Renewable Energy 215 (2023) 118986

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Challenges of renewable energy communities on small Mediterranean islands: A case study on Ponza island

Alessandro Corsini [a], Giovanni Delibra [a], Isabella Pizzuti [b,*], Erfan Tajalli-Ardekani [b]

[a] Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, Italy
[b] Department of Astronautical, Electrical and Energy Engineering, Sapienza University of Rome, Italy

ARTICLE INFO

Keywords:
Renewable energy communities
Isolated power systems
Water desalination
Green energy transition
Python smart energy system modelling
pyRES

ABSTRACT

Italy has reconsidered incentives on Renewable Energy Sources (RES) to implement the EU clean energy transition and Renewable Energy Communities (REC). Legislation on RECs shifted the focus of incentives from production to self-consumptions. In this paper, the REC model is studied in a minor island disconnected from the national grid, with strongly seasonal energy load and water demand. This is a typical Mediterranean scenario where energy demand is covered by Diesel gensets and water supply is provided with tankers. The implementation of RES is investigated, exploiting the current REC model of incentives. Two sub-optimal REC configurations were defined using time-dependent simulations on pyRES, an in-house code for energy systems. Results show the economical unfeasibility of REC when there is a poor mix of users. In contrast, REC can achieve economic profitability including industrial demand of a desalination unit (DES). The increase of self-consumption guaranteed from the DES allows to increase the NPV of the community and results in major cuts in CO_2 emissions (60% of those related to water supply and 10% of those from Diesel gensets) and a reduction of fuel costs of 22%. This method can be applied to investigate the performance of a REC in a local environment and help stakeholders in planning the expansions of RECs on the territory.

1. Introduction

EU clean energy transition programme and energy system decarbonization strategies rely on increased penetration of Renewable Energy Sources (RES) in power generation grids, resulting in a number of technical challenges. To mention but a few: grid frequency stability [1,2], RES discontinuity [3,4], matching of generation with highly fluctuating loads [5], and implementation of storage systems for energy backup and demand shift and flexibility [6].

In addition to these elements, Italy strongly relies on a widespread PV diffusion to achieve the target of 51 GW of installed RES power by 2030 [7]. This is mostly associated by the concurrent effect of the low quality of wind and the legislative, social and environmental barriers in on-shore wind turbine installations.

For these reasons, energy transition needs to account for the increasing popularity of domestic and industrial PV systems spread across the country and the challenges that their connection to the power grid entails. After years of economic incentives boosting mostly utility-scale PV plants [8,9], Italian government has recently changed the legislation and incentives scheme for PVs and RES in general, promoting the new paradigm of Renewable Energy Communities (REC) in accordance with the "Clean Energy for All Europeans" Package (CEP) [10]. The main objective is to drive the integration of energy generation and consumption on a local scale within areas contoured by medium and low voltage grid maps. In this scenario RECs are seen as tools to mitigate the negative impact of renewables on power grid and to guarantee their further penetration in the market, without any other incentives.

The current REC legislation [11,12] is based on the idea of incentivizing the self-consumption of the community and in so doing promoting a direct involvement of citizens and local actors in the economic, social and environmental development of their territory. The REC is a new renewable power-sharing model based on three pillars: i) decentralization and localization of energy production, ii) self-production and collective consumption, and iii) direct involvement of consumers [13,14]. In this context, local MV and LV power grids are considered more as an energy reserve than just energy distribution infrastructures.

The performance analysis of a REC implies a multidisciplinary approach, involving legal and social aspects. These are related to the

* Corresponding author.
E-mail addresses: alessandro.corsini@uniroma1.it (A. Corsini), giovanni.delibra@uniroma1.it (G. Delibra), isabella.pizzuti@uniroma1.it (I. Pizzuti), erfan.tajalliardekani@uniroma1.it (E. Tajalli-Ardekani).

https://doi.org/10.1016/j.renene.2023.118986
Received 8 January 2023; Received in revised form 26 June 2023; Accepted 1 July 2023
Available online 3 July 2023

legal handling of the REC, the revenue sharing policy implemented and a token-based shared economy that can implement different strategies to further involve prosumers and consumers in the REC [15–17].

From a technical viewpoint, the main advantages of RECs stem from local consumption of renewable energy finding local (unplanned) power supply-demand balance and enabling RES technologies integration in new urban contexts. From an economic point, then, REC share benefits on electricity bills. As discussed in Ref. [18], in fact, the assessment of economical revenue of a REC based on PV plants is a key factor to boost its adoption. As for the study of energy and financial metabolism of RECs many authors address the key issues. For example, in Bartolini et al. [19], the authors studied a REC composed of 3 separate blocks of 50 end users to represent an urban district and focused on multiple scenarios with different integration of multi-energy systems and storage, focusing on optimal configurations. In Musolino et al. [20] the authors addressed relevant features emerging from 24 RECs in Italy highlighting the importance of local context in the REC formation and social differences between actors and background between North and South Italy. Kallis et al. [21] provide a comparison of 17 different RECs assembled on islands all over the world, focusing on three major social issues: general principles and considerations to engage with the local community; features of islands potentially affecting engagement processes; and experiences from a number of islands where community members participated in discussions on proposals for renewable energy projects. “Particular attention was directed at examining techniques used to encourage participation, gain trust, and manage intra-community disagreements and conflicts with project developers and sponsors over projects and the management of engagement processes”. This is quite important given the intrinsic social nature of the RECs. In Tomin et al. [22] the authors report on the development of a two-level strategy to plan and then operate a REC under uncertainty of decision maker preferences. They used an optimization method to minimize OPEX, risks of power shortage and CO_2 emissions, smooth peak loads and optimize the energy exchange between different microgrids, applying their method to three remote villages in Japan with a mix of wind, solar and biomass RES. They found a solution with significant benefits for REC members, with up to 75% of reduction of the electricity tariff, a strict CO_2 emission cut and increase of renewable energy fraction. Ang et al. [23] studied a solution with a mix of solar, wind and marine energy for Eastport (Maine, USA). They found a series of optimal solutions but concluded that the optimization becomes increasingly challenging with the increase of RES penetration, especially above 90% of annual energy demand. The last 10% in fact requires disproportionate effort to be achieved. Bartolini et al. [24] investigated the performance of a district with a mix of PV, CHP fueled by a mix of hydrogen and natural gas with BES and hydrogen storage. Their study demonstrated the potential of a multi-generation and storage approach, but also highlighted the drawbacks of using storage technologies instead of interacting with the electric grid with respect to CO_2 emissions because of roundtrip efficiency of the storage system operations.

1.1. REC as a transition model for the smaller islands

This article focus is on the technical aspects involving the optimal selection of users and prosumers and their integration into a local community [21] and the challenges of the implementation of RES on a minor island scenario [25]. To this aim, a geographically- and power-isolated case study was selected: a minor island not connected to the national power grid that also required clean water supply from the mainland. *Ponza* is in fact a small island that offers particularly challenging constraints and requires creative aspects that can help building a profitable REC. In what follows particular importance is in fact given to the implementation of a REC on Ponza together with a desalination plant. This operation increases the energy load of the island but allows to store excess of PV production in form of fresh water stored in a tank and in so doing to better mix with the highly seasonal load of the island. Even if the introduction of desalination systems in RECs is scarcely discussed, their integration with RES is quite-well documented. In fact, in Kasaejan et al. [26] the authors provided a review of latest findings in coupling RO desalination with solar energy providing a series of example applications with different TRL. More recently, Saidi et al. [27] discussed the performance of a solar-powered HDH desalination system. The authors carried out numerical studies and experiments to investigate how operating parameters affect freshwater production and the Gain Output Ratio (GOR). The numerical findings indicate that daily production of fresh water increases with the temperatures of the feed water and air in the humidifier, as well as the humid air temperature at the dehumidifier inlet. On the contrary, increasing the cooling water temperature in the dehumidifier has a negative impact on the system production of fresh water. Abedi et al. [28] investigated the integration of solar chimneys with HDH desalination systems, focusing on how the two systems need to be tuned to work together properly. Geng and Gao [29] discussed the integration of reverse osmosis (RO) desalination systems with Ocean Thermal Energy Conversion (OTEC) systems finding that a combined cooling desalination and power double Kalina cycle has higher net power output, thermal and exergy efficiency and SUCP. They also examined in detail the costs of all the components and the influence of different cycle parameters on its performance. Dezhdar et al. [30] used TRNSYS to perform an optimization of a new solar-wind based energy system to produce clean water, electricity, cooling and heating with battery storage and fuel-cell-hydrogen tank and electrolyzer. They applied this concept to the city of Zanjan, exploring performance and optimization of the layout. They derived some best practice for sizing of components but still lacked a discussion on the high costs of this layout. Pietrasanta et al. [31] studied the integration of desalination with geothermal energy, developing a tool for the selection of the best configuration of the desalination system (RE vs MED) and the geothermal powerplant (single vs double flash) providing a full economic comparison of the various solutions.

This manuscript investigates the possibility of building a REC on a small Mediterranean island, addressing the challenges of sizing the PVs in a scenario where energy demand increases by a factor of 5 during summertime and exploring how the current model of revenues for RECs in Italy are not viable in this context. However, including a desalination system (DES) in the mix of electric loads with a storage tank the latter can be used to store clean water and in so doing balancing the energy and financial flows of the REC and reducing the overall CO_2 emissions of the island. The combination of a REC incentive system based on self-consumption rather than renewable energy production, the DES, their interactions and the following drop in emissions and fuel consumptions are the major novelties of this contribution. Previous literature in fact reports on the use of a DES to achieve peak shaving in Diesel genset operations [32] while in this work it is demonstrated how the storage tank of the desalinator can store excess of PV production in form of clean water to be used later during the year. Moreover, this REC incentive system potential is not yet investigated in open literature.

The paper is organized as follows: first, an overview of the relevant EU and Italian legislation on RECs is given, then the numerical methodology for REC modelling is discussed, then an overview on the Ponza case study is given and two scenarios are considered, without and with desalination system. Finally, conclusions are drawn.

2. Renewable energy communities: EU and Italian legislations

In 2019, the European Union approved the “Clean Energy for all Europeans” legislative package (CEP), consisting of eight directives for the development of a legal framework to allow the energy transition and to give a pivotal role to citizens in the energy sector. In particular, the Renewable Energy Directive II (RED II) [33] contains important guidelines for the development of renewables and the definition of a REC. Internal Electricity Market (IEM) [34] aims to adapt the EU electricity market to the technological and structural changes taking place recently. In Italy, the process of transposition of RED II began with 2020 “Milleproroghe” decree [35], which paved the way for the experimental phase. The first energy communities were developed according to the following technical constraints: REC plants included in the REC:

- had to be new and powered by RECs,
- with a maximum nominal power of 200 kW

and the community members had to be located in the same low-voltage electricity grid.

The legislative decree which definitively transposed RED II and IEM was adopted on December 2021 and increased the maximum size of each plant to 1 MW and removed the limit on secondary substations allowing the inclusion of members connected to the same primary substation. The Regulatory Authority for Energy, Networks and the Environment (ARERA) defined the economic incentives related to the shared electricity in Ref. [36], dividing the financial contributions to RECs into three types:

1. return of tariff components based on shared energy;
2. awards on amount of shared energy;
3. sale of excess of renewable energy produced to the grid [37].

The performance of the community can be defined by the calculation of shared energy, renewable energy production, energy sold to and purchased from the grid. This is done in a limited number of papers available in the open literature. For example, Mocecchi et al. [38] proposed an optimization process to simulate the energy fluxes between REC members to evaluate its financial feasibility. Ghiani et al. [39], studied the possibility of increasing RES penetration in a small REC on Sardinia. In Ref. [40] Zulianello et al. discuss the Italian implementation of REC incentives. Di Silvestre et al. [41] discuss a series of REC experiences around the world and compare them to the Italian scenario, advocating a further extension of incentives to social and other benefits based on the use of blockchain. Mutan et al. [42] developed a series of indicators for the economic feasibility of RECs.

3. Methodology

Design, analysis, and management of the Ponza RECs were computed using pyRES, an in-house open-source Python code for energy system analysis developed at DIMA-Sapienza. pyRES is characterized by a modular structure, based on the logic of the object-programming. In Fig. 1 a black-box diagram of pyRES is shown for a generic energy system. This is characterized by a series of input data that include technical datasheets of the power production and storage systems, meteorological data from available historical datasets or weather forecast for RES and the energy load to cover. Given the input and the connection between the users, plants and storage systems, the kernel of pyRES reconstructs the quarter-hour energy demands within a series of consumer and prosumer clusters, calculate the energy, financial and environmental performance of the systems and the eventual interaction with the storage systems. The code exploits the machine learning libraries like *sk-learn* [43], *Keras* [44], *TensorFlow* [45] and *PyTorch* to manage the controller strategy of the system and to reconstruct the quarter-hour energy demand of each user in the system using auto-encoders trained over data collected in previous works. pyRES includes an optimization module based on genetic algorithms, particle swarm and other methods implemented in the *Pymoo* library [46]. It can be used to optimize i) the size of power plants and storage systems and ii) the number of users of the community. Multi-objective optimization account for energy, financial and environmental impact performance, that are the output of the software. Since the final economics of the REC in part depend on local incentive mechanisms, the customization of the financial module is of key importance to the analysis of revenues. In fact, the economics of the REC will be in part responsible for the optimization results and will impact the selection process of optimal solutions.

This output of pyRES is given in quarter-hour basis and later aggregated in weekly, monthly and finally in a yearly summary. Time-advancement of the solution is discretized with 1st order approximation.

In Fig. 2 the pyRES model for Ponza REC is shown. For the present work, the pyRES modules for PV panels, desalination and storage tank are used, and a controller is developed to implement a strategy for balancing the energy production of the desalination system and its tank, Customized control logics and REC-specific incentive models based on the Italian legislation were implemented and tested. The optimization module is used first to identify the best prosumers and consumers mix in the REC and then to size the storage system.

3.1. Model components

The PV module in pyRES is based on an empirical equivalent circuit model to predict the current-voltage characteristics of a single PV module. This circuit consists of a DC current source, diode, and resistor. The model extrapolates the performance provided by the manufacturer data sheet using a single module equivalent circuit to predict the

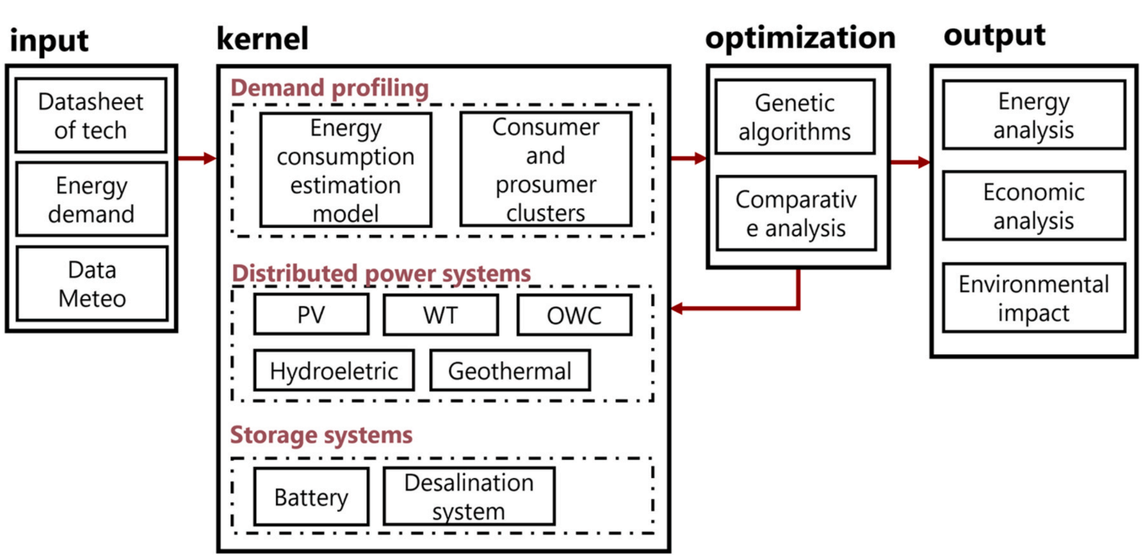

Fig. 1. A black box scheme of pyRES.

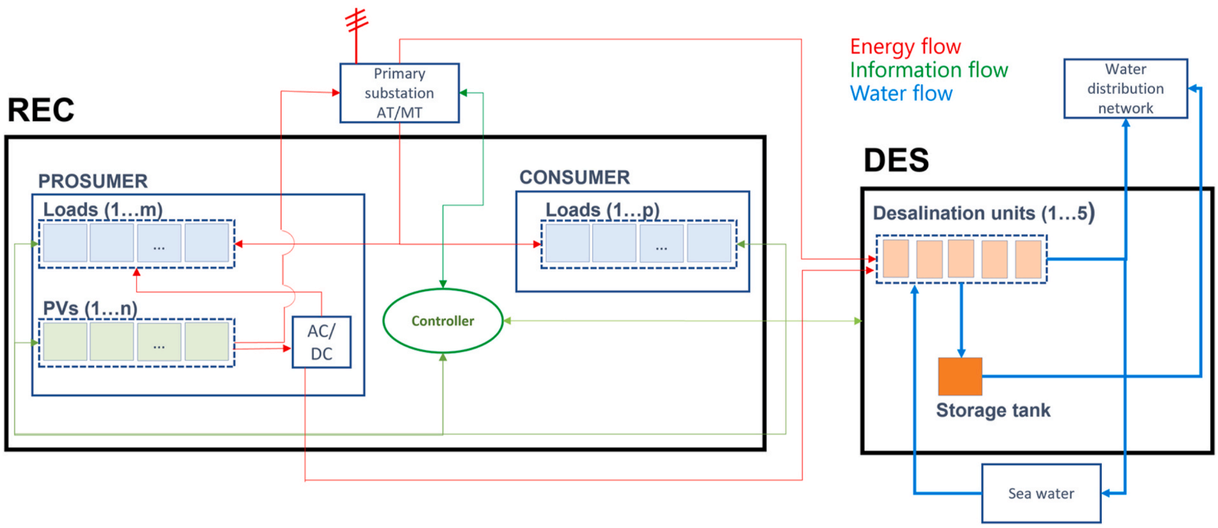

Fig. 2. Scheme of Ponza REC with integrated DES in pyRES.

performance of a multi-module array. This model comes from the four-parameter (ILref, I0ref, gamma, Rs) equivalent circuit model developed largely by Townsend and expanded by Duffie and Beckman. Results were validated against those calculated by TRNSYS Type 103 [47]. The quarter-hour difference in computed power output for the whole year is always in the range of [−0.96:1.012] mW.

The desalination system in pyRES simulates one or more desalinations unit integrated with a water storage tank. The number of desalination units, the production capacity la capacity [m^3/h], the consumption curve [kWh/m^3] of each unit, the minimum and maximum level of the tank constitute the model parameters. This module calculates the electricity demand starting from the clean water demand. Size selection for the storage tank was based on an optimization analysis carried out with NSGA-II algorithm for multi-objective optimization [48]. This algorithm was selected in the library for the high-accuracy and short time to solution in two-objectives optimization problems. The reduction of water demand from the mainland and the minimization of on/off switches of the desalination units during the year were selected as objective functions to keep the desalination energy demand as constant as possible. The only considered constraint on the optimization was the total lack of wasted desalination water. A tank is also present and allows to store clean water exploiting overproduction energy from PVs. Energy and clean water flows are managed by the controller module.

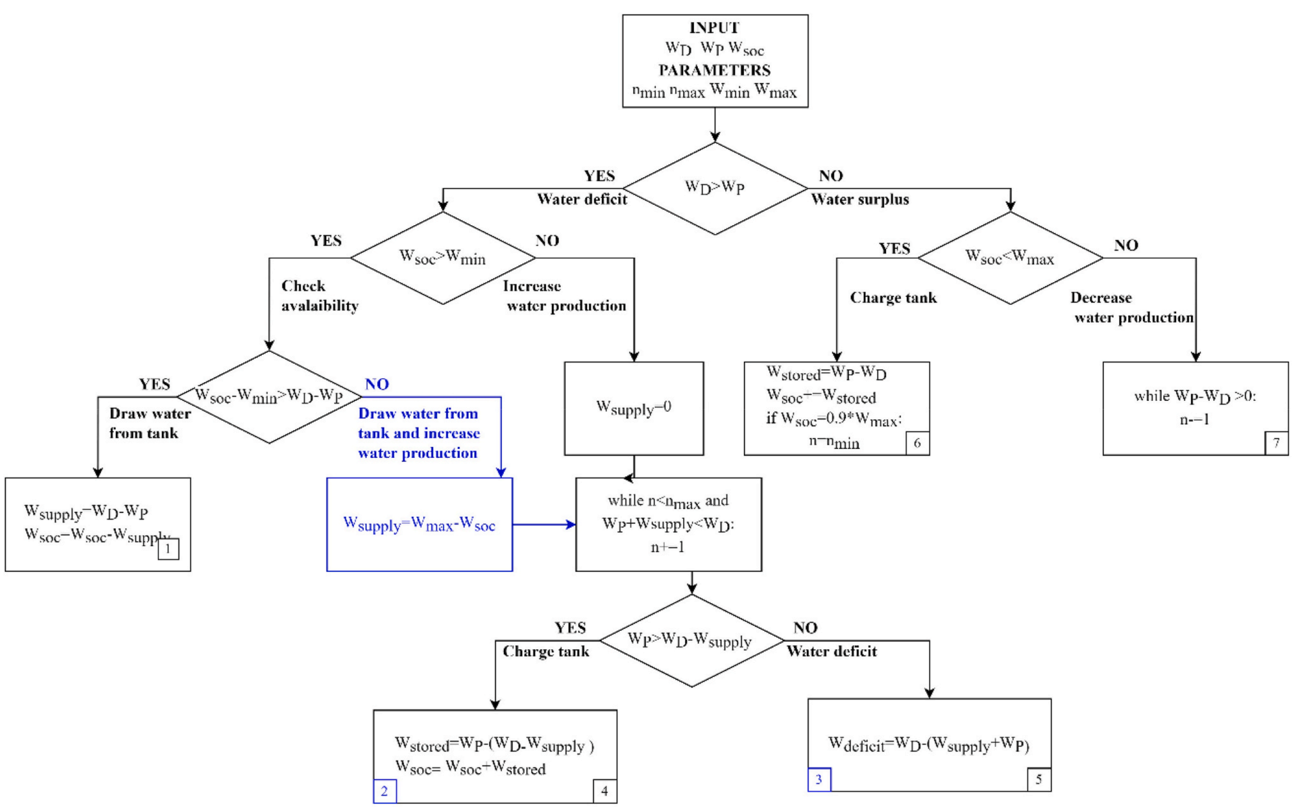

Fig. 3. Flow chart for management of energy and desalination.

The control logic for energy and water desalination management is based on keeping constant the desalination load. This is achieved by a system that exploits the storage tank to level the water demand according to the logic shown in Fig. 3. For each time step of the simulation, the controller requires water demand, the tank state of charge and the water production calculated during the previous time-step. The control logic prioritizes the constancy of active desalination units.

So, if $w_D > w_P$ the desalination units are not sufficient to cover the request and the controller first tries to fulfill the demand using the storage system. If the tank does not have a sufficient amount of stored water, the number of desalination units is increased up to fulfilment of the demand. Otherwise, if $w_D < w_P$ the controller tries to store the water surplus in the tank and if this is already filled up to the maximum the number of desalination units is decreased. In case the production is not sufficient to cover the demand the water deficit is covered with tankers from the mainland – in this case, the water is stored in the same tank, mostly during summertime as will be shown later.

4. Case study: Ponza island

The case study is the island of Ponza, in the Mediterranean Sea, with a total surface of 7.5 km^2. The number of inhabitants is remarkably dependent on its touristic vocation and spans from 3300 in winter to 55,000 in summer. This circumstance leads to severe issues in energy and water system management. Electric energy is supplied by two Diesel engine power stations. Respectively, a main power station of 6.2 MW with four engines, and a peak-shaving station with 2.6 MW installed power and two engines, typically operating only in summertime. On December 31, 2020, the total PV power installed was 300 kW, covering 3.4% of the electric load. In Fig. 4 the electricity demand during the year is shown and it is evident how during summertime the power demand peaks to more than 5 MW, while during most of the year the power demand is between 0.5 and 1.5 MW.

Clean water is supplied by tanker ships from the mainland. The water demand amounts to 388,000 m^3 per year corresponding to 229 ship trips and producing 2602 tons of CO_2, Fig. 5 [32].

The water distribution company responsible for the clean water supply on Ponza is scrutinizing the possibility of installing a reverse osmosis desalination plant with multiple units, and a total power between 300 and 350 kW, corresponding to a production capacity of 1500 m^3/day.

A summary of the desalination system is given in Table 1.

The introduction of a desalination plant on Ponza would of course increase the energy load (the increase is estimated for reverse osmosis plants between 4 and 6 kWh/m^3) [50,51]. So, the introduction of the desalinator should be compensated using RES. When dealing with RES in Ponza context, a series of restrictions need to be considered, regarding land and sea usage, environmental and historical heritage protection laws. The configuration of the REC must comply with the relevant legislation: European council directives [52,53] included Ponza and its surrounding seabed in the official list of SPAs (Special Protection Areas) and SIC (Site of Community Importance), respectively. The management plans of these areas are conferred to the regional institution. On Ponza, the realization of a renewable production plant is ruled by the national Legislative Decree 28/2011 [12]. To conclude land availability and environmental regulations are factors limiting the possibility of installing large-size on-shore wind turbines and off-shore installations are prohibited. The conclusion is that PVs are basically the only viable RES available to assemble a REC on Ponza.

The available solar radiation on this site was derived from quarter-hour data from PVGIS [54], that for a 1 kW PV module estimates an annual energy production of 1468 kWh, with a year-to-year variability of 43 kWh.

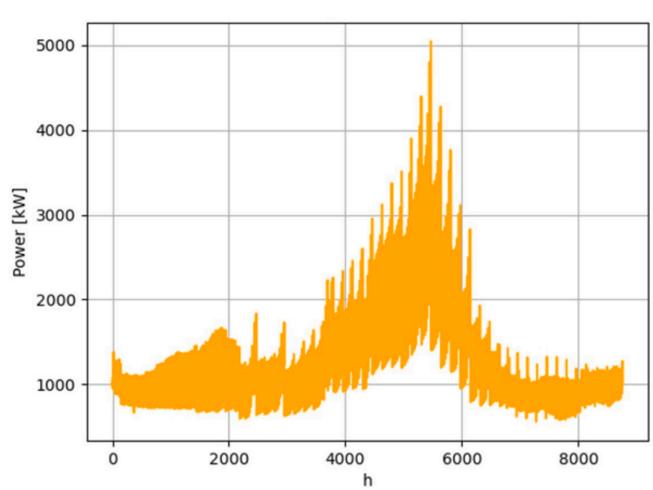

Fig. 4. Electric power load of Ponza during the year [32].

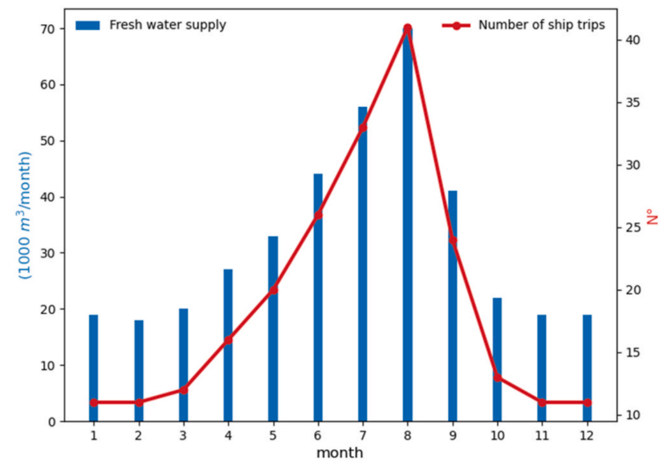

Fig. 5. Clean water supply demand of Ponza [49].

Table 1
Desalination system description.

Desalination station	5 units × 300 m^3/day Water flow 5 x 12.5 m^3/h Electric power 5 x 70 kWp Global specific energy consumption 5.32 kWh/m^3

4.1. REC prosumers and consumers characterization

The selection of potential REC members for Ponza relied on a GIS analysis of *Cala dell'Acqua* residential area (where the DES is supposed to be installed). This analysis allowed to identify four classes of actors for the REC: residential prosumers, residential consumers, restaurants, and hotel prosumers. For each of them, a typical electric load was provided by Ponza electric company that operates on the island and are in quarter-hourly format and used for the current study. PV plants were sized according to the roof and parking space availability on Ponza restaurants and hotels. For residential buildings, it was assumed a PV size of 3 kW for all the prosumers. In the REC assembly phase, residential consumers and prosumers were treated as two separate classes, each spanning from 0 to 400 members. However, the sum of possible residential consumers and prosumers is set to a maximum of 400, given the total amount of residential spaces in that area, with the underlying idea that each of them can enter the REC as a prosumer or a consumer.

The maximum number of restaurants and hotels was selected according to the actual number of structures present in this area, according to Table 2.

Table 2
REC consumers and prosumers.

Class	Description	Potential PV size [kW]	Electricity consumption [MWh/year]	Maximum number of members
1	Residential prosumers	3	4	400
2	Residential consumers	–	4	
3	Restaurants	7	21	10
4	Hotels	50	200	10

4.2. Scenarios

In the following, design of a REC in this context is discussed and a comparison will be made among two major scenarios: a REC dealing with the actual electric load, and another where a desalination plant is included accounting for the clean water supply scenario. A storage tank will also be considered to shift water production and usage.

Economical revenue of the REC is calculated according to the directives listed in the Introduction.

5. Results

In the first scenario, a REC was assembled without accounting for the DES, using an NSGA-II optimization strategy that selected the best prosumers and consumers mix to maximize self-consumption and net present value (NPV). Pareto front of this optimization is shown in Fig. 6, where solutions with a high value of annual self-consumption and increased coverage of the electric load results unfeasible because NPV is negative. Economically feasible solutions are therefore those in the upper-left portion of the front, that span from a 395 to 413 members, with a PV nominal power between 213 and 310 kWp. The coverage of the electric load never exceeds 20% of the yearly demand and this is mostly due to the abrupt increase of the load during summertime. In fact, considering only the load of the residential population, the coverage increases to about 50% of the demand. The lack of a diverse enough mix of prosumers and consumers, the limited number of available solar roofs and the lack of energy-demanding business activities on Ponza result in the REC model not being economically viable. One could argue that the current generation scenario is well above the average energy price and thus that the REC incentives should be tuned to make it more attractive, however, there is still a desalination plant to account for that could change the scenario.

The introduction of the DES in the community was then investigated starting from a solution on the Pareto front that guarantees a coverage of the electric demand of 40% for the whole year, shown as a pink cross in Fig. 6. A water storage tank was considered, with a capacity to be selected from 100 m^3 to 3000 m^3. The objective space of the optimization for the storage tank is shown in Fig. 7. Given the fact that the four solutions on the Pareto front have a similar water deficit, the solution that ensured the minimum number of switches on/off of the desalination units was selected as optimal. This corresponds to a water tank with 3000 m^3 capacity.

The energy performance of the system is summarized in Fig. 8, where the PV production is shown together with the demand of the REC and the DES. The solution without DES has an overall electric coverage of 40% for the whole year. However, this comes with a strong unbalance between seasons, as in fact across spring the coverage spikes to 140%. This is of course a problem as most of the incentivizing mechanism is based on self-consumption and all the over-production is acquired from the grid at a minimum tariff. Adding the DES electric load to the REC lowers the coverage to an average value of 22% and rebalances the uneven distribution between different months. In fact, in this case the energy coverage peaks at about 50% during May, resulting in a much more convenient tariff as self-consumption increases.

This is further confirmed when looking at the time-dependent metabolism of the system, Fig. 9. For a typical spring week, in fact, the PV production exceeds 500 kW during the central hours of the day, with REC peak demand of 200 kW and DES constant demand of 200 kW.

In summer the effect of tourism is to strongly increase both energy demands, with the PV systems now able to provide less than 2/3 of the demands at peak production. A similar scenario characterizes winter

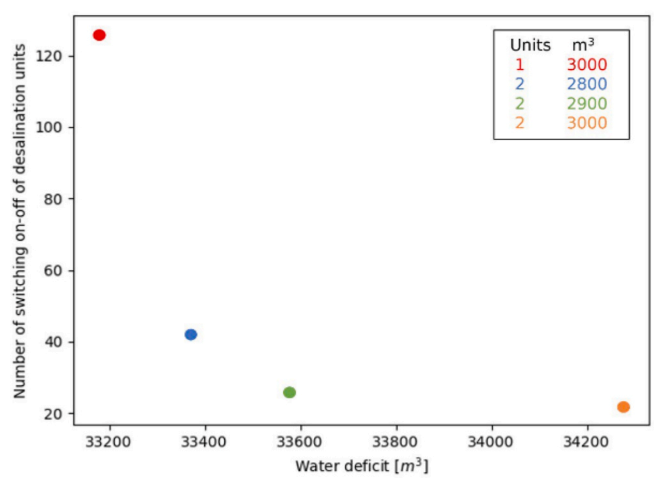

Fig. 7. Objective space of NSGA-II optimization for the storage tank.

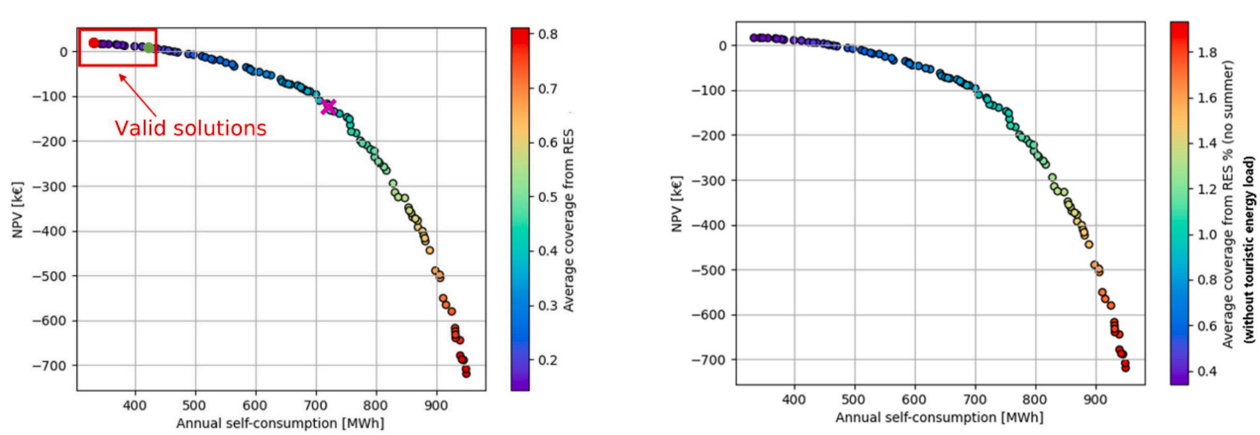

Fig. 6. Pareto front for REC assembly without desalination plant. Solutions are coloured with average coverage of the energy demand of the whole REC (left) and that without the loads associated with summer tourists (right).

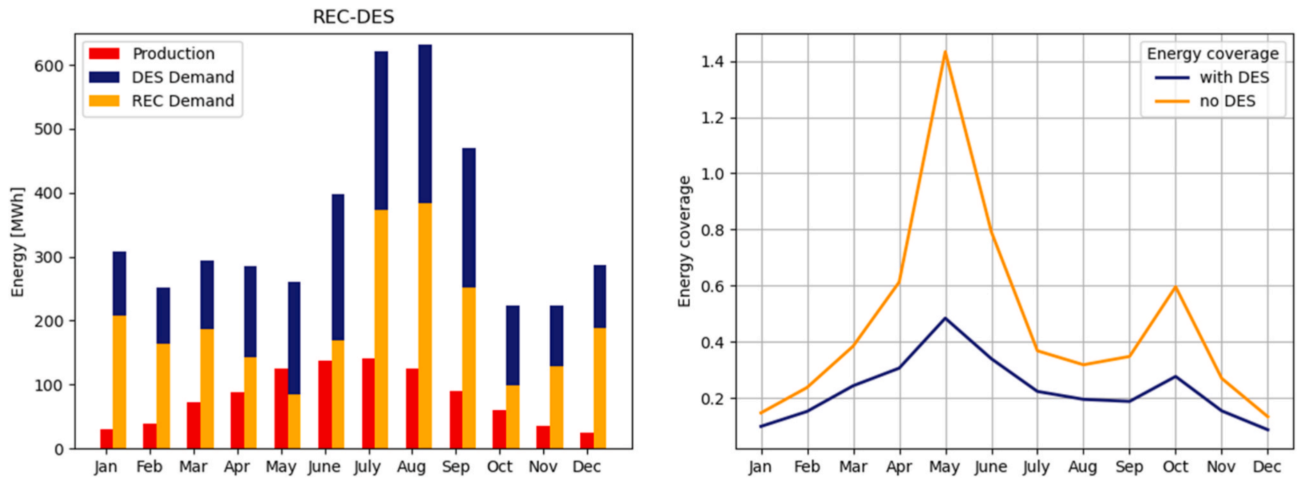

Fig. 8. Energy performance of the REC when operating with and without desalination plant, monthly summary (left) and energy load coverage (right).

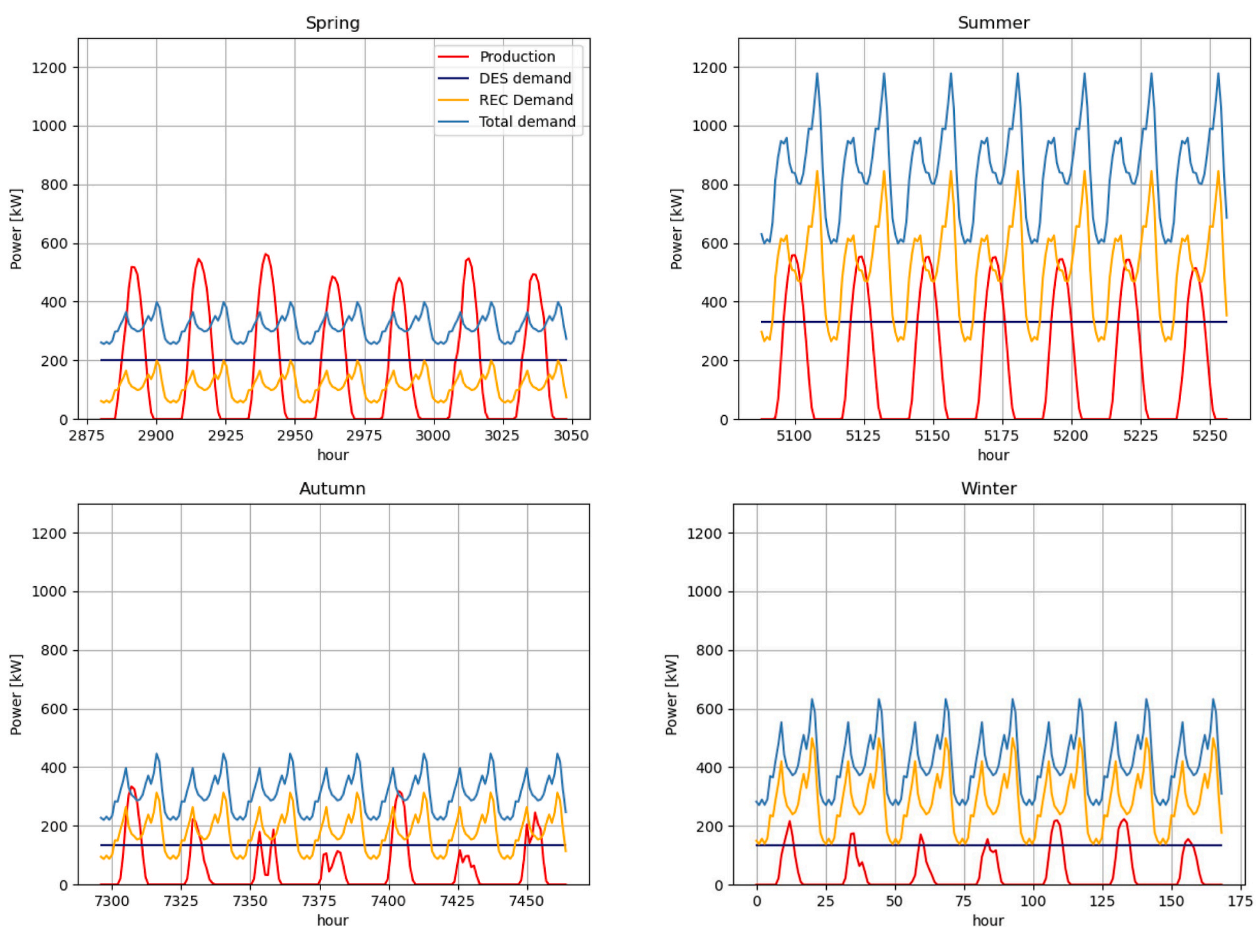

Fig. 9. Energy performance of the REC when operating with and without desalination plant, weekly trends for each season.

months, with both demand and production strongly reduced, while in autumn the conditions are like those of spring, in terms of power demand, but can be strongly affected by adverse weather/irradiance conditions for the production of PVs.

The water supply scenario is summarized in Figs. 10 and 11. The main advantage of the introduction of the DES is the strong reduction of the dependence on mainland supply as in this scenario this is required only during summertime at peak touristic season. The DES and the storage tank are in fact able to provide enough water to cover the demand for the rest of the year. The control logic implemented results in 2–5 units being active during the year, corresponding to the water production shown in Fig. 10 right. In the same figure water fluxes from and to the storage system are shown and it is evident how the tank is used continuously during the year.

The controller logic mode during the year is shown in Fig. 11, with different modes summarized in the flow chart of Fig. 3, that highlight charges (mode 1,2,4) and discharges (mode 6) of the tank all around the year, the water deficit during summertime (mode 3 and 5). Mode 7 – a

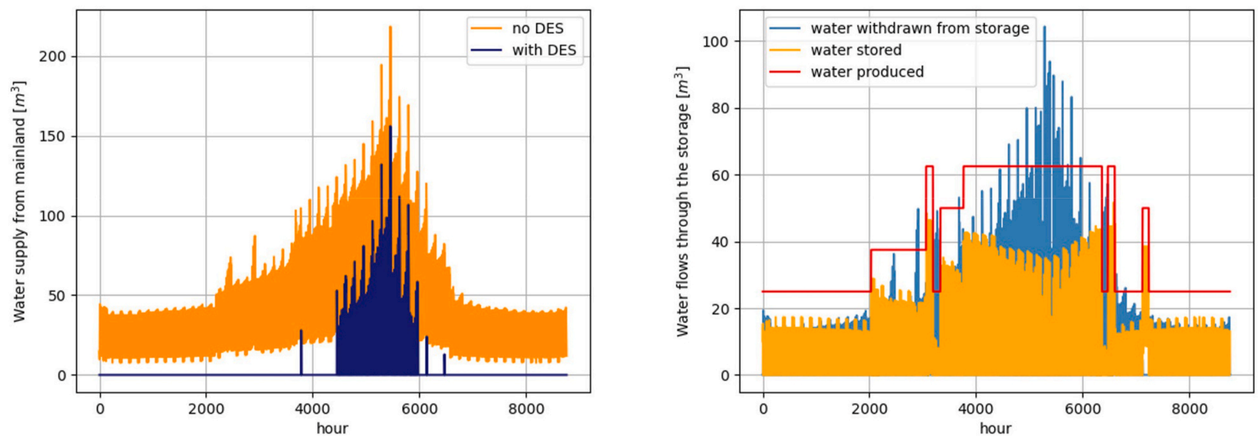

Fig. 10. Water supply from mainland (left) and water fluxes from and to the storage tank (right) for 1-year operations.

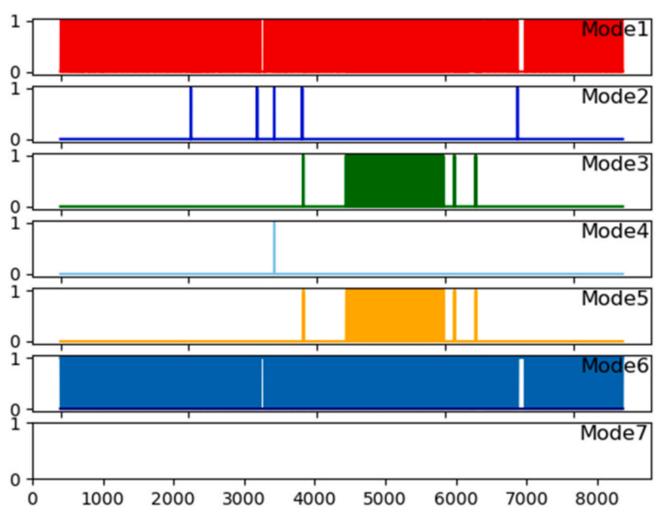

Fig. 11. Controller logic (right) for 1-year operations.

Table 3
REC performance.

	DES powered by Diesel gensets	REC w/o DES	REC with DES
Supply from mainland [1000 m^3]	34	388	34
DES water production [1000 m^3]	354	–	354
Electricity withdrawn from the grid by DES [MWh]	1876	–	1679
CO_2 emissions from water supply [tons CO_{2eq}]	228	2602	228
CO_2 emissions from water production [tons CO_{2eq}]	813	–	727
Total CO_2 emissions [tons CO_{2eq}]	1041	2602	955
REC energy production [MWh/year]		968	968
REC energy demand [MWh/year]		2379	2379
Self-consumption [MWh/year]	–	730	927
Surplus energy [MWh/year]	–	238	41
Initial investment [k€]	1200	1200	1200
Return on tariff [k€]		113	144
Awards on self-consumption [k€]		1518	1926
Revenues from the sale of surplus energy [k€]		234	42
NPV [k€]		−134	34

decrease of DES load due to 100% full tank is never achieved.

The overall performance of the two different scenarios is summarized in Table 3, together with the performance of the DES driven by the Diesel gensets already available on the island.

6. Conclusions

Dealing with isolated power systems of minor Mediterranean islands is necessary to address the challenges of clean energy transition. These power systems in fact heavily rely on fossil fuels and the intricate legal scenario limits the selection of RES mostly to PV systems. Even if these have the advantage of increasing their production in summertime, when the load on the island is higher, the increase in production is not able to withstand the increase in load associated with tourism.

In this scenario the current REC economical model was tested showing that on an island like Ponza, with a limited mix of prosumers and industrial activities, it is difficult to assemble REC able to self-sustain its capital costs, mostly because of a surplus of energy production during spring and autumn that corresponds to a low tariff from the TSO. However, these islands usually don't have direct access to clean water and rely on supply from the mainland. This means that the introduction of a desalination plant with a storage system in the REC can help increasing self-consumption and in so doing the NPV of the REC and at the same time it can have a significant impact in reducing more than 60% of CO_2 emissions for water supply, with a further 10% cut of emissions related to Diesel gensets.

Even in these conditions, however, the scenario could be perfected. From a technical point of view, in fact, the REC could be extended to different communities of Ponza, maybe also to the whole island. The excess of electric load from the DES is in fact sufficient to stabilize the self-consumption of a much larger REC. From a social point of view the REC model implies also different strategies that could be related to services to the local community and, since part of the problems come from the number of summer tourist, strategies to remunerate the REC could involve the tourism on the island. Finally, the current Diesel genset scenario benefit from special tariffs for power generation that compensate the oversized system required for summertime operations. A possible way to promote RECs is to study a similar system for RECs on minor islands with better incentives with respect to those on the mainland. Further extension of this work could be the inclusion within the REC of the whole Ponza residents and small-sized enterprises. Finally, since the REC legislation leaves the redistribution of incentives within the users to private agreements, a deeper investigation of the revenue sharing between prosumers and consumers would be necessary to understand how revenue should be split to cover capital costs of prosumers. The methodology proposed to investigate the energy and economics of the REC is general and relies on transient modelling of the energy system. For different applications, minor changes are required to the financial module to account for local tariffs or different incentive schemes. Further applications however can include different technologies and control strategies. In this case the major changes required are related to adjust the control logic described in Fig. 3 to account for different energy conversion and storage systems, and. To tackle this problem, we are currently working on an improved controller based on reinforced learning, able to learn how to control the system.

This method and the pyRES software can be used to design and optimize a REC and to simulate different power and storage scenarios, including thermal loads. They can be used to provide information to local governments that plan to increase the number of RECs on the territory – this work is in fact financed by Regione Lazio (the regional government for Rome area in Italy), that decided to help stakeholders like municipalities, schools, churches, technicians and engineers or simple citizens in assembling their local REC. A user-friendly and simplified version of the code will in fact be made available in the near future to possible stakeholders to help them in sizing and planning new RECs. Further stakeholders include banks, that finance installations of PV and other renewables, small, medium and large enterprises, that want to reduce their energy costs and carbon footprint increasing their quota of renewable energy creating a REC with their neighbours.

CRediT authorship contribution statement

Alessandro Corsini: Funding acquisition, Supervision. **Giovanni Delibra:** Conceptualization, Methodology, Writing – review & editing. **Isabella Pizzuti:** Methodology, Software, Validation, Visualization, Formal analysis, Writing – original draft. **Erfan Tajalli-Ardekani:** Software.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

Acknowledgements

This work received fundings from *Regione Lazio*under the collaboration agreement between Regione Lazio and Dept. of Mechanical and Aerospace Engineering of Sapienza University of Rome on Renewable Energy Communities. Authors acknowledge also the insights gained from attendees and reviewers from the 17th Conference on Sustainable Development of Energy Water and Environment Systems (SDEWES) in October 2022 in Paphos, Cyprus, that have contributed to improve this paper with their comments.

Nomenclature

Abbreviations

DES	DESalination System
GIS	Geographical Information System
REC	Renewable Energy Community
RES	Renewable Energy Source
PV	Photovoltaic

Symbol Unit Quantity

G	[W/m^2] Global irradiance
W_D	[m^3] Water demand
$W_{deficit}$	[m^3] Water required from mainland supply
W_{min}	[m^3] Minimum amount of water stored in the tank
W_{max}	[m^3] Maximum amount of water storable in the tank
W_P	[m^3] Water production
W_{SOC}	[m^3] Water tank state of charge
W_{stored}	[m^3] Water to storage tank
W_{supply}	[m^3] Water supply from storage

References

[1] Seyfettin Vadi, et al., A review on optimization and control methods used to provide transient stability in microgrids, Energies 12 (18) (2019) 3582, https://doi.org/10.3390/en12183582.

[2] Qi Wang, et al., Analysis on the coupling characteristics of frequency stability and voltage stability in weak connected power grid with high ratio of clean energy, Energy Rep. 8 (2022) 1432–1437, https://doi.org/10.1016/j.egyr.2021.11.118.

[3] Simon R. Sinsel, Rhea L. Riemke, Volker H. Hoffmann, Challenges and solution technologies for the integration of variable renewable energy sources—a review, Renew. Energy 145 (2020) 2271–2285, https://doi.org/10.1016/j.renene.2019.06.147.

[4] Marco Antonelli, Umberto Desideri, Alessandro Franco, Effects of large scale penetration of renewables: the Italian case in the years 2008–2015, Renew. Sustain. Energy Rev. 81 (2018) 3090–3100, https://doi.org/10.1088/1742-6596/1868/1/012025.

[5] Baraa Mohandes, et al., A review of power system flexibility with high penetration of renewables, IEEE Trans. Power Syst. 34 (4) (2019) 3140–3155, https://doi.org/10.1109/TPWRS.2019.2897727.

[6] Salman Hajiaghasi, Salemnia Ahmad, Mohsen Hamzeh, Hybrid energy storage system for microgrids applications: a review, J. Energy Storage 21 (2019) 543–570, https://doi.org/10.1016/j.est.2018.12.017.

[7] Piano Nazionale Integrato per l'Energia e il Clima 2030 (PNIEC). https://www.mase.gov.it/energia/energia-e-clima-2030#:~:text=Cos%27è,nostro%20Paese%20verso%20la%20decarbonizzazione. (Accessed 25 June 2023).

[8] P. Lazzeroni, S. Olivero, M. Repetto, Economic perspective for PV under new Italian regulatory framework, Renew. Sustain. Energy Rev. 71 (2017) 283–295, https://doi.org/10.1016/j.rser.2016.12.056.

[9] Decreto ministeriale, Incentives of electricity generation from renewable sources". https://www.gazzettaufficiale.it/eli/id/2019/08/09/19A05099/sga, 2019. (Accessed 5 May 2022).

[10] Clean energy for all Europeans package. https://energy.ec.europa.eu/topics/energy-strategy/clean-energy-all-europeans-package_en. (Accessed 4 January 2023).

[11] Decreto Legge del 30 dicembre 2019, n. 162, convertito nella Legge 28 febbraio, 2020, n.8; normativa integrata poi con la direttiva 318/2020/R/eel del 04 agosto, 2020.

[12] 03/03/2011, n. 2, Attuazione Della Direttiva 2009/28/CE Sulla Promozione Dell'uso Dell'energia da Fonti Rinnovabili, Recante Modifica e Successiva Abrogazione Delle Direttive 2001/77/CE e 2003/30/CE. https://www.gazzettauff

iciale.it/eli/id/2011/03/28/011G0067/sg, 2011. (Accessed 5 May 2022). Available online:.
[13] Vladimir Z. Gjorgievski, Snezana Cundeva, George E. Georghiou, Social arrangements, technical designs and impacts of energy communities: a review, Renew. Energy 169 (2021) 1138–1156, https://doi.org/10.1016/j.renene.2021.01.078.
[14] Binod Prasad Koirala, et al., Local alternative for energy supply: performance assessment of integrated community energy systems, Energies 9 (12) (2016) 981, https://doi.org/10.3390/en9120981.
[15] Matteo Zatti, et al., Energy communities design optimization in the Italian framework, Appl. Sci. 11 (11) (2021) 5218, https://doi.org/10.3390/app11115218.
[16] A. Cielo, et al., Renewable Energy Communities business models under the 2020 Italian regulation, J. Clean. Prod. 316 (2021), 128217, https://doi.org/10.1016/j.jclepro.2021.128217.
[17] Matteo Moncecchi, Stefano Meneghello, Marco Merlo, A game theoretic approach for energy sharing in the Italian renewable energy communities, Appl. Sci. 10 (22) (2020) 8166, https://doi.org/10.3390/app10228166.
[18] Enrique Fuster-Palop, et al., Innovative regression-based methodology to assess the techno-economic performance of photovoltaic installations in urban areas, Renew. Sustain. Energy Rev. 149 (2021), 111357, https://doi.org/10.1016/j.rser.2021.111357.
[19] A. Bartolini, F. Carducci, C.B. Muñoz, G. Comodi, Energy storage and multi energy systems in local energy communities with high renewable energy penetration, Renew. Energy 159 (2020) 595–609, https://doi.org/10.1016/J.RENENE.2020.05.131.
[20] M. Musolino, G. Maggio, E. D'Aleo, A. Nicita, Three case studies to explore relevant features of emerging renewable energy communities in Italy, Renew. Energy 210 (2023) 540–555, https://doi.org/10.1016/J.RENENE.2023.04.094.
[21] Gina Kallis, et al., The challenges of engaging island communities: lessons on renewable energy from a review of 17 case studies, Energy Res. Social Sci. 81 (2021), 102257, https://doi.org/10.1016/j.erss.2021.102257.
[22] N. Tomin, V. Shakirov, V. Kurbatsky, R. Muzychuk, E. Popova, D. Sidorov, A. Kozlov, D. Yang, A multi-criteria approach to designing and managing a renewable energy community, Renew. Energy 199 (2022) 1153–1175, https://doi.org/10.1016/J.RENENE.2022.08.151.
[23] Y.Q. Ang, A. Polly, A. Kulkarni, G.B. Chambi, M. Hernandez, M.N. Haji, Multi-objective optimization of hybrid renewable energy systems with urban building energy modeling for a prototypical coastal community, Renew. Energy 201 (2022) 72–84, https://doi.org/10.1016/J.RENENE.2022.09.126.
[24] A. Bartolini, F. Carducci, C.B. Muñoz, G. Comodi, Energy storage and multi energy systems in local energy communities with high renewable energy penetration, Renew. Energy 159 (2020) 595–609, https://doi.org/10.1016/J.RENENE.2020.05.131.
[25] Daniele Groppi, et al., A review on energy storage and demand side management solutions in smart energy islands, Renew. Sustain. Energy Rev. 135 (2021), 110183, https://doi.org/10.1016/j.rser.2020.110183.
[26] A. Kasaeian, F. Rajaee, W.M. Yan, Osmotic desalination by solar energy: a critical review, Renew. Energy 134 (2019) 1473–1490, https://doi.org/10.1016/J.RENENE.2018.09.038.
[27] S. Saidi, R. ben Radhia, N. Nafiri, B. Benhamou, S. ben Jabrallah, Numerical study and experimental validation of a solar powered humidification-dehumidification desalination system with integrated air and water collectors in the humidifier, Renew. Energy 206 (2023) 466–480, https://doi.org/10.1016/J.RENENE.2023.02.048.
[28] M. Abedi, X. Tan, J.F. Klausner, A. Bénard, Solar desalination chimneys: investigation on the feasibility of integrating solar chimneys with humidification–dehumidification systems, Renew. Energy 202 (2023) 88–102, https://doi.org/10.1016/J.RENENE.2022.11.069.
[29] D. Geng, X. Gao, Thermodynamic and exergoeconomic optimization of a novel cooling, desalination and power multigeneration system based on ocean thermal energy, Renew. Energy 202 (2023) 17–39, https://doi.org/10.1016/J.RENENE.2022.11.088.
[30] A. Dezhdar, E. Assareh, N. Agarwal, A. bedakhanian, S. Keykhah, G. fard, N. yeganeh zadsar, M. Aghajari, M. Lee, Transient optimization of a new solar-wind multi-generation system for hydrogen production, desalination, clean electricity, heating, cooling, and energy storage using TRNSYS, Renew. Energy 208 (2023) 512–537, https://doi.org/10.1016/J.RENENE.2023.03.019.
[31] A.M. Pietrasanta, S.F. Mussati, P.A. Aguirre, T. Morosuk, M.C. Mussati, Water-renewable energy Nexus: optimization of geothermal energy-powered seawater desalination systems, Renew. Energy 196 (2022) 234–246, https://doi.org/10.1016/J.RENENE.2022.06.146.
[32] Alessandro Corsini, Eileen Tortora, Sea-water desalination for load levelling of gen-sets in small off-grid islands, Energies 11 (8) (2018) 2068, https://doi.org/10.3390/en11082068.
[33] EU Directive 2018/2001 on the Promotion of the Use of Energy from Renewable Sources, 2018.
[34] EU Directive, 944 on Common Rules for the Internal Market for Electricity and Amending Directive 2012/27/EU, 2019.
[35] DL #183. https://www.gazzettaufficiale.it/eli/id/2021/03/01/21A01259/sg, 31-Dec-2020. (Accessed 4 January 2023).
[36] ARERA. Delibera 4/10/2020—318/2020/R/EEL.
[37] Decreto ministeriale, Individuazione della tariffa incentivante per la remunerazione degli impianti a fonti rinnovabili inseriti nelle configurazioni sperimentali di autoconsumo collettivo e comunità energetiche rinnovabili, 2020.
[38] Matteo Moncecchi, Stefano Meneghello, Marco Merlo, Energy Sharing in Renewable Energy Communities: the Italian case." 2020 55th International Universities Power Engineering Conference (UPEC), IEEE, 2020, https://doi.org/10.1109/UPEC49904.2020.9209813.
[39] Emilio Ghiani, et al., Planning of a smart local energy community: the case of Berchidda municipality (Italy), Energies 12 (24) (2019) 4629, https://doi.org/10.3390/en12244629.
[40] Matteo Zulianello, Valerio Angelucci, Diana Moneta, Energy community and collective self-consumption in Italy, in: 2020 55th International Universities Power Engineering Conference (UPEC), IEEE, 2020, https://doi.org/10.1109/UPEC49904.2020.9209893.
[41] Di Silvestre, Maria Luisa, et al., Energy self-consumers and renewable energy communities in Italy: new actors of the electric power systems, Renew. Sustain. Energy Rev. 151 (2021), 111565, https://doi.org/10.1016/j.rser.2021.111565.
[42] Guglielmina Mutani, Silvia Santantonio, Simone Beltramino, Indicators and representation tools to measure the technical-economic feasibility of a renewable energy community. The case study of villar pellice (Italy), Int. J. Sustain. Dev. Plann. 16 (2021) 1–11, https://doi.org/10.18280/ijsdp.160101.
[43] F. Pedregosa, G. Varoquaux, A. Gramfort, V. Michel, B. Thirion, O. Grisel, E. Duchesnay, Scikit-learn: machine learning in Python, J. Mach. Learn. Res. 12 (2011) 2825–2830, https://doi.org/10.48550/arXiv.1201.0490.
[44] A. Gulli, S. Pal, Deep Learning with Keras, Packt Publishing Ltd, 2017.
[45] M. Abadi, P. Barham, J. Chen, Z. Chen, A. Davis, J. Dean, X. Zheng, Tensorflow: a system for large-scale machine learning, Osdi 16 (2016, November) 265–283, https://doi.org/10.48550/arXiv.1605.08695, 2016.
[46] Julian Blank, Kalyanmoy Deb, Pymoo: multi-objective optimization in python, IEEE Access 8 (2020) 89497–89509, https://doi.org/10.1109/ACCESS.2020.2990567.
[47] TRNSYS 18 User Manual – Standard Component Library Overview.
[48] Kalyanmoy Deb, et al., A fast and elitist multiobjective genetic algorithm: NSGA-II, IEEE Trans. Evol. Comput. 6 (2) (2002) 182–197, https://doi.org/10.1109/4235.996017.
[49] Alessandro Corsini, Eileen Tortora, Ennio Cima, Preliminary assessment of wave energy use in an off-grid minor island desalination plant, Energy Proc. 82 (2015) 789–796, https://doi.org/10.1016/j.egypro.2015.11.813.
[50] Young M. Kim, et al., Overview of systems engineering approaches for a large-scale seawater desalination plant with a reverse osmosis network, Desalination 238 (1–3) (2009) 312–332, https://doi.org/10.1016/j.desal.2008.10.004.
[51] Eleeja Shrestha, et al., Carbon footprint of water conveyance versus desalination as alternatives to expand water supply, Desalination 280 (1–3) (2011) 33–43, https://doi.org/10.1016/j.desal.2011.06.062.
[52] EU Directive 92/43/EEC 21st May 1992 on the Conservation of Natural Habitats and of Wild Fauna and Flora.
[53] EU Directive 2009/147/EC 30th November 2009 on the Conservation of Wild Birds.
[54] PVGIS-geographical assessment of solar resource and performance of photovoltaic technology. http://re.jrc.ec.europa.eu/pvgis/. (Accessed 5 May 2022). Available online:.