to achieve a significant integration of renewable energies in the island's energy system, reducing dependence on fossil fuels and CO_2 emissions. In particular, it is found that the optimal combination of wind energy, solar PV energy and hydrogen storage when the system still relies on conventional energy sources allows coverage of up to 87.01% of the island's total energy demand with renewable sources, reaching an LCOE of 0.251 €/kWh. Furthermore, implementation of this system significantly reduces emissions, contributing to decarbonization of the island's energy sector. However, the optimal solution when no fossil fuel energy is relied upon is unfeasible due to the number of wind turbines that would have to be installed which far exceeds the available surface area. Although none of the 100% renewable scenarios is feasible, the percentage of RES penetration obtained from the simulations of the scenarios that still rely on conventional energy sources is quite promising.

In the scenarios aimed at covering only desalination electricity demand, a similar situation arises as with the scenarios which aim to cover the island's total demand, but in this case one of the scenarios may be feasible. The excess electricity produced in these 100% renewable systems is the biggest problem to be faced, although these excesses could be sold directly to the main grid, thereby significantly lowering the LCOE. The LCOE of the optimal scenario when conventional generation is retained is 0.601 €/kWh, with 91.65% integration of renewables, a value very similar to the 0.625 €/kWh obtained when considering a 100% renewable scenario.

In all cases, the percentage of renewable energy integration exceeds the 10% that is currently available, confirming that it is possible to implement an economical and feasible system with a high percentage of renewables. Furthermore, the integration of battery storage and flywheels ensures system stability by compensating for fluctuations inherent to renewable energy, thereby maintaining continuous supply.

The findings of this study can provide practical guidance for local authorities and utility companies in the Canary Islands and beyond. By recognizing the crucial role of surplus wind power directed toward hydrogen production and desalination, policymakers can formulate incentives or tariffs to accelerate project deployment.

Although the focus here is on Lanzarote, the proposed approach has clear potential applicability to other archipelagos, especially those with significant tourism-driven demands and water scarcity. Adapting the scenario models to different resource endowments, regulatory frameworks, and demand profiles would further confirm the robustness of these solutions.

Finally, certain limitations warrant attention. For instance, land-use constraints, cost assumptions, and seasonal demand variations could significantly influence the feasibility of high-RES scenarios. Future research could conduct pilot demonstrations, expand the methodology to multi-year analyses, or perform more detailed grid simulations. Additionally, life-cycle assessments of the technologies and a deeper exploration of policy mechanisms—such as the Canary Green Hydrogen Strategy —could help integrate these systems into real-world energy and water strategies. These steps would refine the approach further and ensure its continuing relevance for decarbonization efforts on islands with limited resources.

CRediT authorship contribution statement

Carlos Matos: Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Ricardo Linares:** Validation, Investigation, Formal analysis, Data curation, Writing – original draft. **Alejandro Romero-Filgueira:** Software, Investigation, Data curation. **José A. Carta:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization, Data curation. **Pedro Cabrera:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, 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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Appendix

Table A1
Relevant results from 100% renewable optimal solutions for total energy consumption of the island.

	Total consumption (%)	AC primary load (%)	Excess electricity (%)	LCOE (€/kWh)
Scenario 2	0.441	0.441	99.6	10.25785
	0.442	0.442	99.6	10.32123
Scenario 4	0.586	0.442	99.4	10.19504
	0.601	0.442	99.4	10.20267
	0.672	0.442	99.3	10.2387
	0.454	0.442	99.5	10.26864
	0.53	0.439	99.5	10.28689
	0.455	0.443	99.5	10.31945
Scenario 5	0.58	0.44	99.4	10.26234
Scenario 6	1.53	0.971	98.4	5.002052
Scenario 7	1.53	0.974	98.4	4.993192
	1.51	0.974	98.5	4.994671
	1.46	0.969	98.5	5.010889
	1.23	0.965	98.8	5.099246
	1.24	0.972	98.7	5.1066
	1.22	0.972	98.8	4.733845
	1.32	0.974	98.7	4.734048
	1.24	0.969	98.7	4.747828
	1.03	0.972	99	4.843148
	1.01	0.959	99	4.862293
Scenario 8	1.33	1.05	98.7	4.99195
	1.35	1.04	98.6	5.021553
	1.27	1.05	98.7	5.022192
	0.734	0.586	99.3	8.824448
	0.447	0.423	99.6	12.17699
	0.326	0.309	99.7	16.62404
	0.0513	0.0486	99.9	105.0306
	0.0247	0.0234	100	218.1639

Table A2
Relevant results from 100% renewable optimal solutions for desalination electricity consumption of the island (selected compromise solution in red, lower and upper Pareto fronts in yellow).

	Total consumption (%)	AC primary load (%)	Excess electricity (%)	LCOE (€/kWh)
Scenario 2A	0.442	0.442	99.6	10.45047
	0.442	0.442	99.5	11.68639
Scenario 4A	70.3	44.5	27.3	0.6255906
	52.4	22.7	45.7	0.6922358
	84.4	50	8.46	0.6947032

(continued on next page)

Table A2 (*continued*)

	Total consumption (%)	AC primary load (%)	Excess electricity (%)	LCOE (€/kWh)
	48.2	16.7	50.1	0.7815805
	34.8	11.7	64	0.8472031
Scenario 7A	1.36	0.967	98.6	5.154073
	1.35	0.966	98.6	5.156117
	1.35	0.967	98.6	5.156438
	1.23	0.973	98.7	5.283303
	1.21	0.959	98.8	5.329443
	1.23	0.975	98.7	5.355589
Scenario 8A	1.47	1.05	98.5	5.388885
	1.34	1.05	98.6	5.442229
	1.37	1.04	98.6	5.473625
	1.33	1.05	98.6	5.497818
	1.32	1.04	98.7	5.568315
	0.966	0.765	99	7.253911
	0.0613	0.0486	99.9	105.5217
	0.0295	0.0234	100	218.5914

Table A3
Relevant results from optimal solutions which retain the conventional energy sources for total energy consumption of the island (selected compromise solution in red, lower and upper Pareto fronts in yellow).

	AC primary load (MWh/yr)	Conventional power (MWh/yr)	Fuel cell (MWh/yr)	LCOE (€/kWh)	PV power production (MWh/yr)	Wind power production (MWh/yr)	Emissions (t/yr)	% RES	1- %RES
Scenario 1	844625	844626	0	0.3654469	0	0	533791	0	100
	844625	844625	0	0.3652076	0	0	533791	0	100
Scenario 3	844625	135103	40548	0.2056673	563824	678095	85383	90.46941	9.530581
	844625	211556	46998	0.2083146	0	1136267	133700	84.83274	15.16725
	844625	260795	35832	0.2501523	0	1429497	164819	84.89130	15.10869
	844625	226204	25238	0.2513272	206823	1282882	142958	87.00832	12.99167
	844625	98284	21763	0.2715293	956724	0	62114	90.87234	9.127654
	844625	580061	29013	0.3220707	342707	0	366590	39.05523	60.94476
Scenario 9	844625	844626	0	0.3698708	0	0	533874	0	100
	844625	844654	0	0.3700802	0	0	533872	0	100
Scenario 10	844625	132365	43991	0.2051809	554362	546213	83653	89.63414	10.36585
	844625	187632	39887	0.2178047	0	955873	118581	84.14452	15.85547
	844625	242227	33277	0.250456	0	1411050	153084	85.63773	14.36226
	844625	95013	22140	0.2714912	963978	0	60047	91.21171	8.788282
	844625	577287	30512	0.3220652	349847	0	364837	39.71809	60.28190
Scenario 11	844625	21759	1228	1.562059	346277	9144513	13751	99.97630	0.023698
	844625	145007	40837	0.1940386	262676	824710	91643	88.61105	11.38894
	844625	154474	32414	0.204514	260422	843037	97625	88.02847	11.97152
	844625	211862	46681	0.210756	0	1117940	133894	84.60842	15.39157
	844625	222681	40295	0.2207166	0	1117940	140731	83.87439	16.12560
	844625	98064	22500	0.2734954	963864	0	61975	90.95705	9.042949
	844625	451590	47327	0.2955084	553329	0	285398	57.08325	42.91674
Scenario 12	844625	121480	37962	0.2064315	519763	637248	76774	90.77218	9.227816
	844625	215064	38932	0.2149739	0	955873	135917	82.22419	17.77580
	844625	98064	22500	0.2734954	963864	0	61975	90.95705	9.042949
	844625	451590	47327	0.2955084	553329	0	285398	57.08325	42.91674
	844625	844756	0	0.3698708	0	0	533874	0	100
	844625	844754	0	0.3700802	0	0	533872	0	100
	844625	31950	6840	0.8567135	549313	1142495	20192	99.73403	0.26596
	844625	33289	7354	1.2835751	0	4569980	21038	99.92722	0.07277

Table A4
Relevant results from optimal solutions which retain the conventional energy sources for desalination electricity consumption of the island (selected compromise solution in red, lower and upper Pareto fronts in yellow).

	AC primary load (MWh/yr)	Conventional power (MWh/yr)	Fuel cell (MWh/yr)	LCOE (€/kWh)	PV power production (MWh/yr)	Wind power production (MWh/yr)	Emissions (t/yr)	% RES	1- %RES
Scenario 1A	89500	89631	0	0.7684363	0	0	56646	0	100
	89500	89631	0	0.7686457	0	0	56646	0	100
Scenario 3A	89500	17673	1687	0.5540132	27111	91634	11169	87.20360	12.79639
	89500	26784	2106	0.5717905	0	109961	16927	80.71021	19.28978
	89500	28837	1216	0.6163431	9079	146615	18225	84.47498	15.52501
	89500	32073	1385	0.6180697	0	146615	20269	82.18915	17.81084
	89500	9598	2815	0.6260105	98352	0	6066	91.33516	8.66483

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Table A4 (*continued*)

	AC primary load (MWh/yr)	Conventional power (MWh/yr)	Fuel cell (MWh/yr)	LCOE (€/kWh)	PV power production (MWh/yr)	Wind power production (MWh/yr)	Emissions (t/yr)	% RES	1- %RES
	89500	63742	3586	0.6804443	27236	0	40284	32.59367	67.40632
	89500	86330	3337	0.7185012	0	0	54559	3.721954	96.27804
	89500	86329	3337	0.7187106	0	0	54559	3.721966	96.27803
Scenario	89500	89631	0	0.7684363	0	0	56646	0	100
9A	89500	89631	0	0.7686457	0	0	56646	0	100
Scenario	89500	31571	1289	0.6203054	0	136553	19952	81.36445	18.63554
10A	89500	9718	2813	0.6259373	98381	0	6141	91.23853	8.761467
	89500	63742	3586	0.6804443	27236	0	40284	32.59367	67.40632
	89500	86330	3337	0.7185012	0	0	54559	3.721954	96.27804
	89500	86329	3337	0.7187106	0	0	54559	3.721966	96.27803
	89500	446	577	0.7418619	97947	273106	282	99.88010	0.119890
	89500	24801	783	0.9389907	29405	136553	15674	87.05189	12.94810
	89500	5108	277	3.182628	0	4824880	3228	99.89424	0.105750
Scenario	89500	16958	1615	0.5955724	28865	91634	10717	87.80643	12.19356
11A	89500	18810	1108	0.6048381	30262	91634	11888	86.73598	13.26401
	89500	24188	1860	0.6139352	0	128288	15287	84.32756	15.67243
	89500	25770	1497	0.6207848	0	128288	16286	83.43377	16.56622
	89500	10273	2661	0.6638871	98352	0	6492	90.76903	9.230963
	89500	50750	2994	0.691702	54472	0	32073	53.10322	46.89677
Scenario	89500	12855	1208	0.6015303	48852	91035	8124	91.65023	8.349763
12A	89500	27960	1574	0.6166056	0	91035	17670	76.81001	23.18998
	89500	9901	2652	0.6638771	98077	0	6257	91.05053	8.949461
	89500	51693	3043	0.6916362	49933	0	32669	50.61245	49.38754

Data availability

Data will be made available on request.

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