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Multi-carrier based optimization of renewable energy communities in small non-interconnected islands

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ABSTRACT

Small islands encounter major obstacles in the path toward energy sustainability, mainly due to their dependence on isolated grids and imported fossil fuels. The intermittency of solar and wave energy systems can be mitigated relying on Renewable Energy Communities, whose main aim is to share the renewable energy produced among community members. Although Renewable Energy Communities are mainly based on electricity sharing, further advantages might be attained by introducing a multi-energy approach, exploiting also thermal, freshwater, and hydrogen final consumption. This study proposes a method for the integration of a Renewable Energy Community on small islands based on multi-energy systems analysis and optimization. As applicative case study, the methodology is here applied to Favignana, a small island in the Mediterranean Sea. The research analyzes step by step various scenarios aimed at increasing the share of renewables, particularly solar and wave energy. All the scenarios were evaluated exploiting a multi-objective mixed-integer linear programming algorithm coordinating many equipments to minimize annual costs, annual primary energy use and annual carbon emissions. The analysis shows that renewable energy penetration increases from 13–18% in the baseline up to 75% with the integration of electrical storage and hydrogen-based technologies. Consequently, a huge reduction of fossil fuels can be obtained through an advanced Renewable Energy Community and the integration of hydrogen use for mobility. Smart management of desalination plants for freshwater production can be fully integrated to enhance the energy sharing and the decarbonization of these energy systems.

1. Introduction

This section provides the overall context of the study and outlines the challenges associated with renewable energy integration in small non-interconnected islands. The following subsections introduce the motivation, review the relevant literature, and highlight the research gaps addressed in this work.

1.1. Motivation

Energy production from Renewable Energy Sources (RES) represents one of the main challenges for ensuring energy sustainability. Small non-interconnected islands, due to their variety of renewable resources, small size, and seasonal energy fluctuations, can be considered open-air laboratories for the research of the best energy mix. One of the main challenges that these islands face is the lack of connection to the mainland power grid that usually prevents a large integration of intermittent renewable energies that could endanger the power system secure operation [1]. In detail, despite the availability of commercial technologies and the results achieved worldwide, the energy sector in small non-interconnected islands still depends heavily on fossil fuel power plants [2]. Furthermore, the lack of interconnection makes it difficult to manage fluctuations in energy demand and supply, especially during peak seasons of tourism [3]. Being isolated, small non-interconnected islands do not benefit from the economies of scale or the stability that an interconnected grid could offer. This increases the costs and environmental impact of the fossil fuel-based energy mix [4]. Therefore, adopting solutions based on renewable energy, such as solar, wind, and marine power, combined with energy storage

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systems, is essential, since this would reduce dependence on fossil fuel imports and improve energy resilience.

1.2. Literature review

Previous studies have shown that small islands are subject to environmental and technological constraints that limit large-scale adoption of renewable energy. From a technical perspective, small islands are often subject to strong seasonal demand swings, since their population ranges from a winter minimum to a summer maximum because of tourism [5].

Numerous studies have shown that the large-scale deployment of renewable energy sources (RES) in small islands is hindered by a combination of environmental and technological constraints. Curto et al. [6] highlighted that restrictions related to landscape protection and land-use planning significantly limit the installation of wind turbines in Mediterranean islands. De Luca et al. [7] analyzed the optimal management of renewable energy in combination with hydrogen production systems and desalination plants, showing how a multi-technology integration can enhance system sustainability despite local constraints. Curto et al. [8] investigated the provision of flexibility services on the island of Pantelleria, demonstrating that an appropriate management of RES, storage systems, and the desalination plant can reduce both operational costs and the emissions associated with fossil-fuel-based electricity generation. Croce et al. [9] proposed a decentralized load control architecture specifically designed for small islands, highlighting how intelligent demand-side management can mitigate grid instability and enable higher penetration of intermittent renewable sources. Beccali et al. [10] characterized the electricity consumption profiles of end-users in a Mediterranean island, showing how the unique demand patterns of isolated systems pose further challenges to the large-scale integration of intermittent RES.

By minimizing RES curtailment and integrating energy storage solutions, the authors estimated that the maximum achievable RES penetration could reach about 60%. Liu et al. [1] assessed the prospects of powering the Maldives with renewable sources, emphasizing not only the achievable benefits but also the substantial obstacles that must be addressed. Curto et al. [11] and Milone et al. [12] investigated the optimization of renewable energy mixes for small islands, addressing both economic and technical factors and discussing the limitations as well as potential pathways for improvement. In Kafetzis et al. [13], an energy management strategy is proposed based on renewable energy sources and storage systems. The proposed supervisory control framework is based on an algorithm that describes the transitions between different operational states of the components within the integrated system. Judge et al. [14] offer a case study on renewable energy sources in small islands in the Pacific, while Bizuayehu et al. [15] gathered technologies and applications of Electrical Storage System (ESS) related to small islands, studying their compatibility based on the specific characteristics of each location. A broader perspective on renewable energy transitions in islands is provided by Meschede et al. [16], who conducted a comprehensive review of 100% renewable energy scenarios in small islands worldwide. The study analyzes 97 case studies and highlights that, while fully renewable island systems are technically feasible, their implementation is still constrained by storage limitations, variability of renewable resources, insufficient grid flexibility, and policy or economic barriers. This review also emphasizes the need for integrated multi-energy approaches and advanced operational strategies to ensure system stability under high RES penetration. The intrinsic intermittency related to some RES can be easily handled introducing Renewable Energy Communities (RECs), entities whose main aim is to locally consume the renewable production as much as possible through the energy sharing among the community members [17]. Although their introduction is relatively recent, the relevance of the RECs topic allowed them gaining a rapid popularity in the international literature. Di Silvestre et al. [18] examined the emergence of energy self-consumers and RECs in the Italian power system, outlining their potential role as new actors in electricity markets. Barabino et al. [19] provided a comprehensive review of energy communities, highlighting current trends, modeling approaches, business models, and optimization objectives, while identifying the main research gaps. Coignard et al. [20] investigated the coexistence of individual and collective objectives within an energy community operating under network constraints, showing how stakeholder goals influence the optimal system configuration. Mussawar et al. [21] explored the role of energy storage in enabling RECs, proposing an urban context-aware modeling and optimization framework and demonstrating its effectiveness through an agent-based case study.

The main benefit of RECs is that they can support the widespread diffusion of intermittent renewable energy systems, reducing their impact on HV grids due to the local energy balance between production and load.

A notable study on RECs introduction in small islands was developed in 2023 for the Italian island of Ponza [22], where researchers applied a multi-objective optimization study aimed at maximizing energy sharing and net present value of the investment. The results show that a PV-based community might help covering about 20% of the domestic load. In an additional scenario where a desalination unit is included in the REC, the optimization allowed sharing energy up to 40% of the final load. In the first months of 2025, a PV-based REC was actually developed in the Elba island, also in Italy.[23] This community covers the whole island territory and was principally promoted by the local hotel companies and tour operators, being Elba a very attractive touristic place. Being very recent, no data on the energy sharing are available [24].

RECs are commonly conceived with respect to electrical energy, since it is easier to produce and inject into the public grid. Nevertheless, in addiction to final electrical load, additional energy uses might be exploited to enhance the energy sharing. Using the renewable energy surplus generated in winter or off-season to produce hydrogen for mobility or power desalination plants would help avoid curtailment, namely the reduction of renewable energy production when it exceeds demand. In detail, in non-interconnected islands, thermal energy is commonly produced from fossil fuels or from electricity using electrical water heaters. Furthermore, decarbonization could also be implemented in the mobility sector relying on hydrogen vehicles. For example, in the article [25], Massaro et al. demonstrated how hydrogen produced through electrolysis powered by renewable energy can be effectively integrated into energy systems. This improves both sustainability and grid flexibility. The proposed energy hub model is highly flexible and can be adapted to address the specific energy challenges of regions like small islands, reducing reliance on external energy sources. Hydrogen energy projects are increasingly being implemented also on small islands to improve energy independence, decarbonize local economies, and reduce the reliance on fossil fuels. These initiatives often utilize surplus renewable energy to produce green hydrogen, which is then used for electricity generation, heating, or transportation, as illustrated in the following examples.

In Utsira (Norway), a wind/hydrogen energy demonstration system was implemented back in 2004, where hydrogen is used as electricity storage system. This island is particularly rich in wind energy. When wind power generation overcomes the final load, hydrogen is produced, compressed and stored. When the production is low or absent, hydrogen is converted in electricity using a fuel cell. Nevertheless, this project proved that the wind energy utilization was only 20% due to the low hydrogen-electricity conversion efficiency. Moreover, fuel cell system experienced some technical issues and was shut down after less than 100 h [26].

In 2007, on the Danish island of Lolland, EU's first residential hydrogen demonstration facility was tested. Excess wind power was used to electrolyze water, producing hydrogen to be later sent to a fuel cell-based micro cogeneration system. Heat and power were then used for homes and public buildings [27].

The BIG HIT project (Building Innovative Green Hydrogen Systems in Isolated Territories), part of the Horizon 2020 initiatives, took place in the Orkney Islands, Scotland. This study focused on the integration of hydrogen systems in small islands. It demonstrated how hydrogen, produced through electrolysis powered by wind and tidal energy, can supply various systems. In particular, it was used for heating, mobility, and energy production in the islands [28].

Last, the Comprehensive hydrogen applications on island (CHYAO) project aims at decarbonizing the small Italian island of Ventotene. The initiative explores the feasibility of using hydrogen to power small ferries and manage waste disposal through hydrogen-activated pyrolysis. The project also includes expanding solar power capacity and integrating electric mobility solutions [29].

Regarding islands with poor water resources, freshwater is usually produced locally with desalination plants, or, as a back-up, imported with tankers. Desalination systems in small islands are among the largest electrical loads and they can be considered as a flexible load to a large extent. Ritschel and Esan [2] examined renewable-energy-based desalination in small islands, underlining the critical contribution of RES to long-term sustainability. Gulagi et al. [30] analyze a transition pathway for the Philippines, highlighting how integrating the sectors of electricity, heating, transport, and desalination can facilitate this shift. Other authors, such as Bogdanov et al. [31] or Curto et al. [7], further explored this topic, proposing transition scenarios of the energy sector in small islands towards renewables, including desalination.

To better integrate these plants into the weak power system of a small non-interconnected island, desalination units may be operated according to the current electrical load so as to provide ancillary services. Only a limited number of authors have already explored this technique. Onda et al. [32] examined the feasibility of controlling the power consumption of desalination plants under mechanical constraints. Imanaka et al. [33] further investigated the capability of desalination systems to compensate renewable energy fluctuations in small islands, employing both mathematical modeling and experimental analyses. Crainz et al. [3] evaluated the economic and environmental benefits of operating desalination units to maximize the efficiency of diesel generators, considering scenarios with and without RES and battery systems. Curto et al. [8] also analyzed the provision of flexibility services in a Mediterranean island, demonstrating how coordinated management of desalination plants can reduce both operational costs and emissions associated with fossil-fuel electricity production. desalination system to maximize the diesel power plant efficiency, with and without the presence of RES and batteries.

This brief literature review allowed highlighting the main approaches commonly used in the introduction of renewable energies in small non-interconnected islands.

As a recap, the following provides a comparison of main aspects included in the relevant literature, showing that a comprehensive research including all these aspect is still missing, to the best of authors' knowledge.

1.3. Research gaps and innovations

The present study allows overcoming the research gaps identified in Table 1, approaching the analysis of RECs based on small non-interconnected islands with a multi-objective optimization approach and performing a multi-energy analysis in a single study. In detail, the main innovations involve the optimal exploitation of solar and marine energy sources, approached through an uncertainty assessment method, the evaluation of many energy vectors and demands (electricity, heating, hydrogen, freshwater) to further improve energy saving, the assessment of uncertain demands, since small islands do not benefit from large scale smoothing, and also a detailed economic analysis involving the inclusion of subsidies for RECs. Moreover, involving the management of local equipment such as desalination systems for freshwater production or electrical water heaters for domestic hot water production allowed the investigation of useful resources for local demand response services. With respect to the time discretization, the study uses twelve standard days with hourly detail, in lieu to the more common approach of peak day or seasonal standard days.

To improve the contribution of RES, a set of progressive scenarios was analyzed and compared, where each step adds to the previous configuration:

- Installation of electrical RES systems
- Installation of electrical storage systems to allow larger RES penetration
- Installation of an integrated green hydrogen production and storage plant fed by the surplus renewable energy production
- Installation of thermal RES plants and thermal storage systems to reduce electrical energy demand
- Management of desalination unit to improve electrical RES penetration

This analysis was performed with a multi-energy, Mixed-Integer Linear Programming (MILP) model implementing a multi-objective optimization approach. Moreover, in order to take into account for the uncertainty related to the intermittent renewable energies and to the final loads, a Monte Carlo algorithm was included in the study, generating several scenarios to be optimized. This approach was already illustrated by some of the authors in [34]. The objective functions alternatively assessed are the annualized economic cost, the annual primary energy use and the annual carbon equivalent emissions for the island energy system. Thus, a total number of 1500 MILP annual optimization runs were performed and analyzed for the present study.

In addition to the optimization studies, the authors performed a detailed grid modeling and power flow analysis in order to assess the actual feasibility of the results obtained by the optimization model, which is based on the energy flows and neglects the grid topology.

The methodology proposed in this work can be readily applied to other small islands, both within the same geographical area and abroad, given the common features that usually define such contexts. The scenarios focused on environmental and technical aspects, using the island of Favignana as a case study. This island, situated near Sicily in the Mediterranean Sea, served as the reference site. The map in Fig. 1 shows the location of the case study.

The paper is structured as follows: Section 2 illustrates the methodology adopted for the development of the optimization mathematical model. In Section 3, the island selected for the case studies is described and the various scenarios are fully described. Section 4 shows the main results of this study, while Section 5 provides a discussion of the results obtained and Section 6 the conclusions of the article.

2. Methodology

For this study, a multi-energy MILP model integrated with a Monte Carlo algorithm for the assessment of economic and environmental benefits was developed. In this section, the main assumptions, strengths and drawbacks are illustrated and discussed.

2.1. Mathematical model description

The mathematical model is composed by linear equations, in order to ensure the uniqueness of the optimal solution. Variables of the problem are related to the sizing and operation of main equipment and to the energy and mass flows exchanges with the main grids and networks. Most of these variables are real values, although some integer variables were introduced, thus requiring a MILP algorithm.

An energy hub model was selected due to its high capacity to simulate time-dependent energy systems resorting to energy and mass balance equations related to each timestep [35]. The main assumptions considered in the model are as follows:

Table 1
Main features of the studies from the literature review.

Ref.	Small Islands	Renewables energies	RECs	Hydrogen	Desalination	Optimization	Multi-Objective
[1]	Yes	Yes	No	No	Yes	No	No
[2]	Yes	Yes	No	No	No	Yes	No
[3]	Yes	Yes	No	No	Yes	Yes	No
[6]	Yes	Yes	No	No	No	Yes	No
[7]	Yes	Yes	No	Yes	Yes	Yes	Yes
[8]	Yes	Yes	No	No	Yes	Yes	Yes
[9]	Yes	Yes	Yes	No	No	No	No
[11]	Yes	Yes	No	No	No	No	No
[12]	Yes	Yes	No	No	No	Yes	No
[10]	Yes	Yes	No	No	No	No	No
[13]	Yes	Yes	No	Yes	No	Yes	Yes
[14]	Yes	Yes	No	No	Yes	No	No
[15]	Yes	Yes	No	No	No	Yes	Yes
[22]	Yes	Yes	Yes	No	Yes	Yes	Yes
[26]	Yes	Yes	No	Yes	No	No	No
[27]	Yes	Yes	No	Yes	No	No	No
[20]	No	Yes	Yes	No	No	No	No
[28]	Yes	Yes	No	Yes	No	No	No
[29]	Yes	Yes	No	Yes	No	No	No
[30]	No	Yes	No	Yes	Yes	Yes	No
[31]	No	Yes	No	No	Yes	No	No
[32]	No	No	No	No	Yes	No	No
[33]	No	Yes	No	No	Yes	No	No

Fig. 1. Aegadian islands in the Mediterranean sea (Italy).

- Linear equations to describe objective functions and constraints;
- Balance equations evaluated in steady state conditions;
- Efficiency and loss parameters are considered only for equipment (no grid losses);
- The energy system performance were evaluated according to twelve standard days with hourly time-steps.

Errors introduced by these assumptions were considered as negligible since the energy systems in non-interconnected islands can be considered with limited extensions and limited losses. Moreover, authors relied on gross final demands, thus incorporating also grid losses. Regarding the annual variation of generation and load, referring to a standard day for each month of the year is a common strategy in renewable energy planning studies.

2.2. Objective functions

The sizing and operation of the REC can be optimized according to three objective functions:

- Annualized Cost, given by the sum of the CAPital EXpenditure (CAPEX) and the annual OPerating EXpenditure (OPEX). CAPEX are related to the purchase of new equipment and were annualized using the Capital Recovery Factor (CRF) of each investment, while OPEX include equipment operation, the supply of energy from the main grid, and economic incentives (considered as negative costs).
- Annual Primary Energy Use, given by the sum of the Embodied Energy (EE) and the annual Operating Energy (OE). EE is related to the purchase of new equipment and was annualized dividing each term for the respective technical life, while OE include equipment operation and the supply of energy from the main grid. This quantity was evaluated resorting to average Life Cycle Assessment indicators from literature.
- Annual Carbon Equivalent Emissions, given by the sum of the Embodied Carbon (EC) and the annual Operating Carbon (OC). EC is related to the purchase of new equipment and was annualized dividing each term for the respective technical life, while OC include equipment operation and the supply of energy from the main grid. This quantity was evaluated resorting to average Life Cycle Assessment indicators from literature.

2.3. Renewable energy production

This section introduces the key equations employed to evaluate renewable energy production based on climatic data.

Since landscape preservation goal set by Italian law prevents the installation of large plants on small islands, the assessment of wind turbines or concentrating solar power was excluded from the present study. Conversely, the installation of PhotoVoltaic (PV) panels, Wave Energy Converters (WEC), and Solar Thermal Collectors (STC) was assessed.

2.3.1. Photovoltaic system

The electrical energy generated by PVs accounts for losses depending on the external air temperature and on the solar radiation. For each time-step and Monte Carlo scenario, the temperature of photovoltaic cells was estimated using Eq. (1):

$$T_{\text{cell}}(t) = T_{\text{air}}(t) + \frac{G_{\text{sol}}(t)}{G_{\text{NOCT}}} \cdot (\text{NOCT} - T_{a,\text{NOCT}}) \tag{1}$$

Here, T_{air} represents the ambient air temperature, G_{sol} is the global solar radiation consisting of the three primary radiation components, and NOCT (Nominal Operating Cell Temperature) is the operational temperature of the cell under standard irradiance G_{NOCT} of 800 W/m^2 and an air temperature $T_{a,\text{NOCT}}$ of 20 °C.

Once the cell temperature is determined, the PV system's efficiency η_{PV} is calculated using Eq. (2):

$$\eta_{\text{PV}}(t) = \eta_{\text{PV},0} \cdot \left[1 + \beta_{\text{PV}} \cdot \left(T_{\text{cell}}(t) - T_{\text{ref}}\right)\right] \tag{2}$$

where $\eta_{\text{PV},0}$ is the PV cell efficiency in standard conditions, T_{ref} is the reference temperature equal to 25 °C, and β_{PV} is the PV cell temperature coefficient.

The power generated by the PV system is then obtained by multiplying several factors, including solar radiation, PV system efficiency, Balance Of Plant (BOP) efficiency, the area of a single module, and the number of modules to be installed. The power is calculated using Eq. (3):

$$E_{\text{PV}}(t) = \eta_{\text{PV}}(t) \cdot \eta_{\text{BOP}} \cdot G_{\text{sol}}(t) \cdot A_{\text{PV}} \cdot N_{\text{PV}} \tag{3}$$

In order to take into account for the proper spacing among two close rows, the following formula was used to assess the minimum distance d_{PV} with respect to the average tilt angle β and the sun declination δ:

$$d_{PV} = sin\beta \cdot tg(\beta + \delta) + cos(\beta) \tag{4}$$

In Eq. (4), a value of $\delta = 23.5$ was selected, using the value relative to the winter solstice.

2.3.2. Solar thermal collector systems

The thermal energy generated by STCs accounts for heat losses to the surrounding air, which depend on the external air temperature. For each time step and Monte Carlo scenario, the collector efficiency is expressed by the following Eq. (5):

$$\eta_{\text{STC}}(t) = \eta_0 - a_1 \cdot \frac{T_m - T_{\text{air}}(t)}{G_{\text{sol}}(t)} - a_2 \cdot \frac{\left[T_m - T_{\text{air}}(t)\right]^2}{G_{\text{sol}}(t)} \tag{5}$$

Here, T_m represents the average temperature of the heat transfer fluid inside the collector, while η_0, a_1, and a_2 are performance coefficients specific to the collector.

The thermal energy output is calculated based on collector efficiency, global solar radiation, the collector's surface area, and the number of units to be installed, following Eq. (5):

$$H_{\text{STC}}(t) = \eta_{\text{STC}}(t) \cdot G_{\text{sol}}(t) \cdot A_{\text{STC}} \cdot N_{\text{STC}} \tag{6}$$

2.3.3. Sea wave energy converter systems

The electrical energy generated by WECs depends on key parameters such as significant wave height (H_s) and peak period (T_p). For each time step and Monte Carlo scenario, the available specific wave power P_w in shallow water conditions, namely the situation that is commonly realized in small islands, is expressed by the following Eq. (7) [36]:

$$P_w = \frac{\rho \cdot g^{1.5}}{16} \cdot H_s^2(t) \cdot \sqrt{d_w} \tag{7}$$

where ρ is the seawater density (1025 kg/m^3), g is the gravity acceleration (9.81 m/s^2), H_s indicates the significant wave height, which is the average height of the highest one-third of the waves (m), and d_w indicates the local average water depth (m).

The energy generated by the WEC system is then obtained by multiplying the specific wave power, the length of the WEC device, its conversion efficiency, and the length of the time-step, and the number of units to be installed, as in Eq. (8):

$$E_{WEC} = P_w(t) \cdot L_{WEC} \cdot \eta_{WEC} \cdot \Delta t \cdot N_{WEC} \tag{8}$$

2.4. Constraints

In the optimization model, each equipment to be simulated was described using specific constraints. Equipment were thus divided in generators, converters and storage systems. Generators are equipment producing renewable energy, whose operation was already described. These components cannot be operated according to any specific logic since they are constrained at producing when the renewable energy is available. Thus, these components are characterized only with a sizing variable (number of units). Converters are equipment converting a form of energy into another. Equipment falling into this category are water ELectrolyzer (EL), hydrogen Fuel Cell (FC), DEsalination System (DES), and Electric Water Heater (EWH). These components are described with constant conversion terms, one operational variable for each time-step and with a rated size variable. Operational variables for converters are constrained to be between zero and the rated size of the components. An example of constraints for a converter is provided in Eqs. (9)–(11) with reference to EL.

$$H_{2,EL}(t) = K_{EL,eh2} \cdot E_{EL}(t) \tag{9}$$

$$W_{EL}(t) = K_{EL,ew} \cdot E_{EL}(t) \tag{10}$$

$$E_{EL}(t) \leq S_{EL} \tag{11}$$

In the above equations, E are the electrical energy flows, H_2 are the hydrogen flows, W are the water flows, K are the conversion parameters, and S is the rated size. In the subscripts, $eh2$ means "from electricity to hydrogen" while ew stands for "from electricity to water". A detailed description of the constraints included in this model is available in [25].

Storage systems were described as equipment able to collect a specific amount of energy or mass during a specific time-step and releasing it during a different time-step. Storage systems were considered for electricity (ESS), thermal energy (TSS), hydrogen (H2SS) and freshwater (WSS). These components are described with constant charging and discharging efficiencies, a self-discharge rate, five operational variables for each time-step (state of charge, input flow, output flow, and two Boolean variables) and with a rated capacity variable. Boolean variables were included to implement the logic condition that the system could not charge and discharge at the same time-step. Additional constraints impose the balance between two subsequent time-steps, to link the inlet or outlet flows to the capacity of the system through a Depth of Charge (DOC) and a Depth of Discharge (DOD) rate, and to permit the repetition of the standard day. An example of constraints for a storage system is provided in Eqs. (12)–(17) with reference to ESS.

$$\delta_{ESS,in}(t) + \delta_{ESS,out}(t) \leq 1 \tag{12}$$

$$E_{ESS,in}(t) \leq Q_{ESS} \cdot \delta_{ESS,in}(t) \tag{13}$$

$$E_{ESS,out}(t) \leq Q_{ESS} \cdot \delta_{ESS,out}(t) \tag{14}$$

$$SOC_{ESS}(t+1) = SOC_{ESS}(t) \cdot (1 - K_{ESS,loss}) + K_{ch} E_{ESS,in}(t) - \frac{E_{ESS,out}(t)}{K_{disch}} \tag{15}$$

$$DoDS_{ESS} \leq SOC(t) \leq DoCS_{ESS} \tag{16}$$

$$SOC(1) = SOC(24), \forall\ days \tag{17}$$

In the previous equations, $\delta_{ESS,in}$ and $\delta_{ESS,out}$ are Boolean variables indicating the status of the storage system. In detail, $\delta_{ESS,in}$ is equal to zero if the system is not charging, conversely it is equal to one. $E_{ESS,in}$ and $E_{ESS,out}$ are the input and output flows of the battery, Q_{ESS} is the upper limit for the system capacity, SOC is the state of charge of the storage system, K_{ch} and K_{disch} are the charging and discharging efficiencies, respectively, $K_{ESS,loss}$ is the self-discharge rate.

In addition to the constraints describing equipment, the energy hub model was simulated setting that, for each time-step, energy and mass balances had to be respected. These constraints were set for electrical energy, thermal energy, hydrogen and freshwater, and are illustrated in Eqs. (18)–(21).

$$E_{PV}(t) + E_{WEC}(t) + E_{FC}(t) - E_{ESS,in}(t) + E_{ESS,out}(t) + E_{PP}(t) = \\ = E_{load}(t) + E_{EL}(t) + E_{DES}(t) + E_{EH}(t) \tag{18}$$

$$H_{STC}(t) + K_{EH,eh} \cdot E_{EH}(t) - H_{TSS,in}(t) + H_{TSS,out} = H_{load}(t) \tag{19}$$

$$K_{EL,eh2} \cdot E_{EL}(t) - H_{2,HSS,in}(t) + H_{2,HSS,out}(t) = H_{2,demand}(t) + K_{FC,eh2} \cdot E_{FC}(t) \tag{20}$$

$$K_{DES,ew} E_{DES}(t) + W_{grid}(t) - W_{WSS,in}(t) + W_{WSS,out} = W_{demand}(t) \tag{21}$$

In the previous equations, E, H, H_2, and W indicate electricity flow, heating flow, hydrogen flow and freshwater flow, respectively. Subscripts commonly indicate the name of the equipment whose the flow is related, where PP stands for Power Plant and the other symbols were already explained. Otherwise, subscripts indicate that the flow is from the grid or is a final load/demand.

2.4.1. Energy sharing

The main aim of a REC is sharing the renewable electricity production among the community members. According to the Italian incentive scheme, the sharing of renewable electricity occurs when a production system is injecting into the grid and, in the same hour, at least another community member is consuming energy. This is considered as virtual energy sharing since the unique geographical limit for two users being members of the same community is that they belong to the grid under the same primary station. In this study, the whole island territory constitutes a REC and the energy sharing occurs through the island distribution grid. Since the whole island constitutes the community, and the island is not connected to the mainland, the whole production is shared within the community. It is worth mentioning that electricity from the fuel cell was included in the community renewable energy production together with energy from PV and WEC systems since the combination of water electrolyzer, hydrogen storage system and fuel cell can be considered as an equivalent renewable electricity storage system.

2.5. Uncertainty

As mentioned in the Introduction, the optimization performed for this study considers the uncertainty related to renewable energy availability and to final demands using a Monte Carlo algorithm. In detail, a proper Probability Distribution Function (PDF) was employed for each of these quantities and for each time-step. The Monte Carlo algorithm generates several scenarios according to the values allowed by the PDF and uses these values as input parameters for the optimization study. The optimal solutions are then treated with statistical methods and compared in terms of rated sizes and energy production to evaluate the effective benefits.

In this study, the uncertainty of solar irradiance was assessed using the Beta distribution function [25,37,38]. The Beta distribution function depends on two parameters, ω and ψ, and on the non dimensional solar irradiance Θ, evaluated as the ratio between the average hourly solar irradiance and the solar constant. When ω and $\psi \geq 0$ and $0 \geq \Theta \geq 1$,

$$f(\Theta) = \frac{\Gamma(\omega)\Gamma(\psi)}{\Gamma(\omega) + \Gamma(\psi)} \Theta^{\omega-1}(1-\Theta)^{\psi-1} \tag{22}$$

where Γ is the Euler Gamma function.

The input parameters ω and ψ were evaluated from the average value μ and the standard deviation σ according to Eqs. (23)–(24)

$$\omega = \frac{\mu^2 \cdot (1-\mu)}{\sigma^2} - 1 \tag{23}$$

$$\psi = \frac{\mu \cdot (1-\mu)^2}{\sigma^2} - 1 \tag{24}$$

Regarding the uncertainty related to air temperature, wave height, as well as all the final demands, these quantities were modeled through the normal distribution function, which depends on μ and σ as illustrated in Eq. (25) for the temperature [25,37].

$$f(T) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{T-\mu}{\sigma}\right)^2} \tag{25}$$

3. Case study: Favignana island

This section presents the case study selected for the analysis, focusing on the island of Favignana. The following subsections describe the existing energy and resource systems and introduce the scenarios assessed in the optimization framework.

3.1. Existing system description

Favignana, a small island situated close to Sicily and belonging to the Aegadian Islands archipelago, was selected as the case study for this analysis. The economy of the Aegadian Islands is primarily based on tourism, particularly during the summer season, which attracts up to 102 million visitors annually. This pronounced seasonality leads to a highly variable energy demand, presenting significant challenges for the island's energy sustainability.

As with many other small Italian islands, Favignana has an autonomous electrical grid that is not connected to the mainland. Since 1970, energy production and distribution on the island has been managed by S.E.A. S.p.A., with an annual energy output of around 15 million kWh [39]. The thermoelectric power plant, located approximately 100 m from the coast, consists of seven diesel engines, with an installed capacity of 12 MW [40].

The island's transport system relies primarily on private vehicles. Despite some initiatives to promote sustainable mobility, the situation remains critical, especially during the summer months when the number of visitors increases. Among the measures implemented are traffic restrictions during the peak season and the activation of a public transport service consisting of three bus lines that connect the island's main areas. Additionally, the Municipality of Favignana has developed a Sustainable Mobility Plan, which reports that in August, around 1500 private cars land on the island, adding to those already present. Data also show that 59% of tourists use rental vehicles, with a clear preference for bicycles (63%), followed by motorbikes (29%) and cars (8%). 28% of visitors use their own vehicles, while only 13% opt for public transport, mainly due to limited schedules and infrequent service. To address these issues, a new ministerial decree has been introduced, further tightening restrictions on vehicle access. As of summer 2024, motor vehicles owned by non-residents are banned from entering and circulating on the island during the high season, with the aim of preserving the environment and improving quality of life during the tourist peak [41,42].

The production of domestic hot water in Favignana is currently mainly reliant on traditional electric water heaters [43], installed in private homes, tourist accommodations, and public services. However, in some more modern or recently renovated structures, high-efficiency electric water heaters and solar panels are used. Although the transition towards more sustainable hot water production systems is underway, it remains limited. Currently, about 15%–20% of renovated homes have adopted more advanced technologies, such as solar thermal or high-efficiency water heaters. However, the majority of families still depend on traditional systems, which incur high costs and have a significant environmental impact.

Regarding freshwater uses, the island of Favignana has no internal freshwater sources, which results in a complete dependence on external water resources. Although a desalination plant is installed in the island [43], the water supply is currently provided by tanker ships coming from the mainland. This solution highlights several critical issues, such as the reliance on non-local resources, the high cost of transportation, and the environmental impact of these activities. To address these challenges, and as part of the “Green Islands” project, a plan has been initiated for the construction of a new desalination plant. This facility will convert seawater into freshwater, improving the island’s water self-sufficiency while also reducing the associated environmental impacts and emissions [44].

In Favignana and across the other islands of the archipelago, the development of renewable energy is restricted by national laws safeguarding the environment and natural heritage. Currently, the installed capacity of photovoltaic systems on the island is about 880 kW. To enhance the archipelago’s energy sustainability, local administration of the Aegadian Islands joined several initiatives promoted by the European Union, such as the Pact of Islands [45] and the Covenant of Mayors [46], while the local electrical company is active in several research projects. The European Union promotes these measures to enhance energy efficiency in small islands, decrease reliance on fossil fuels, and thereby lower CO_2 emissions. The installation of renewable energy systems on Favignana is strongly influenced by the environmental and landscape constraints imposed by the island’s unique territorial characteristics [47]. For this reason, the urban center, located in the northern-central part of the island, was identified as a potentially suitable area for photovoltaic installations. However, important historical buildings, such as the Florio tuna factory and other structures dating back to the late 19th century, have been excluded from consideration due to conservation restrictions. The installation site of wave energy converters has been identified offshore, in response to the coastal erosion affecting many of the island’s shorelines. This approach allows for an increase in renewable energy production while minimizing visual and environmental impacts and preserving the cultural and architectural heritage of the urban area. Local authorities, in collaboration with relevant institutions, are already working on targeted measures to mitigate this erosion, and the installation of WEC devices will further help to protect the most vulnerable coastal areas. Fig. 2 shows a satellite image of the island, where the yellow shaded circle marks the urban area designated for photovoltaic installations, the red lines highlight coastal zones exposed to seabed erosion risk, and the light blue circle outlines the area allocated for WEC deployment.rea for the installation of WECs.

3.2. Scenarios assessment

In order to assess possible decarbonization strategies for Favignana, the following five scenarios were investigated:

- **Scenario 1: Electrical Renewable Generation**. This scenario considers the installation of two complementary renewable energy technologies: photovoltaic and sea wave converters. The analysis focuses on energy production from these sources and their ability to meet the energy demand in an isolated grid, without using storage systems. The goal is to evaluate the amount of energy that can be optimally generated from these renewable sources and their ability to meet the energy demand of the isolated grid within a renewable energy community.
- **Scenario 2: Electrical Renewable Generation and Storage**. This scenario includes the integration of the same renewable energy sources but with the addition of battery storage systems. The excess energy produced during high generation periods is stored and used when renewable production is low or insufficient. The energy stored in the batteries reduces the need for non-renewable energy in load-peak hours, optimizing the use of renewable resources and increasing the efficiency of the isolated grid.
- **Scenario 3: Electrical Renewables + Hydrogen**. This scenario adds to the previous configuration a hydrogen production system made up of an electrolyzer powered by excess energy from renewable sources. The produced green hydrogen is compressed and stored in a hydrogen tank to be used later for electricity generation through fuel cells or to decarbonize the island mobility system powering hydrogen vehicles. The energy demand expands to include the energy needed for hydrogen production and sustainable mobility. Hydrogen provides a long-term storage solution and increased flexibility in managing the isolated grid.
- **Scenario 4: Electrical and Thermal Renewables + Hydrogen**. In this scenario, all elements from the previous configurations are integrated, with the addition of solar thermal collectors, which contribute to meeting the domestic hot water demand. Since hot water is commonly produced using electric water heaters, this approach allows reducing the final electricity load relying on locally produced renewable thermal energy. The excess thermal energy produced by the collectors can be stored in the thermal storage systems to be used at later times, during periods of low production. Electric heater is still considered as back-up system, with its usage evaluated to satisfy the residual thermal demand. The management of the available electrical and thermal energy is optimized by the mathematical model, which determines the optimal balance between the use of solar thermal collectors, thermal storage, and electric heating to meet the overall energy demand for both thermal and electrical needs.
- **Scenario 5: Electrical and Thermal Renewables + Hydrogen + Smart Water Management**. In this scenario, all the elements considered in the previous scenarios are maintained, but with the addition of a desalination management system. In detail, local desalination system is managed to meet the final demand producing when electricity is not produced by the local power plant, thus exploiting renewable energies or storage systems. A key aspect of this configuration is the reduction of dependence on water transport from tankers, which causes high costs and carbon equivalent emissions.

3.3. Data collection

In order to analyze and optimize the energy system in Favignana, datasets on energy use patterns, renewable resources, and available infrastructure were compiled.

3.3.1. Final loads

The average electrical load was evaluated using the actual load data every 15 min measured in three years that were provided by the local electrical company, S.E.A. S.p.A. These data were used to evaluate a standard day for each month with hourly detail. As the load data were collected from the substations located on the island, the values already include the share supplied by the existing PV installations.

Fig. 2. Favignana island satellite view with indication of RES installation sites.

Moreover, these data also take into account for the distribution grid losses, that were neglected in the model development phase. Having data spanning for three years allowed evaluating average values and standard deviation for each hour of the monthly standard days.

Final load data were reduced to 75% to guarantee a minimum spinning reserve from the fossil fuel power plant [5]. In addition, when domestic hot water and freshwater production were included in the optimization, electricity used for these services was excluded from the final electrical load to be satisfied.

The average daily water demand for the island was estimated based on a per capita requirement of 215 liters/inhabitant/day, aligned with ISTAT data [48]. The resident population was set at 1800 inhabitants, combined with monthly tourist inflows. For each month, the average water demand was determined by multiplying the total number of people (residents and tourists) by the per capita requirement and the number of days in the month. Hourly distribution was derived by applying percentage coefficients to the daily demand, with peaks during high-usage hours (8 AM–10 AM and 7 PM–9 PM). Uncertainty related to water demand was estimated as ranging between ± 10% of the average value for each hour of the monthly standard days. The water cost was set at 11.67 €/m^3 (excluding VAT), based on information gathered from a dedicated report [49].

The average thermal demand for domestic hot water production was determined by applying an energy conversion coefficient of 0.25 kWh per liter of hot water consumed. Uncertainty related to domestic hot water demand was estimated as ranging between ± 10% of the average value for each hour of the monthly standard days.

The hydrogen demand for mobility on the island of Favignana was estimated based on a projected adoption rate of hydrogen cars by both residents and tourists, combined with usage patterns and seasonal fluctuations. The resident population was set at 1800 inhabitants, with a 0.8% adoption rate (14 vehicles), each consuming 1.667 kg/day and used for 22 days/month, resulting in a fixed monthly demand of 513.33 kg/car. Tourist demand was calculated assuming a 5% adoption rate (capped at 100 available vehicles), with each vehicle used for 3 days/month and consuming 2.500 kg/day. For each month, the total hydrogen demand was determined by summing resident and tourist contributions. Uncertainty related to water demand was estimated as ranging between ± 10% of the average value for each hour of the monthly standard days.

3.3.2. Solar energy

The hourly solar radiation, divided on its three components, and hourly average air temperature were gathered using the PVGIS database [50]. Values were collected for the period 2005–2023 and then used to evaluate average values and standard deviation for each hour of the monthly standard days.

The potential area for PV and STC installation was assessed through GIS tools combined with building data provided by the Italian Revenue Agency database [51], resulting in 394,148 m^2 for the entire island and 162,727 m^2 for the urban sector. According to the approach outlined in [52], the latter estimate was corrected for roof sections already used by other installations or affected by shading, yielding a final value of 73,227 m^2.

3.3.3. Sea wave energy

Hourly WEC output for a typical year was calculated through Eq. (7), using significant wave height and mean water depth data from the Italian Sea Waves Network [53], under the assumption of a 15% converter efficiency.

The available wave power was calculated based on data gathered from WERATLAS database [54].

The main parameters used for the case studies are recapped in Table 2 for the equipment and in Table 3 for the carriers.

Table 2
Main parameters for the equipment used in the case studies.

Component	Investment cost [€/unit]	Embodied primary energy [MJ/unit]	Embodied carbon emissions [kg $CO_{2\text{-eq}}$/unit]	Useful life [years]
PV [kW_{el}]	779.87	4581.48	357.73	25
WEC [kW_{el}]	4017.60	3153.24	670 538.10	15
ESS [kWh_{el}]	44.59	540.00	76.28	8
EL [kW_{el}]	1274.00	168 635.00	28.00	20
FC [kW_{el}]	1532.44	71 466.13	11.87	12
HSS [kg]	171.33	3222.22	0.05	50
EH [kW_{el}]	0	0	0	15
STC [m^2]	500.00	3745.52	210.56	16
TSS [kWh_{th}]	26.18	201.54	10.97	20
DES [kWh]	0	0	0	25
WSS [kg]	195.50	10 545.38	573.85	12

Table 3
Main parameters for the carriers used in the case studies.

Carrier	Operating cost [€/unit]	Operating primary energy [MJ/unit]	Operating carbon emissions [kg $CO_{2\text{-eq}}$/unit]
Electricity [kWh]	0.3031	11.8	0.7089
Hydrogen [kg]	20	213.52	11.9478
Water [kg]	14.2374	0	0

4. Results

This study evaluated the possible benefits deriving from the integration of renewable energies, hydrogen and smart management technologies in isolated grids as the island of Favignana through five incremental scenarios. The optimization model was applied to the five scenarios in order to compare the differential change in performance in terms of the three objective functions, namely annualized cost, annual primary energy use and annual carbon equivalent emissions. For each analysis, 100 uncertainty runs were simulated and optimized. Main detail on each scenario are discussed in the following subsections. Thus, a total number of 1500 MILP annual optimization runs were performed and analyzed for the present study.

The generic consideration is that introducing renewable energies in the Favignana energy system contributes in the reduction of costs, primary energy use and carbon emissions to a large extent. Moreover, the inclusion of the citizens in a renewable energy community makes the investments highly profitable, leading to an annual subsidy that overcomes the annualized costs. For this reason, the annualized cost evaluated for each objective function, each scenario and each uncertainty case is always negative, meaning that there is a net income.

Scenario 1

The renewable energy production is always very limited, between 13% and 18% of the island final load. This result is justified by the fact that the load in winter is very lower than in summer, forcing the algorithm to identify as optimal low values of rated sizes. On a seasonal basis, RES share in winter is equal to 25%–30%, but it lowers down to 8% in July. This result allows keeping a sufficient spinning reserve. In economic optimization, PV sizes are slightly higher than in other optimization criteria. PV size is always way much higher than WEC's, demonstrating that the latter technology still needs a significant improvement in terms of manufacturing process, reducing costs and impacts.

Scenario 2

The installation of electrical energy storage systems allows a huge increase in the RES installation. In detail, the renewable energy share over the load is between 71% and 75% of the island final load, independently on the optimization criterion. The upper limit was imposed by the threshold set to keep a minimum spinning reserve.

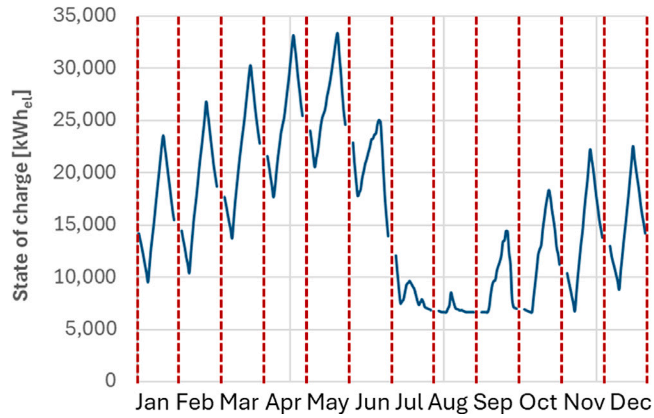

Fig. 3. Average battery state of charge trend over the twelve standard days in Scenario 2.

PV size on average is between 950 kW_p in minimum cost studies and 1000 kW_p in minimum primary energy and carbon emissions studies. WEC is almost never installed, with only two cases over 100 in minimum cost studies and zero cases in minimum primary energy and carbon emissions studies. Battery cumulated capacity is independent on the optimization criterion and its value is almost always equal to the upper bound set for the study, equal to about 33,300 kWh. The daily trend of battery schedule, illustrated in Fig. 3, shows that these systems are used every day of the year, with charging phase by day and discharge by night. Moreover, ESS progressively accumulates energy from January to May helping in Summer months, when the demand is higher due to the tourists. This trend is almost the same independently on the optimization criterion and uncertain conditions.

Scenario 3

In this scenario, where the local mobility is integrated using hydrogen cars, there is the largest variability among equipment sizes depending on the optimization criterion.

In detail, hydrogen-based technologies allow always keeping the target of 75% renewable energy penetration. On average, photovoltaic production by day is exploited to charge batteries and feed the electrolyzer, with fuel cells being employed to cover load peaks and batteries being discharged by night. In all the optimization studies, hydrogen production is between 530 and 545 tons/year over an average demand of 44 tons/year, meaning that hydrogen production is exploited as electrical energy storage system for a large extent, in addition to meeting mobility demand. One possible reason can be that, in both Scenarios 2 and 3, battery storage systems already reached the upper bound allowed in the optimization study. This is also proven by the fact that the PV size is almost three times higher with respect to the previous scenario, on average.

A graphical representation of average daily trend of electricity flows is shown in Fig. 4. Although this graph is related to minimum carbon emission studies, these results are valid also for studies with the other objective functions.

PV size is between 2650 kW_p and 2850 kW_p independently on the objective function. The unique exceptions are two scenarios in minimum primary energy studies, where a value of 1000 kW_p was selected as optimal. WEC technology is almost always disregarded. Nevertheless, it was selected as optimal in two minimum cost studies and in two minimum primary energy studies, with rated size up to 110 kW_p, corresponding to minimum primary energy studies with lower PV

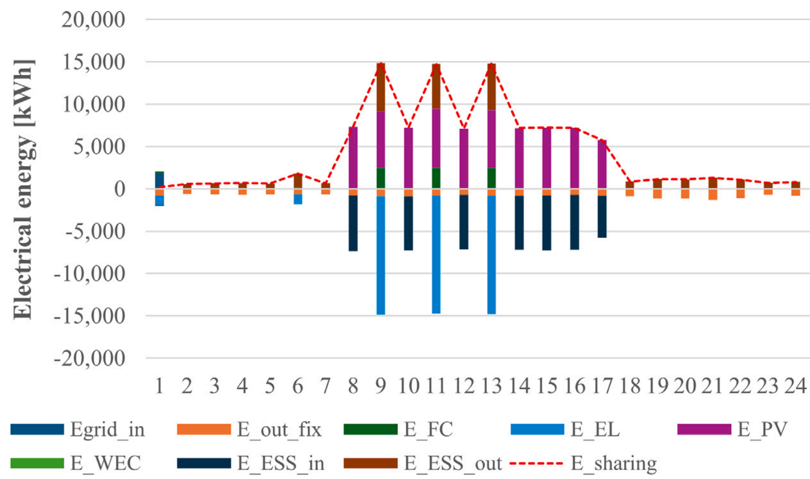

Fig. 4. Average daily trend of electricity flows in Scenario 3 with minimum carbon emissions.

size. Battery cumulated capacity is almost always equal to the upper bound set for the study, equal to 33,300 kWh, although in minimum primary energy studies this technology was not selected as optimal in a single uncertain case.

Primary energy studies tend to rely less on exploiting hydrogen technologies for energy storage, with rated size of electrolyzers and fuel cells being almost the half with respect to minimum carbon emissions studies. In detail, fuel cell size spans between 1400 and 2500 kW, while electrolyzers size spans between 6000 and 14,500 kW, with higher values being preferred in minimum carbon emissions studies and lower values in minimum primary energy studies.

Scenario 4

In this scenario, where thermal energy demand is included in the optimization process, solar thermal collectors provide a negligible contribution to domestic hot water production independently on the optimization criterion. In detail, they are effectively unused (installed surface: 0 m^2) in minimum cost and minimum primary energy studies, while 1 m^2 of STC is installed in a single minimum emission study over 100. Consequently, the hot water demand is primarily met using pre-installed electric water heaters, requiring a cumulative thermal storage capacity of 2807 kWh.

Renewable energy penetration is mainly ensured by photovoltaic systems, which maintain consistent sizing across all optimization cases, ranging from 2838 to 3262 kW_p. This confirms the central role of PV in the system's energy balance. Again, wave energy converters are not considered in any of the configurations.

Energy storage system (ESS) are installed almost at their maximum considered size, roughly 32,000 kWh, in minimum primary energy and minimum emission studies, highlighting their importance as energy storage systems for excess PV electricity. In minimum cost studies, the optimal size is reduced to about 27,000 kWh, with two only uncertain cases with lower values.

Hydrogen storage (HSS) is also consistently present, with a capacity of 223.7 kg, as well as in Scenario 3. This aspect shown that this storage system plays a secondary role compared to ESS. Fuel cells (FC) help cover peak electrical demands, with installed capacity of about 1300 kW_{el} in minimum primary energy studies and between 2400 and 2500 kW_{el} in the others. From an environmental perspective, CO_2 emissions remain relatively high, particularly from the electric component, with values between 13,000 and 14,000 kg CO_2. Additional emissions come from hydrogen systems and fuel cells, reflecting the energy-intensive nature of electric water heating without the support of solar thermal systems.

Economically, this scenario reflects a trade-off between reliability and investment cost. While the exclusion of STC reduces capital expenditure, reliability is ensured by higher-cost technologies such as PV and ESS. The associated investment ranges from 2070 to 3262 € for PV and from 16,299 to 27,368 € for ESS, depending on the optimization objective. In cost-minimization cases, a slight downsizing of these technologies is observed, suggesting a compromise between performance and affordability.

Scenario 5

Including freshwater final demand to the optimization study allowed finding a very interesting result: in minimum primary energy and minimum carbon emission studies, hydrogen-based technologies are downsized, with respect to the previous Scenario 3 and 4, in order to produce also freshwater for the island! Although the water flows related to electrolyzer and fuel cell were integrated in the study in order to quantify these flows and compare them with the current water demand, the outcome was that the amount of water produced by the fuel cell during its operation was highly over the usual island demand.

Regarding heat technologies, since renewable electricity is also used for freshwater production in this scenario, STC is installed, although with limited penetration.

PV and ESS are also downsized since electricity final load related to desalination unit was highly reduced.

Storage systems are always considered optimal technologies, with only freshwater storage being disregarded.

Scenarios comparison

In the following Fig. 5, main results are collected with respect to the rated size of each equipment. In detail, mean, max, min, mode and median values of rated values are here presented.

Moreover, results in terms of objective functions are illustrated in Fig. 6.

In detail, it is evident that the optimal solutions in scenarios 1 and 2 are almost independent on the optimization criteria, since the clouds are overlapped. These results start to differ from Scenario 3 onward, as additional final loads are introduced in the analysis. More in detail, results related to minimum primary energy studies and minimum carbon emissions studies are almost always very close, highlighting that these functions are bounded to each other, while costs in different scenarios depend on different aspects. Last, the percentage contribution of single energy carrier or equipment to the objective function for each Scenario and each optimization study is illustrated in Fig. 5. It is evident that the power plant still contributes to primary energy use and carbon

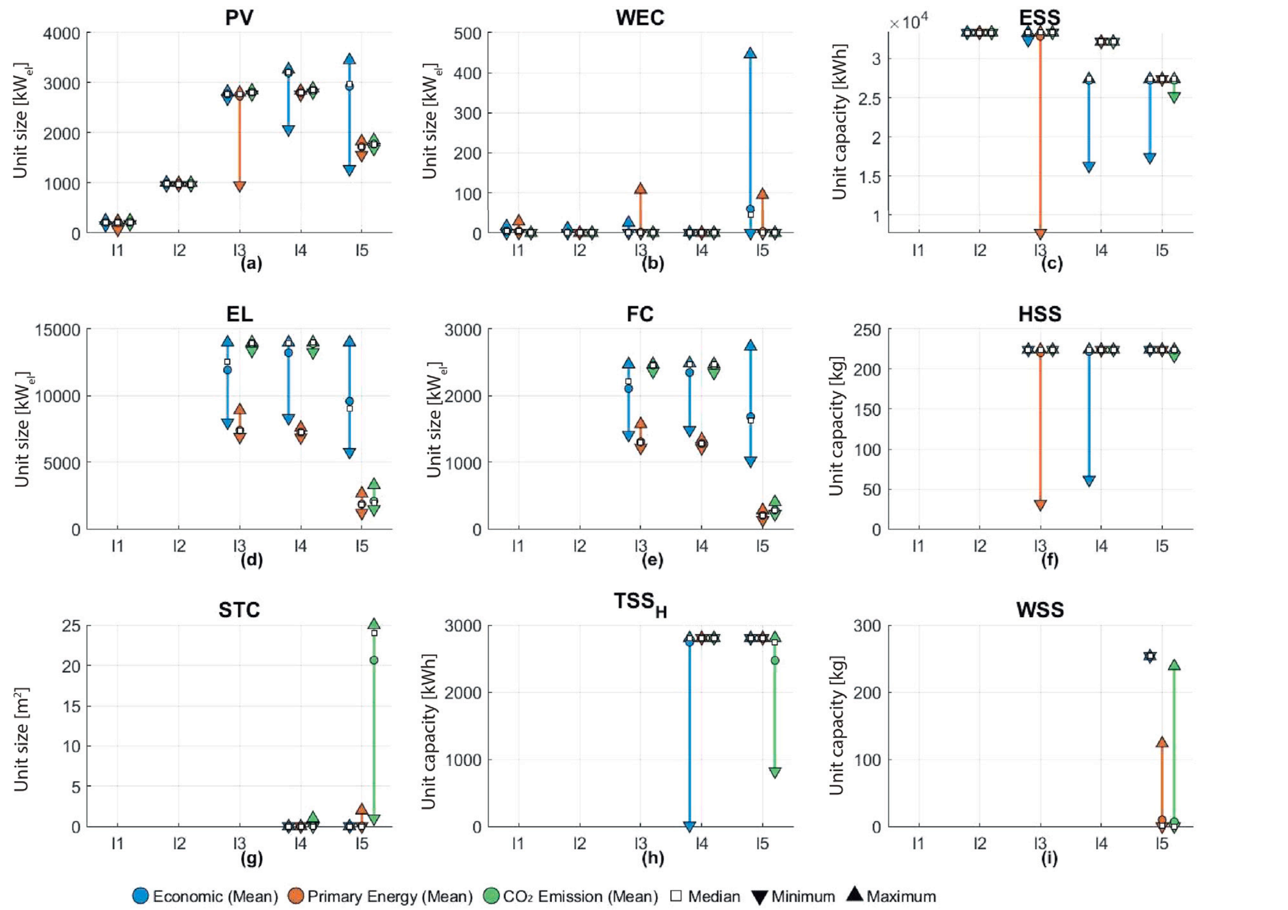

Fig. 5. Mean, max, min, mode and median values of rated size of equipment in the five scenarios according to three objective functions minimization alternatives over 100 uncertainty simulations.

emissions for a large extent, although the retrofit alternatives significantly reduce the total impact related to the Favignana energy system. The second highest contribution, on average, is given by the embodied impact of batteries, due to their complex production process and the very large capacity that should be installed in many optimal solutions. Last, WEC contribution in terms of embodied carbon is quite high in the few cases when this component is selected in optimal solution, due to its non-standardized manufacturing process. Fig. 7 shows the comparative analysis of the impact of the different technologies on costs, primary energy use, and carbon equivalent emissions.

Renewable energy community contribution

The various scenarios and optimization studies analyzed under uncertain production and consumption conditions assessed in the present paper rely on the fundamental hypothesis of making the whole Favignana island a renewable energy community. This aspect is allowed by the current Italian regulation, with specific reference to small islands, stating that a single REC covering the whole islands can be constituted in case of small non interconnected islands [55]. Since the current calculation method for REC subsidy depends on the hourly price in the single power market zone (in this case, the Sicilian market zone), an average subsidy value equal to 110 €/MWh was set in the simulations. This contribution allows making the annualized cost in each of the 1500 optimization studies always negative, meaning that incomes overcome costs due to the electricity purchase from the grid and equipment supply. In particular, Scenario 1 includes exclusively electrical renewable energy technologies, which represent the only energy carrier directly incentivized within the Renewable Energy Community (REC) framework. In this scenario, the economic benefit associated with energy sharing reaches an average value of approximately 1.17 million euros per year. This value, obtained as the average of simulations conducted under uncertainty conditions, is representative of the order of magnitude of the economic contribution associated with the REC mechanism.

With the progressive introduction of additional technologies and energy services in the subsequent scenarios, the overall economic benefit further increases. This confirms that the impact observed in Scenario 1 represents a lower bound of the achievable REC contribution, rather than an upper limit. In detail, incomes are about 2 orders of magnitude higher than costs, making the introduction of a REC in Favignana, as well as in other small non interconnected islands, highly attractive. Moreover, it becomes on average more attractive progressing from Scenario 1 to Scenario 4, while Scenario 5 appears as less appealing. Nevertheless, this apparent growth of costs is due to the fact that Scenario 5 also includes costs for water supply management.

5. Grid stability analysis under optimal scenarios

It is well known that intermittent renewable energy technologies provoke congestions and voltage fluctuations into power systems. This aspect is more evident the lower the grid is wide and meshed. For this reason, once the optimization results were obtained and analyzed, the authors further investigated the feasibility of these optimal solutions with respect to voltage rise, grid congestions and frequency stability. First, the existing 20 kV electrical grid of Favignana was modeled on NEPLAN environment, also including the local power plant and the residential loads.

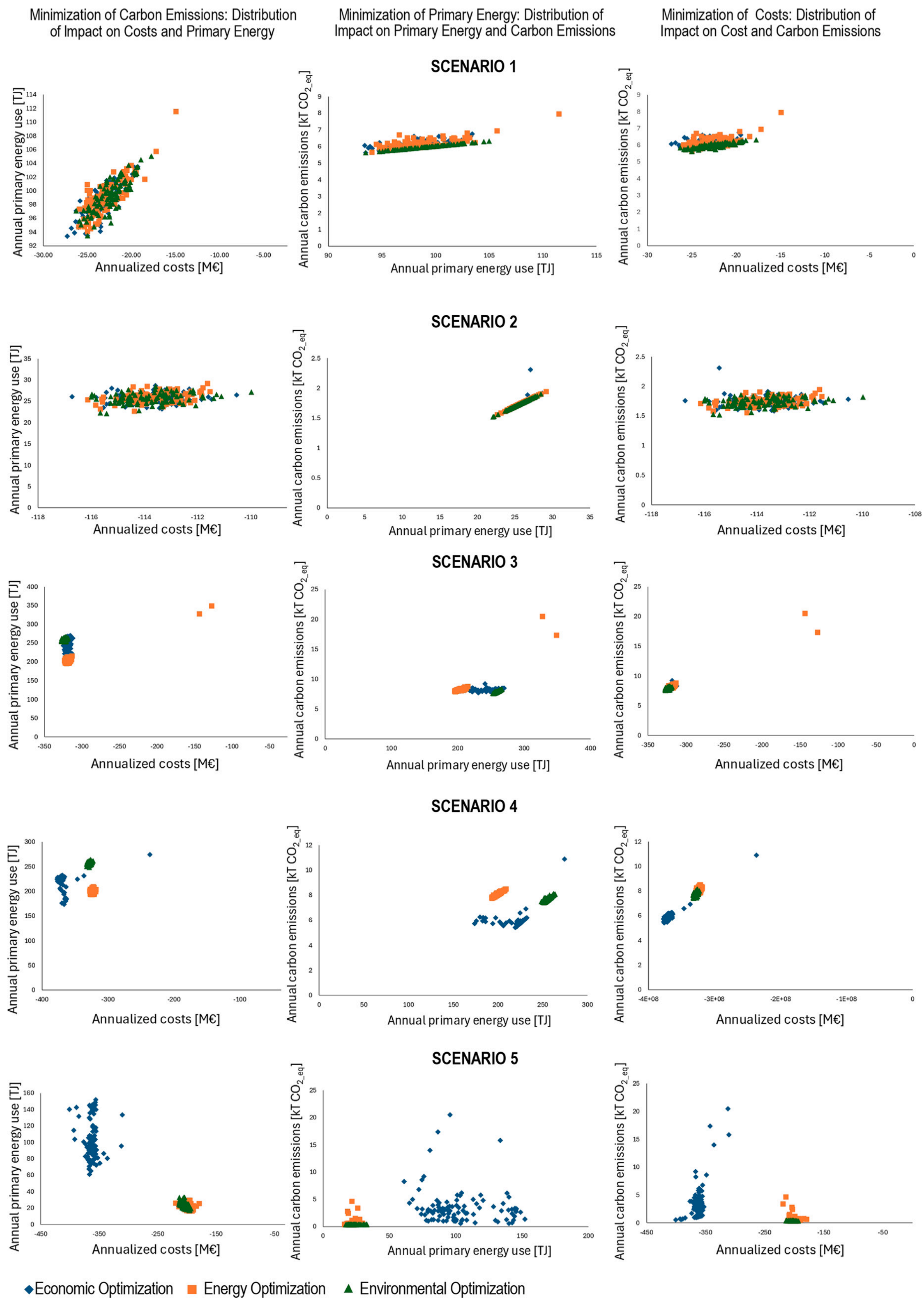

Fig. 6. Values of objective functions in the five scenarios according to three objective functions minimization alternatives over 100 uncertainty simulations.

A load flow analysis was performed for the most critical standard days in Scenario 3 and 5, assessing how the voltage was influenced by the inclusion of the equipment according to the optimization results.

Moreover, a transient analysis was also performed on the grid, assuming that the renewable energy production or the hydrogen technologies might be subject to a fault and be suddenly disconnected

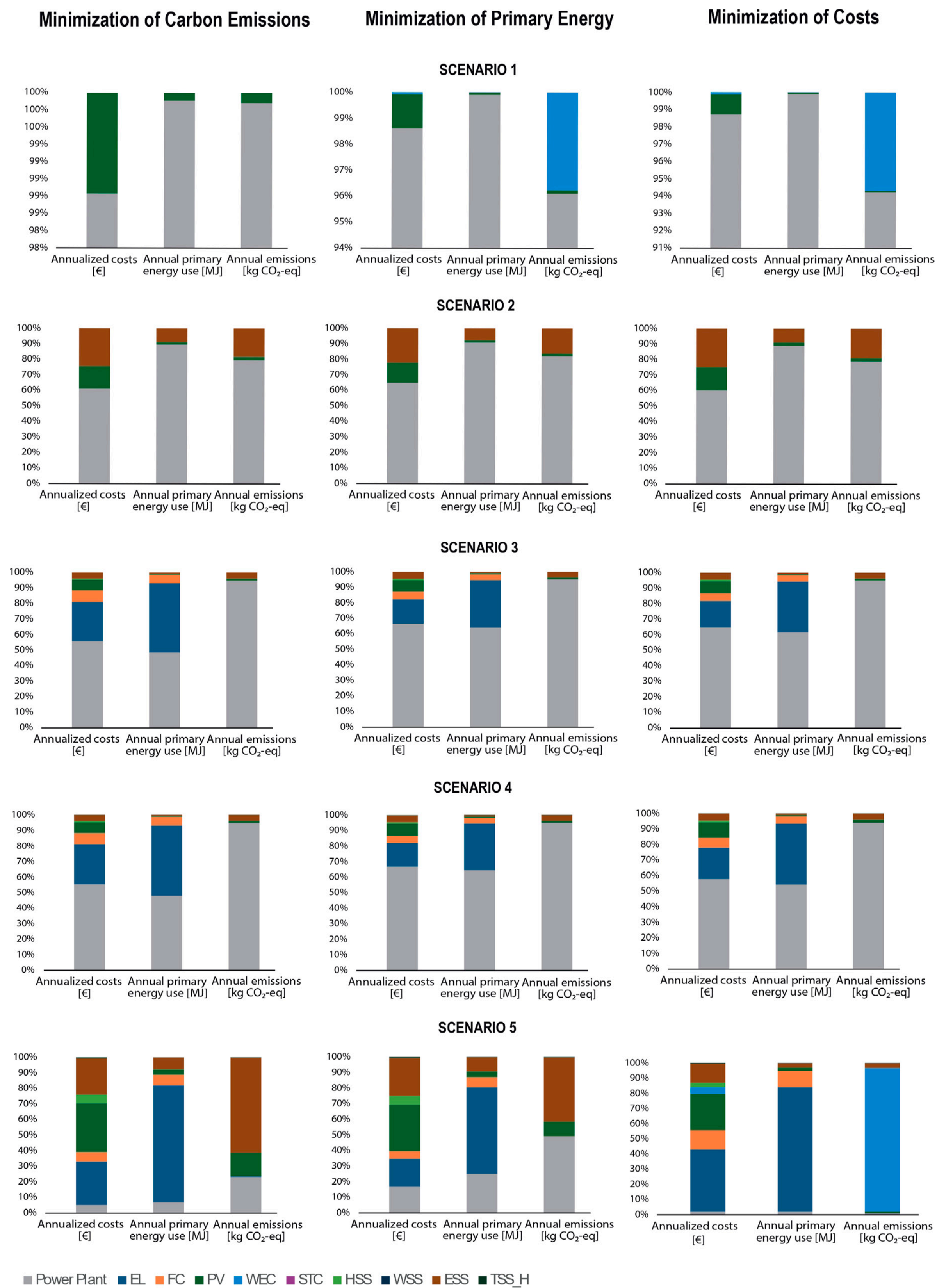

Fig. 7. Comparative analysis of the impact of technologies on costs, primary energy use, and carbon equivalent emissions.

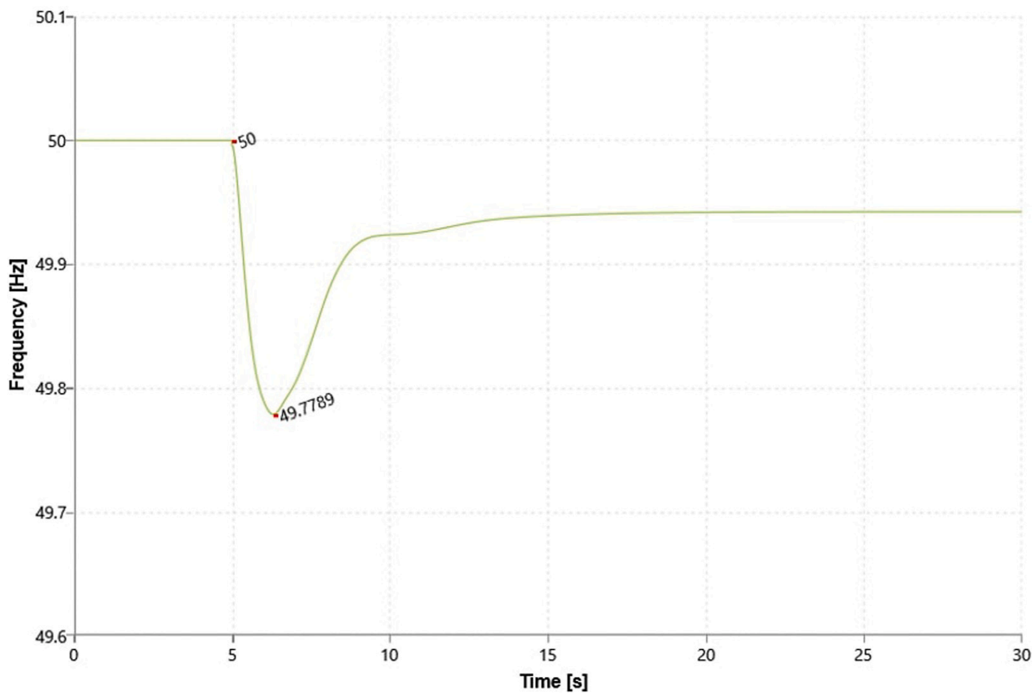

Fig. 8. Underfrequency transient that occurs in the event of sudden disconnection of one of the photovoltaic systems. As can be seen from the graph, the frequency remains above the minimum permitted value of 47.5 Hz.

from the main grid, analyzing the influence on the grid frequency. The analyses show that the voltage at the nodes ranges between 99.7% and 101.8% of the nominal value. The variability falls within an acceptable range. However, the grid is subject to overloads in 151 out of 288 simulations and should be upgraded by installing new parallel lines in some sections. The additional investment required to improve the network has been estimated based on the unit cost data for single-circuit high-voltage overhead lines reported in [56]. From these, the cost per kilometer for a 20 kV line was calculated using linear regression. Given the length of the sections affected by the overload and the number of parallel lines to be added, the additional investment for upgrading the grid was estimated at 453,000 euros, that reduces the annual revenue.

With respect to the frequency analysis, the grid is able to support the fault of these components, as shown in Figs. 8 and 9.

6. Discussion

The energy transition of small islands requires an integrated approach that considers multiple technological, economic, and environmental factors. A key aspect related to small islands energy systems is that reducing fuel consumption simultaneously contributes in minimizing the three objective functions selected for this study. Thus, each retrofit intervention tend to reduce these three criteria, making them non-conflicting objectives. It is worth noting that the environmental indicators are evaluated using average life-cycle assessment coefficients derived from literature, which are inherently subject to uncertainty; however, since the same coefficients are consistently applied across all scenarios, the comparative assessment and the relative ranking of the solutions remain robust. Nevertheless, an interesting outcome from this study is that, although Fig. 6 shows that the clouds of results are quite concentrated, these results are achieved with different equipment combinations and schedules, as demonstrated by Fig. 5.

Furthermore, the study highlights the importance of storage systems for island-based energy systems. In detail, energy and water demand on islands is heavily influenced by tourism, with summer peaks tripling winter consumptions of energy and water resources. This requires scalable and flexible solutions allowing seasonal energy storage, in order to accumulate extra production during winter to be exploited in summer. The outcome of this study is that, in the optimal solutions, batteries and hydrogen storage systems are used to overcome renewable energy penetration limits, since their installation is crucial to compensate the intermittency of renewable sources. Additionally, thermal energy and water storage systems are also used to better integrate island resources, in this case helping in matching production and consumption trends. Nevertheless, their use is also related to intermittency of renewables, since TES accumulates hot water produced by electric heaters powered by PV and WEC, while WSS stores water produced during PV extra production periods.

With respect to Scenario 5, the optimal solutions in terms of minimum primary energy use and minimum carbon equivalent emissions involved that the water demand was covered by the production from the fuel cell. In detail, renewable electricity is exploited to produce green hydrogen in the water electrolyzers, which is then converted into electricity exploiting the fuel cell. In this way, the desalination unit is employed only to restore water reserves when hydrogen is not used into the fuel cell but fuels cars. Nevertheless, an important quantity of feedback water from an external source (*i.e.*, the mainland) is also necessary during summer.

This result might suggest an innovative employment for hydrogen-based technologies, integrating the water generated as by-product into the water distribution system. It is worth to mention that, according to the study described in [57] related to polymer electrolyte membrane fuel cells and molten carbonate fuel cells, water produced in these devices could effectively be used as a source of clean freshwater, if properly treated.

Although it is unlikely to exploit water from fuel cells for public water production, this is for sure an important warning for regions where water infrastructures are poor, since important quantities of additional wastewater might be included into pipelines.

7. Conclusion

This study presents and applies an optimal planning approach for integrating RECs on small non-interconnected islands, focusing on the

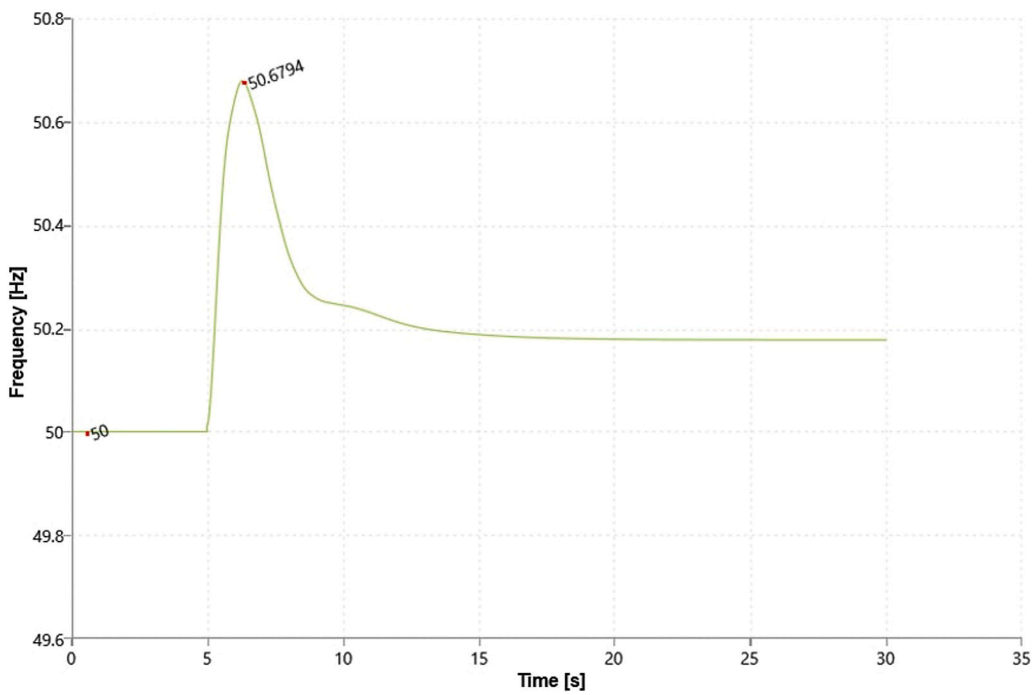

Fig. 9. Overfrequency transient that occurs in the event of sudden disconnection of the node where the electrolyzer and fuel cell are installed and from which part of the users' electricity demand is drawn. The frequency reaches a peak of approximately 50.68 Hz, which is below the maximum limit of 51.5 Hz.

Table 4
Abbreviations.

Acronym	Definition
BOP	Balance Of Plant
CAPEX	Capital Expenditure
CHP	Combined Heat Power
CRF	Capital Recovery Factor
DES	Desalination System
DoC	Depth of Charge
DoD	Depth of Discharge
EC	Embodied Carbon
EE	Embodied Energy
EL	Water Electrolyzer
ESS	Energy Storage System
EWH	Electric Water Heater
FC	Fuel Cell
GIS	Geographic Information System
H2SS	Hydrogen Storage System
HV	High Voltage
ISTAT	Italian National Institute of Statistics
MILP	Mixed-Integer Linear Programming
NOCT	Nominal Operating Cell Temperature
OC	Operating Carbon
OE	Operating Energy
OPEX	Operating Expenditure
PDF	Probability Distribution Function
PP	Power Plant
PV	Photovoltaic
RECs	Renewable Energy Communities
RES	Renewable Energy Sources
SOC	State of Charge
STC	Solar Thermal Collectors
TSS	Thermal Storage System
WEC	Wave Energy Converters
WSS	Water Storage System

use of a well-established technology—photovoltaics —and an emerging one—wave energy converters. The integration of RES on the island notably enhances the economic viability of renewable energy adoption. Integration was assessed through five progressive scenarios taking into account for different equipment and final demands of the island.

The investigation method was based on an energy hub simulation and optimization model with linear equations and a MILP solution algorithm. Three among the most common objective functions were selected for this study: annualized costs, annual primary energy use and primary carbon equivalent emissions. These functions were evaluated according to a Life Cycle assessment perspective, including both embodied and operating contributions. A total number of 1500 MILP annual optimization runs were performed and analyzed for the present study. Input parameters such as renewable energy availability and final demands were subject to uncertainty analysis, in order to repeat each optimization study 100 times under different conditions, resorting to a Monte Carlo algorithm.

The analysis indicates that coupling diesel generators with such technologies leads to lower costs, fewer emissions, and reduced primary energy requirements, with the best-performing solution revealing that each intervention tends to improve all three goals. Furthermore, it was demonstrated that the more aspects and loads are included in the analysis, the more appealing the solution becomes. Moreover, relying on a REC allows the island to receive national subsidies to cover the costs for energy bills and reinvest them in social projects for the community.

Additional research studies to the present paper should involve conducting similar analyses on other small islands worldwide to compare the main outcomes. Additionally, a comprehensive grid stability assessment will be carried out, along with an evaluation of the optimal placement of equipment on the island.

Nevertheless, since each of the small non interconnected island possesses peculiar features, comparisons between different locations can be risky or misleading. For this reason, a further improvement of

Table 5
Latin symbols.

Symbol	Description
a_1	Linear heat loss coefficient
a_2	Quadratic heat loss coefficient
A_{PV}	Surface area of one PV module
A_{STC}	Surface area of one solar thermal collector
d_{PV}	Minimum normalized distance between PV rows
d_w	Average water depth
DoC_{ESS}	Depth of charge limit
DoD_{ESS}	Depth of discharge limit
E	Electrical energy flows
$E_{DES}(t)$	Electrical energy to desalination unit at time t
$E_{EH}(t)$	Electrical energy to electric heater at time t
$E_{EL}(t)$	Electrical energy to electrolyzer at time t
$E_{ESS,in}(t)$	Energy charged into storage at time t
$E_{ESS,out}(t)$	Energy discharged from storage at time t
$E_{FC}(t)$	Electrical energy from fuel cell at time t
$E_{load}(t)$	Electrical energy demand at time t
$E_{PP}(t)$	Electrical energy from power plant at time t
$E_{PV}(t)$	Electrical energy from PV system at time t
$E_{PV(t)}$	Power generated by the PV system
$E_{WEC}(t)$	Electrical energy from WECs at time t
$f(T)$	Probability density function of temperature
$f(\Theta)$	PDF of solar irradiance (Beta distribution)
G_{sol}	Global solar radiation
$G_{sol}(t)$	Solar irradiance on collector surface at time t
g	Gravity acceleration
H	Heating flow
$H_2, demand(t)$	Hydrogen demand at time t
$H_2, EL(t)$	Hydrogen flow from electrolyzer at time t
$H_2, HSS, in(t)$	Hydrogen stored at time t
$H_2, HSS, out(t)$	Hydrogen released from storage at time t
$H_{load}(t)$	Thermal energy demand at time t
$H_{STC}(t)$	Thermal energy from solar collectors at time t
$H_{TSS,in}(t)$	Thermal energy stored at time t
$H_{TSS,out}(t)$	Thermal energy discharged at time t
H_s	Wave height
$H_s(t)$	Significant wave height at time t
K	Conversion parameters
K_{ch}	Charging efficiency
$K_{DES,ew}$	Conversion factor electricity to freshwater
K_{disch}	Discharging efficiency
$K_{EH,eh}$	Conversion factor electricity to thermal energy
$K_{EL,eh2}$	Conversion factor electricity to hydrogen
$K_{EL,ew}$	Conversion factor electricity to water
$K_{ESS,loss}$	Self-discharge rate of storage system
$K_{FC,eh2}$	Conversion factor hydrogen to electricity
L_{WEC}	Length of WEC device
N_{PV}	Total number of PV modules
N_{STC}	Number of solar thermal collectors
N_{WEC}	Number of WEC units
P_w	Wave Power
$P_w(t)$	Wave power per unit length at time t
Q_{ESS}	Maximum energy capacity of storage system
S	Rated size
S_{EL}	Rated power capacity of electrolyzer
$SOC_{ESS}(t)$	State of charge of storage at time t
T	Random variable for temperature
T_{air}	Ambient air temperature
$T_{air}(t)$	Ambient air temperature at time t
T_{cell}	PV cell temperature
T_m	Mean temperature of heat transfer fluid
T_p	Peak wave period
T_{ref}	Reference temperature
W	Water flows
$W_{demand}(t)$	Freshwater demand at time t
$W_{EL}(t)$	Water flow consumed by electrolyzer at time t
$W_{grid}(t)$	Freshwater from grid at time t
$W_{WSS,in}(t)$	Freshwater stored at time t
$W_{WSS,out}(t)$	Freshwater released from storage at time t

Table 6
Greek symbols.

Symbol	Description
β	PV tilt angle
β_{PV}	Temperature coefficient
$\Gamma(\cdot)$	Euler Gamma function
δ	Solar declination angle
$\delta_{ESS,in}(t)$	Binary variable for storage charging at time t
$\delta_{ESS,out}(t)$	Binary variable for storage discharging at time t
Δt	Time step
η_0	Zero-loss efficiency of collector
η_{PV}	Efficiency in standard conditions
$\eta_{STC}(t)$	Efficiency of solar collector at time t
η_{WEC}	WEC conversion efficiency
Θ	Non-dimensional solar irradiance
μ	Mean value of input variable
ρ	Seawater density
σ	Standard deviation of input variable
ψ	Second parameter of Beta distribution
ω	First parameter of Beta distribution

this research could involve the development of proper indicators for the quantification of energy saving potentials in small islands.

CRediT authorship contribution statement

Domenico Curto: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Data curation, Conceptualization. **Maria Luisa Di Silvestre:** Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition. **Miriam Mantegna:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Daniele Milone:** Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Francesco Montana:** Writing – review & editing, Writing – original draft, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Salvatore Ruffino:** Writing – review & editing, Writing – original draft, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gaetano Zizzo:** Writing – review & editing, Writing – original draft, Software, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Data availability

The data that has been used is confidential.

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