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Research article

Optimum green energy solution to address the remote islands' water-energy nexus: the case study of Nisyros island

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HIGHLIGHTS

- The energy needs of Nisyros island along with its water scarcity issues are analyzed.
- Green electrification of a remote island's desalination units can be achieved using the local RES-potential.
- Economic and environmental benefits can accrue from the exploitation of PV-based installations in insular locations.

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ABSTRACT

A great number of islands are dispersed across the Aegean Archipelagos, most of which have restricted water resources, affecting in this way the economic growth of local societies. To confront this issue, the solution addressed by the relevant stakeholders is the particularly costly and of questionable quality process of potable water transportation from the mainland using tanker ships. An alternative strategy consists of the deployment of seawater desalination configurations, leading however to a quite notable increase in the pertinent load demand.

Nisyros island is a remote volcanic island, located in the center of the Greek island complex of Dodecanese, in the southeast (SE) Aegean Archipelagos, which is an area characterized by plentiful Renewable Energy Sources (RES). In the present work, a systematic effort to evaluate the per economic sector energy needs of the island and its current water resources status and infrastructure has been conducted. Moreover, the solar energy potential prevalent in the island has been identified. To this end, a PV-based power configuration has been introduced, under the prism of covering in a sustainable way the island's desalination units' energy needs and decrease the environmental burden. The inherent first installation cost estimation reveals the economic benefits that can be attained in such a case. The feasibility of the proposed green energy solution unveils the prospects of comparable applications in relevant remote insular locations.

1. Introduction

The presence of more than 85,000 islands consists a particular trait of the global geography [1]. Among them, approximately 13% are inhabited. Focusing on the Greek region level, the Aegean Archipelagos, located in the East Mediterranean Sea, is an area of great interest, as, according to official data [2], an extensive number of islands (exceeding 2500) forms the landscape, with only 7% of them being inhabited. A semi-arid climate [3], the lack of endogenous conventional energy resources [4] as well as the relatively long distance from the mainland [5] consist their main characteristics.

Owning to the specific climate type, significant water resources scarcity for both domestic and agricultural use is present for the vast majority of small- and medium-sized Aegean Archipelagos islands, deteriorating the life quality of inhabitants, especially during the summer [6]. This can be visualized through the declining tendency that the annual rainfall has shown the past 40 years, being in the order of 22 mm/year for the area under consideration (Figure 1) [7] and can be

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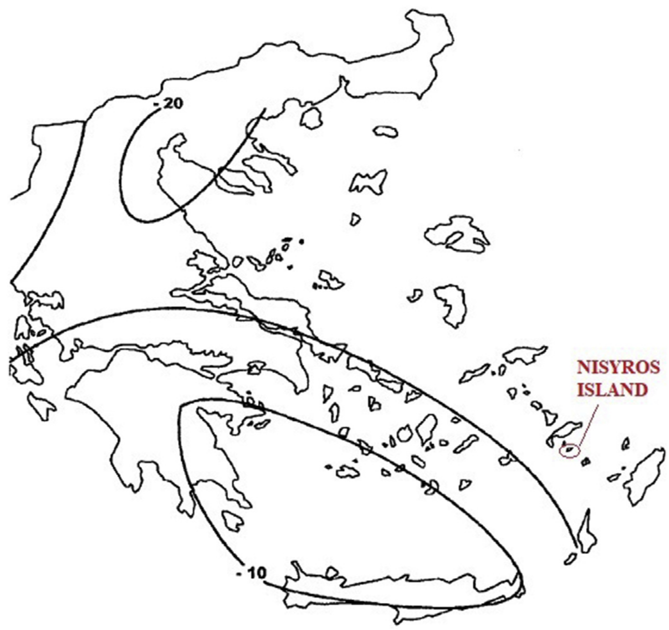

Figure 1. Spatial distribution of the decreasing rainfall tendency in Aegean Archipelagos islands (Figure adapted from Kaldellis et al. [7]).

mainly attributed to the variations in topography that govern the rainfall's distribution [3].

For a more comprehensive analysis, one shall consider also that, in several islands, the situation is even worse as groundwater pollution due to fertilizers of agricultural activities and saltwater intrusion because of coastal aquifers over-exploitation has been noted [8]. Besides, owning to the touristic bloom, the summer average water demand, strongly correlated with the islands' active population, doubles and, in some cases, triples concerning the corresponding annual value [7, 9]. The specific situation jeopardizes the economic development of these remote locations as, on a global level, water is an undisputed contributor to economic progress [10].

The solution addressed by the Greek State in conjunction with the local authorities is the particularly costly and of questionable quality process of potable water transportation from the mainland, using tanker ships [11]. In some cases, the cost may even reach 10 €/m^3 [9]. Under this framework and as an alternative to the aforementioned policy, extended research has been conducted on seawater desalination techniques [12, 13, 14], with the vast majority being classified in two categories based on the energy type implemented, that is the thermally-driven and the electrically-driven ones [15]. Among them, the reverse osmosis (RO) techniques are the most widely adopted and applied in most Aegean Archipelagos islands due to the very high efficiencies attained [16]. Nevertheless, their implementation entails an increase in the local load demand by an average value ranging from 2.5 kWh/m^3 to 7.5 kWh/m^3 [7, 17].

On the other hand, fuel mix diversity can be considered as a prerequisite for a sustainable energy future [18]. Suffice it to say that almost all Aegean Archipelagos islands are characterized by plentiful Renewable Energy Sources (RES) potential [16]. In this framework, the implementation of seawater RO desalination techniques in combination with RES can lead to decreased installation and operation costs and alleviate from the environmental burden associated with the fossil fuels usage [19]. Therefore, it is of paramount importance to pinpoint sustainable electrification alternatives for the specific applications of remote islands to diminish their dependence on fossil fuels imports [20, 21, 22, 23, 24].

Between all RES, solar and wind energy hold the lion's share for powering desalination installations [7, 16, 25]. In this context, the present work investigates a sustainable solution that could be implemented in Nisyros island to electrify the seawater RO desalination units with clean energy originated from locally installed PV systems. The rest of the work is organized as follows: Section 2 sheds light on the current status of Nisyros island and its energy infrastructure, providing details for the specific energy requirements of each economic sector. Moreover, the water resources scarcity as well as the techniques implemented to confront it by the island's authorities is identified. Section 3 gives an overview of the island's solar energy potential. A PV-based proposed configuration is examined in Section 4 from both technical and economic perspectives, setting the groundwork for some useful conclusions and thoughts for future work to be cited in Section 5.

2. The case study of Nisyros island

2.1. Nisyros island current infrastructure

Nisyros island is a volcanic Greek island located between the islands of Kos and Tilos in the center of the Dodecanese island complex, that belongs to the SE Aegean Archipelagos (Figure 2) [26]. Nisyros is 58 knots away from the capital of Dodecanese, that is the Rhodes island. It is surrounded by five islets, out of which the largest is Yali, followed by Pergoussa, Pachia, Strongyli and Kandeleoussa (or Fanari) [27]. It is the tenth largest island of the considered complex, with a total area of 41.2 km^2, while its shape resembles that of a cob cone, having a base diameter of 8 km [28, 29].

Figure 3 depicts the demographic evolution of Nisyros island. According to the relevant census of 1951–2011 [30], there exists a constant population decrease till 1981, when the population was stabilized at the present-day levels, having a small increasing tendency from that year onwards. In 2011, the island's population was 1008 inhabitants. Hence, the equivalent mean annual population, based on which any new electrification infrastructure projects shall be designed, can be estimated at approximately 2000 people (considering also the annual volume of the island's visitors). For better visualization reasons, Table 1 presents the passenger traffic for the port of Nisyros island [28]. The great increase noted during the months from May to September can be attributed to the touristic day ships, from which the passengers transported on a monthly basis range from 6000 (May) to 15,000 (August).

Figure 2. Island complex of Dodecanese in the southeast (SE) Aegean Archipelagos.

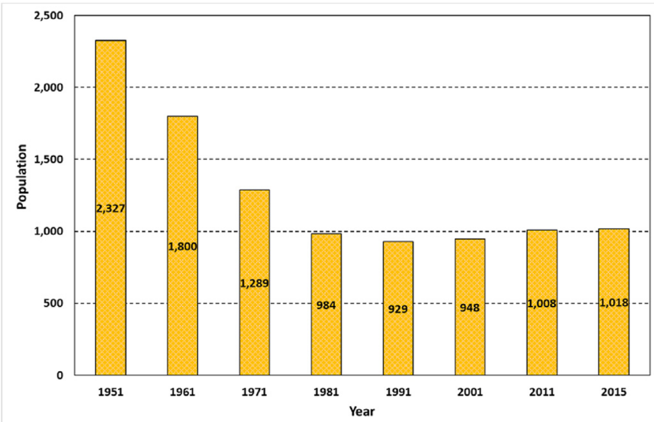

Figure 3. Demographic evolution of Nisyros island (data adapted from HSA [30] and [31]).

Table 1. Passenger traffic of the Nisyros island's port in 2017 [32].

Months	Boarding	Debarkation
January	813	794
February	769	661
March	985	855
April	1,545	1,386
May	7,267	7,134
June	10,493	10,543
July	13,419	13,671
August	18,903	18,438
September	10,512	10,343
October	4,964	4,947
November	1,275	1,132
December	1,107	1,003
Total	**72,052**	**70,907**

2.2. Energy requirements of Nisyros island

A breakdown of the island's energy requirements to the relevant contributing economic sectors is of paramount importance, as it could unveil the sectors where targeted interventions could be implemented. Figure 4 depicts the per economic sector overall energy consumption of Nisyros island during the past decade (2010–2019). Useful remarks can be noted in this context:

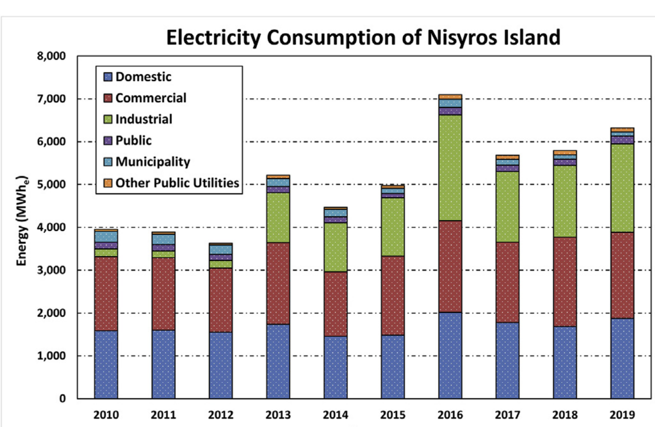

Figure 4. Electricity consumption distribution per economic sector of Nisyros island during the time-period 2010–2019 (Data used: HEDNO [33]).

- A significant fluctuation, which seems to flatten in the years 2017–2019, characterizes the island's total annual electricity consumption, with the last record outreaching the value of 6200 MWh$_e$.
- The domestic, the commercial and the industrial are the main contributing economic sectors to the island's total annual energy requirements, with the public buildings, the municipal lighting and the public entities energy consumption representing approximately 6–7%. The relevant values are accumulated in Table 2.
- The industrial sector's annual electricity consumption presents specific interest as it has noted a substantial increase over the previous years. This can be mainly attributed to the operation of the island's seawater RO desalination units (installed at the island's capital suburbs) that corresponds to approximately 90% of the specific sector's energy requirements. In this framework, it is worthwhile to notice that a characteristic feature of the seawater RO desalination units' operation is the constant power demand throughout the entire 24-hours period of the working days (Monday-Friday), strongly correlated with the constant requirements for potable water provision by the local inhabitants. Hence, the seawater RO desalination units' operation does not affect the island's peak power demand.

Following the previous analysis it can be inferred that dedicated interventions implemented in the three main contributing economic sectors under the scope of energy saving and rational energy use in conjunction with the installation of RES-based and environmentally friendly power stations could alleviate the local inhabitants from both direct and indirect environmental impacts and enhance the island's energy security. Accordingly, economic benefits could also be attained.

2.3. Water supply status of Nisyros island

The Nisyros island's underground and surface waters are remarkably affected by its special geomorphology, with volcanic sulfur rocks and minerals being prevalent throughout the island's territory. Moreover, the absence of water wells reveals that the local inhabitants have ceased their efforts to discover potable water resources. On the other hand, most households are equipped with private rainwater harvesting tanks (with a capacity in the range 5–15 m^3) to cover the irrigation needs of small area crops, as is also valid for the majority of other Aegean Archipelagos islands [6]. These private rainwater harvesting tanks are also fed on a weekly basis by the island's seawater RO desalination units.

A municipal water tank with a capacity equal to 1000 m^3 covers the water needs of the island's capital inhabitants. There also exist two additional water tanks with capacities equal to 500 m^3 and 300 m^3 that satisfy the water needs of Nikia and Emporios villages, respectively. The latter are also filled in with desalinated water generated at the relevant units installed at Mandraki village via municipal water trucks. Lastly, a relevant municipal water tank with a capacity equal to 500 m^3 is installed at Paloi village to cover the local inhabitants' water needs.

The previous analysis has shed light on the severe water scarcity issues that Nisyros island faces, which also affect the island's economic growth. That was the principal reason that led the relevant stakeholders to proceed with the installation of three seawater RO desalination units. The first two units, each one with a capacity equal to 350 m^3/day, were

Table 2. Annual energy requirements per economic sector of Nisyros island.

Economic sector	Energy requirements (MWh$_e$/year)
Domestic	1,500–1,600
Commercial	2,200
Industrial	2,000
Other sectors (Public buildings, municipal lighting, public entities)	400–500
Total	**6,200**

installed in 2013 and 2016, correspondingly, leading to a pertinent increase in the island's annual energy consumption from these years onwards. The problems noted in the normal operation of the considered units in the following two years jeopardized the island's water resources adequacy. In this context, a third unit, with a capacity equal to 300 m^3/day, was installed in 2019 in order to complement the island's required water quantities. Thus, the full load operation of the three aforementioned units can generate totally 1000 m^3 of potable water per day [34]. It is worth mentioning that the decentralized installation option, that is with the equipment enclosed in compact containers, has been implemented in the case of Nisyros island (Figure 5).

Following the previous analysis, it can be inferred that approximately 500–600 m^3 of potable water per day can be generated by the 24-hours operation of the considered seawater RO desalination units during the working days (Monday-Friday) of the summer period, whereas an amount of 1000 m^3 can be simultaneously stored to cover the water needs during the weekends. The lack of the touristic activity during the winter is the root cause of the limited water needs (being in the order of 200–350 m^3/day) compared to the summer ones. Thus, during the winter period, the operation of only one out of three units can be considered sufficient to cover the water needs of the local inhabitants.

Combining the previous data for the summer and winter periods, the average daily production of the seawater RO desalination units' installation can be estimated at 300–400 m^3 of potable water on an annual basis or equivalently, the total annual production is estimated in the order of 100,000 m^3 to 150,000 m^3. Hence, considering also the energy requirements for the operation of the seawater RO desalination units, the per m^3 of potable water energy requirements are calculated in the range 10–12 kWh_e.

3. Solar energy potential of Nisyros island

A weather station, operating under the supervision of the National Observatory of Athens (NOA) from May 2017 [35], has been installed at the roof of a guest house, located near the port of Mandraki village at 5 m height above the ground level. The installation consists of specialized sensors and equipment that transfer critical parameters through communication protocols to NOA's database on a 10-minutes time interval. The technical characteristics of the aforementioned sensors, that is the sensors' type, range, resolution, accuracy and update interval, can be found in Lagouvardos et al. [36]. Thus, following a dedicated statistical process of the local weather station raw data, the island's solar energy potential could be unveiled, whereas useful indications could be retrieved concerning the available wind energy potential. Besides, a reliable identification of the geothermal energy potential can be made on the basis of relevant available scientific works. Finally, the local biomass potential is not considered sufficient to be exploited for power generation scope [37, 38].

Figure 5. Internal view of a containerized seawater RO desalination unit.

On the other hand, the implementation of new wind power plants has often met serious hostility from the local societies [39, 40]. In the same framework, past attempts made by the Public Power Corporation (PPC) of Greece and PPC Renewables (PPCR) to exploit the abundant geothermal energy field of Nisyros island have not thrived, mainly due to the concerns raised and ultimately, the prohibition originated from the local community. It is noteworthy that the aforementioned concerns have been significantly increased, following the operation and shutdown of the geothermal power plant that was installed at Milos island [41]. Thus, in the present work, only solar-based solutions for the electrification of the seawater RO desalination units will be examined.

The periodic character of the island's solar energy potential is unveiled in Figure 6, which depicts the solar radiation variation on the horizontal plane (expressed in W/m^2) for Nisyros island during the time-period May 2017–April 2020. In addition, Figure 7 gives an overview of the mean monthly solar radiation values on the horizontal plane for the entire aforementioned time-period, underlining their intrinsic uniformity.

The total annual solar radiation values on the horizontal plane that Nisyros island "faced" during the years 2018 and 2019, when complete raw data time-series were available, are 2460 kWh/m^2 and 2520 kWh/m^2 correspondingly. The slight discrepancy between the two previous values pinpoints the island's excellent solar energy potential. Consequently, the aforementioned uniformity justifies as reasonable the exploitation of the available solar radiation raw data time-series during the sizing procedure of a potential photovoltaic (PV) array installation, implemented as a possible solution for the green electrification of the island's industrial sector.

4. Proposed integrated solution for the industrial sector of Nisyros island

4.1. Capacity Factor (CF) calculation

Following the analysis carried out in the previous Sections, the exploitation of Nisyros island plentiful solar energy potential can be considered a sustainable solution in order to diversify the island's energy consumption mix and cover its energy requirements in a sustainable manner. Hence, the prospect of installing a PV power station could be further investigated. A thoroughly designed assessment procedure shall be adopted, during which the solar radiation raw data will be imported into dedicated simulation tools to evaluate the finally exploitable solar energy potential. In this framework, the solar radiation raw data retrieved from the local weather station could be utilized [35]. For the specific study, the average values of the solar radiation time-series of years 2018 and 2019 will be used, as complete dataset values are available for them. Thus, applying a statistical analysis of the local solar energy potential raw data and using typical power curves as well as the corresponding technical specifications of existing commercial PV panels, one may estimate with acceptable accuracy (for a preliminary evaluation) the expected energy generation and the CF value, on the basis of the available detailed measurements.

To this end, Figure 8 gives an overview of the pertinent simulation results calculated after importing the aforementioned data into an in-house developed calculation tool [14, 42]. The results obtained present only slight discrepancies with the ones attained by a relevant analysis on the online simulation tool PVGIS [43].

Given the excellent island's solar energy potential, it is indisputable that the considered energy needs could be covered with PV installations dispersed throughout the complete island's territory and not only with a PV installation consisted of PV modules concentrated in a specific area. Thus, the simulation results in Figure 8 present the per MW_p installed proposal for the exploitation of a PV system. To highlight the previous analysis, Figure 9 presents the solar radiation histogram of Nisyros

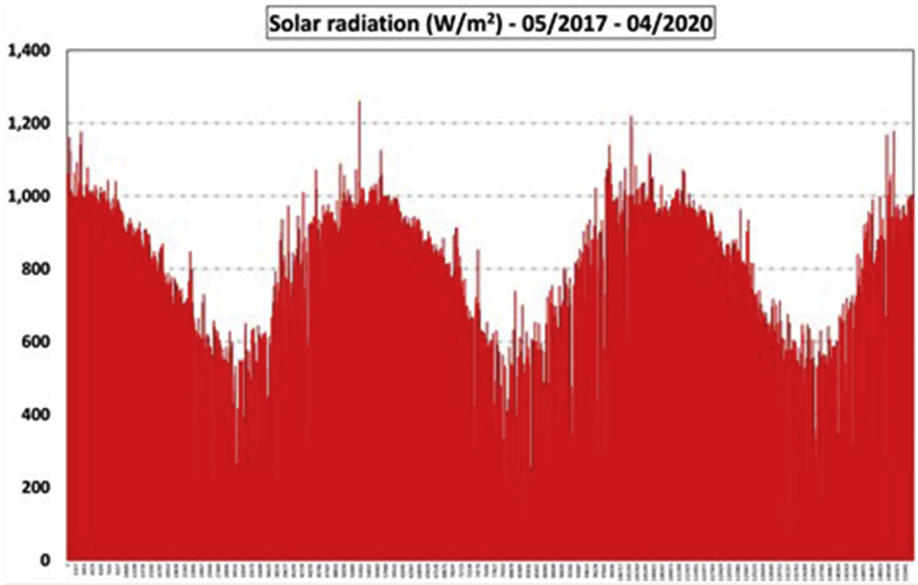

Figure 6. Solar radiation variation (expressed in W/m^2) during the time-period May 2017–April 2020, following the recorded at Nisyros island's weather station raw data statistical process (Data used: NOA, 2020 [35]).

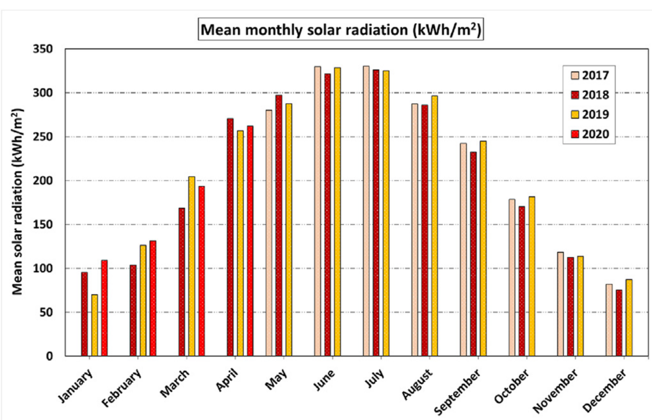

Figure 7. Mean monthly solar radiation values on the horizontal plane for May 2017–April 2020 (Data used: NOA, 2020 [35]).

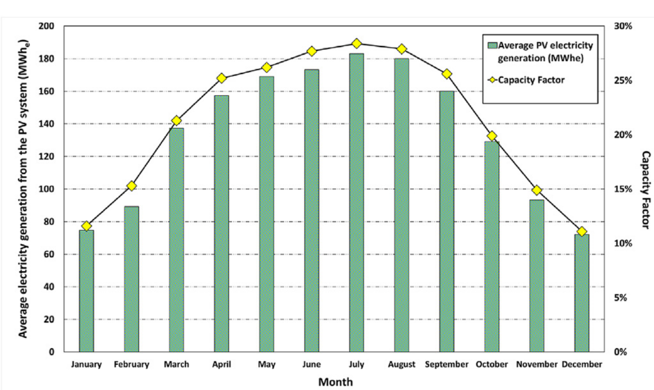

Figure 8. Simulation results for a proposed 1 MW_p PV power plant in Nisyros island.

island's weather station raw data versus non-dimensional typical power-solar radiation curve of a typical commercial PV panel with peak power in the range 250–400 W_p.

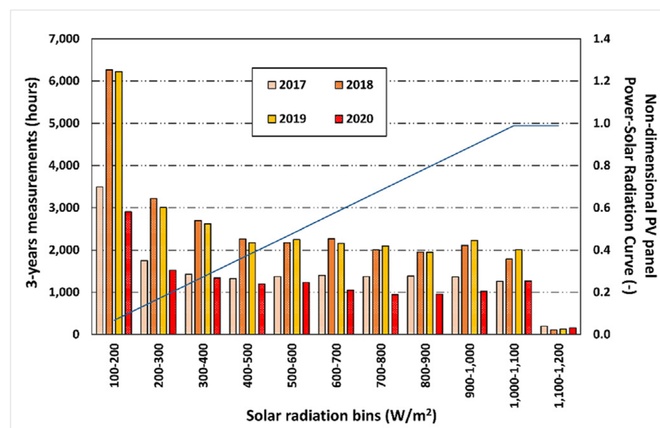

Figure 9. Solar radiation histogram (based on three-years measurements on a 10-minutes basis) versus non-dimensional typical power-solar radiation curve of a typical commercial PV panel at standard day conditions.

The results that have been generated for the CF values are representative of a noteworthy typical PV power system, with typical CF values in the range between 10 and 25% [44]. More specifically, for the summer months (March to October), there have been calculated CF values approximating the highest typical values for such systems (22–25%), while correspondingly, for the winter months (November to February), the corresponding CF values approximate the lowest typical values for such systems (10–15%).

Summarizing, the annual CF has been calculated equal to 21.3%, emphasizing in this way the plentiful solar energy potential that characterizes Nisyros island as well as the promising prospects of a potential PV installation with technical specifications relevant to the ones considered during the specific approach.

4.2. Sizing results

The annual energy requirements of the industrial sector of Nisyros island approach 2000 MWh_e, out of which approximately 90% are related to the operation of the island's seawater RO desalination units, that is 1800 MWh_e, while the rest amount (in the order of 150–250

MWh_e) corresponds to basic industrial applications taking place in the island.

The electrical energy yield of a PV power station can be calculated using Eq. (1) [45], i.e.:

$$E_{PV} = CF_{PV} * P_{PV} * \Delta t \tag{1}$$

where: P_{PV} is the power station's rated power.

Δt is the examined time-period (e.g. equal to 8760 h for one-year time-period).

Considering typical values for the inherent conversion parameters (see Table 3), the PV power station required nominal Alternating Current (AC) capacity will be approximately equal to:

$$P_{PV,AC} = 970 kW \tag{2}$$

whereas the Performance Ratio (PR) and the relevant Direct Current (DC) value for the nominal capacity will be approximately equal to:

$$PR = 0.85 \tag{3}$$

$$P_{PV,DC} = \frac{P_{PV,AC}}{PR} = 1,140 kW \tag{4}$$

Hence, a PV power system with nominal capacity equal to 1140 kW_p shall be installed to achieve the green electrification of Nisyros island's seawater RO desalination units. Figure 10 depicts an overview of the relevant units installation. The red-marked area designates the position of the desalination units facilities, whereas the green-marked one visualizes an indicative location for the installation of PV systems.

4.3. Land requirements

It is of profound importance to identify suitable land areas where the installation of such PV systems could be realized. A dedicated thorough pre-assessment and quest for land availability shall be conducted by the relevant stakeholders in order to electrify in a sustainable manner the island's desalination units. In this context, a consultation of Nisyros island's land uses database, such as the one that is based on the European Union's programme "CORINE" map [47], shall precede. Moreover, the proprietary rights of the available land areas shall be clarified and in case that no sufficient land availability pre-exists, further quest for suitable areas should follow.

Furthermore, the per installed kW_p land area required $S_{PV/kWp}$ depends strongly on the technology that will be selected for the PV modules construction, that is mono-crystalline c-Si, poly-crystalline c-Si, thin-film, e.t.c. [48]. Typical values in the range 10 m^2/kW_p and 14 m^2/kW_p can be found in the literature. Thus, considering the lower limit of the aforementioned variation, the land requirements S_{PV} for the installation of PV power systems deployed to cover the electrification needs of Nisyros island's seawater RO desalination units will be equal to:

$$S_{PV} = S_{PV/kWp} * P_{PV} = 11,400\ m^2 = 1.14\ hectares \tag{5}$$

4.4. First installation cost preliminary analysis

Table 4 gives an overview of the per kW_p installed DC power economic parameters that could be used for a preliminary calculation of the PV-based proposed configuration's cost [14, 49]. Note that the specific economic values are only rough estimations being influenced by several parameters and for this specific preliminary financial analysis have been assumed as turnkey prices. Hence, special attention should be given in order to consider the remote character of the specific application and the limited size of the proposed configuration, meaning that no economies of scale can be attained.

Adding up the corresponding constituents, the total specific turnkey cost is calculated in the order of 1600 €/kW_p. Thus, considering the PV power station required nominal DC capacity, a total first installation cost approximately equal to 1.82 M€ can be estimated. The aforementioned value is not prohibitive, as it can be easily countervailed by the expenditures pertinent to the electrification needs of the examined seawater RO desalination units. Hence, proceeding with a rough estimation, the potential project developer could secure a Simple Pay-Back Period (SPBP) of less than seven years [49].

For a comprehensive analysis, one can estimate the pertinent environmental benefit that can accrue from the examined PV configuration. Hence, considering that approximately 700–800 kg of CO_2 equivalent are emitted per MWh_e generated by the operation of diesel oil-based APS [50], the relevant amount of annual CO_2 savings could be raised up to 1260–1440 tonnes.

Table 3. Typical values for the parameters considered to calculate the PV power station nominal capacity.

Parameter	Typical value	Reference
PV modules nominal efficiency	16%	IFC [46]
PV inverter energy losses derate factor η_{PV_inv}	96.5%	Kaldellis et al. [42]
DC and AC wiring losses derate factor η_{wiring}	98%	Kaldellis et al. [42]
Heterogeneity losses derate factor $\eta_{heterogeneity}$	99%	Kaldellis et al. [42]
Diodes energy losses derate factor η_{diodes}	99%	Kaldellis et al. [42]
Shading energy losses derate factor $\eta_{shading}$	95%	Kaldellis et al. [42]
Temperature losses derate factor $\eta_{temperature}$	96%	Kaldellis et al. [42]

Figure 10. Overview of the seawater RO desalination units installation at Nisyros island. Reproduced from Google.

Table 4. Economic parameters considered for the PV-based proposed configuration economic analysis.

Economic parameter	Value (€/kW_p)
PV modules supply specific turnkey cost	700
Power electronics supply specific turnkey cost*	300
Infrastructure works specific turnkey cost	600

* The DC and AC wiring costs as also the costs for any supplementary electrical and electronic equipment are included in this parameter.

5. Conclusions

Nisyros is a remote volcanic island of the Dodecanese complex in the Aegean Archipelagos. A systematic attempt has been made to shed light on the island's infrastructure and current energy status, analyzing the energy needs of its main contributing economic sectors. Besides, based on data retrieved from dedicated sensors permanently installed in the local meteorological station, the island's abundant solar energy potential was revealed. Due to the severe water deficit issues that the island has dealt with the past decade, three seawater reverse osmosis desalination units have been installed at the island's capital.

The present work investigated the possibility of covering the energy requirements of these desalination units in a sustainable manner, proposing the installation of photovoltaic power stations throughout the island's territory. Under the specific approach, a first estimation concerning the Capacity Factor of the pertinent installation has been carried out. Furthermore, preliminary remarks have been drawn to identify the potential land requirements as also the correlated with the aforementioned implementation first installation cost. Finally, the pertinent environmental benefit was also calculated.

The significant land requirements intrinsic to a PV-only based solution could jeopardize the success of the considered implementation. Alternative solutions, such as hybrid power plants, could be investigated instead for the energy target to be attained, designating the high-quality RES potential of the island and its suitability for energy generation purposes. The last approach could be adopted under the precondition that a suitable siting process and a dedicated consultation with the local society and stakeholders would precede, targeted to smoothen any possible reactions from the local inhabitants. In such a case, the optimum design of the necessary infrastructure works across the complete island's territory from a technical, economic as well as from an environmental viewpoint could be revealed, identifying the most efficient local energy generation mix.

The integration of power electronics and energy storage facilities into the proposed configuration would consist a further upgrade of the island's energy status, bolstering its energy autonomy. In this context, a dedicated techno-economic analysis would be necessitated in order to clarify the relevant aspects of the specific approach. Moreover, the adoption of advanced Demand Side Management (DSM) techniques in the proposed configurations would stimulate the power reliability of consumers. In any case, the sustainable character of the proposed solution enhances its attractiveness and sets the foundations for its implementation in islands of comparable specifications in the wider Mediterranean region.

Declarations

Author contribution statement

Christofis Koroneos & Panagiotis Kollas: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Panagiotis Triantafyllou, Emilia Kondili, Dimitrios Zafirakis, Panagiotis Ktenidis & John K. Kaldellis: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

The data that has been used is confidential.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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