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Off-Grid Methodology for Sustainable Electricity in Medium-Sized Settlements: The Case of Nisyros Island

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Abstract: As a crucial strategy for mitigating climate change and achieving electricity independence, renewable energy sources (RESs) are gaining widespread importance. This study explores achieving electricity autonomy for Nisyros Island, Greece, through RESs. Four scenarios are evaluated, including standalone wind and photovoltaic systems, alongside hybrid options combining both. Each scenario is designed to meet the island's electricity demands while considering economic feasibility and minimal environmental impact. The research findings are that wind-based scenarios offer the most cost-effective solutions, with a three wind turbine setup emerging as the most economical option for full coverage of electricity demands. Hybrid approaches, particularly those incorporating more wind turbines, are also financially viable. Real-world consumption data are integrated into the analysis, providing valuable insights for Nisyros' energy future. Overall, the study demonstrates Nisyros' potential to achieve electricity independence through RESs, with wind resource assessments suggesting that the island could become autonomous. This approach would promote environmental sustainability by reducing the given dependence on fossil fuels. Additionally, it would bring economic benefits for the island's residents in the renewable energy sector. Furthermore, this work allows for the island to achieve electricity independence through renewable energy in alignment with the EU's climate goals.

Keywords: Nisyros island; moderate population; off-grid power production; autonomous island; energy policy

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1. Introduction

Global warming, primarily driven by greenhouse gas emissions such as CO_2 from fossil fuel consumption, presents a critical challenge to humanity [1]. Without effective mitigation, global temperatures are projected to rise by 3–10 °C by 2100. Transitioning to renewable energy sources (RESs), particularly solar and wind energy, is essential for reducing emissions. These technologies, including photovoltaic systems and wind turbines, produce significantly fewer greenhouse gases compared to conventional electricity generation processes [2–4].

The variability of RESs requires hybrid systems that integrate multiple energy sources with storage solutions, such as batteries, to ensure a continuous electricity supply, particularly in remote areas [5,6]. These systems reduce dependence on fossil fuels, lower electricity costs, foster job creation, and enhance energy security [7–9]. Technological advancements are expected to further decrease costs, making hybrid systems increasingly economically viable [10,11].

Innovations in autonomous electricity production via RESs offer promising pathways for sustainable energy, particularly in off-grid settings [12]. Recent studies have explored hybrid systems that combine renewable technologies for electricity, hydrogen, and freshwater production [13]. For instance, techno-economic analyses have highlighted the viability of hybrid PV-WT-PSH/BB systems for meeting varying energy demands in remote areas [14,15]. Furthermore, optimization studies in Indonesia and similar regions underscore the importance of hybrid designs tailored to local conditions [16,17]. Advanced software tools like HOMER further enable the design of optimized energy systems based on economic and resource factors [18].

Case studies demonstrate the effectiveness of hybrid systems. In Denmark, hybrid PV–wind systems with battery storage have demonstrated improved energy management efficiency, reducing operational costs and enhancing sustainability [19]. In Indonesia, hybrid photovoltaic systems have proven to be 19% more cost-effective than diesel generators, showcasing their economic advantages [20]. Research on hybrid energy systems in India, Colombia, and South Africa highlights their potential for rural electrification and emission reduction [21–23]. These systems also reduce reliance on single energy sources, mitigating inefficiencies caused by seasonal fluctuations in solar radiation and wind availability [24]. Additionally, advanced sizing and optimization methods for hybrid PV–battery–wind–diesel microgrid systems further enhance cost efficiency and reliability in off-grid applications [25].

Hybrid systems, despite their higher initial investment costs, offer substantial long-term benefits. Research conducted in Asiatic countries like Jordan and Oman highlights their capacity to enhance reliability, reduce emissions, and lower operational costs [26,27]. Moreover, integrating renewable technologies such as PV–diesel and wind–diesel systems into hybrid designs further improves their performance and economic feasibility in remote regions [28].

In conclusion, these studies collectively underline the benefits of employing hybrid energy systems, which effectively reduce operating costs, environmental impact, and carbon emissions. The selection of the optimal system hinges on various factors, including local electricity resource potential, available incentives, and the specific requirements of the area. Hybrid systems present a promising solution for improving electricity accessibility and sustainability in remote and off-grid regions. However, the aforementioned research studies demonstrate certain weaknesses, primarily related to data, methodology, and research priorities. Many analyses focus on regions located at different geographic latitudes and longitudes, each characterized by unique physical attributes, levels of economic development, and access to technologies and methodologies. A common thread is the absence of land use or spatial data analyses and the lack of precise demographic data regarding electricity consumption.

Recent reviews on sizing approaches for solar photovoltaic-based microgrids highlight the critical need for accurate system dimensioning to optimize cost efficiency and reliability [29]. Similarly, studies on limited-size battery energy storage systems (BESS) have demonstrated their effectiveness in mitigating the impact of renewable energy source volatility in grid-tied microgrids, particularly in developing regions [30]. These works provide valuable insights into addressing key challenges in hybrid system design, such as storage integration and resource variability, ensuring resilience and scalability in diverse geographical contexts.

While the primary goal is to develop cost-effective energy systems with minimal environmental impact, many studies advocate for a hybrid approach that combines renewable and conventional fuels. Remote areas often face high grid extension costs; therefore, off-grid renewable energy systems provide a viable and scalable solution. For instance, a hybrid system implemented in Pakistan successfully delivered clean and affordable electricity to rural villages [31].

In addition to Pakistan, research conducted in Canada, India, Indonesia, and Colombia highlights the benefits of hybrid renewable energy systems combined with diesel generators due to their economic and efficiency advantages. However, a common limitation of such research is the oversight of the environmental footprint caused by diesel emissions and the lack of focus on fully renewable hybrid systems. Exploring options that rely solely on renewable energy sources remains an underdeveloped area [32,33]. A critical factor for renewable energy system performance is the collection of meteorological and electrical load data, ideally spanning a full year with hourly intervals [34]. However, many studies rely on short-term data or less accurate satellite-based sources, which can introduce limitations. For example, a study on hybrid systems in Ghana utilized NASA Surface Meteorology data, highlighting challenges related to data accuracy and availability [35]. Additionally, the lack of dimensional analysis in hybrid system designs hampers their optimization and market integration [36]. Effective annual dimensional analysis requires detailed solar radiation, wind speed data, and population variations, especially in high-tourism areas where electricity demand fluctuates significantly [37].

Studies underscore the increasing popularity of hybrid renewable energy systems, highlighting their potential to efficiently harness diverse energy sources [38]. Optimization strategies for photovoltaic and wind turbine resources in power grids aim to minimize losses and enhance system efficiency [39]. Additionally, research on the techno-economic optimization of hybrid photovoltaic/wind systems under varying meteorological conditions focuses on determining the optimal dimensions of autonomous hybrid systems for electricity autonomy [40].

Islands face challenges with sustainable energy due to fossil fuel reliance and fluctuating costs. Transitioning to renewable energy sources (RESs) offers a solution [41], with Greece's solar and wind potential emphasizing the need for flexibility in managing high RES penetration [42]. Greece exhibits considerable variation in solar potential, ranging from 1500 to 1600 kWh/m^2 in the northern regions to over 1900 kWh/m^2 in the Dodecanese Islands, making it an ideal location for RES deployment [43]. The country's energy transformation over the last two decades, reducing fossil fuel dependency from 53.7% to 33.6% while increasing RESs in the energy mix from 10.8% to 22.8%, demonstrates its commitment to clean energy transitions and aligning with global climate change mitigation objectives [44–46]. Public sentiment is also generally favorable, with studies indicating that 73% of Greek residents are interested in investing in photovoltaic systems, provided that sufficient information and state support are available [47,48].

Despite these advancements, the design and optimization of hybrid systems in Greece remain underdeveloped. Research on small islands like Nisyros highlights the need for targeted studies addressing seasonal energy demands driven by tourism, population fluctuations, and geographic challenges [49]. Furthermore, renewable energy maps, like those developed for Andros Island, provide critical insights for shaping energy policies and facilitating investment in hybrid systems [50,51]. A study specifically analyzed Nisyros Island's potential for achieving energy self-sufficiency through the integration of wind farms, photovoltaic parks, and energy storage systems, emphasizing the feasibility of autonomous hybrid systems in small island contexts [52].

While the general principles of renewable energy integration into small islands have been well explored, most studies focus on larger or more resource-rich regions. Few have comprehensively analyzed the integration of both wind and solar energy systems into small islands with specific demographic and geographical conditions, such as those in the Aegean Sea. This study addresses this gap by providing a detailed modeling of renewable energy solutions for Nisyros Island, exploring the feasibility of achieving electricity autonomy through a combination of wind and solar power. It considers the island's moderate population, seasonal fluctuations in energy demand, and its high solar and wind potential. The novelty of this research lies in its comprehensive evaluation of multiple renewable energy scenarios, specifically tailored to the island's demographic, spatial, and resource limitations. This approach offers a replicable model for similarly situated communities. It contributes to advancing energy autonomy strategies for isolated communities, which are essential for sustainable development and energy security.

However, this study focuses specifically on electricity generation, rather than covering the entire energy demand of the island, such as thermal needs and transportation. While electricity is a significant component of the island's energy needs, it represents only part of the overall consumption. The scenarios explored in this study aim to achieve electricity self-sufficiency, acknowledging that a full energy independence strategy would require further analysis of non-electrical energy sectors. In contrast to analogous studies conducted in other regions, this research focuses on the unique characteristics of Nisyros, a small island in the Aegean Sea. It highlights the distinct challenges and opportunities presented by such geographically isolated islands.

To provide a clearer structure, the manuscript is organized as follows: Section 2 outlines the methodology, detailing the models and data used for energy planning. Section 3 presents the RES scenarios, exploring the various renewable energy configurations tested for Nisyros Island. Section 4 discusses the electricity and economic comparison of the four scenarios, while Section 5 discusses the results and findings in relation to the existing research and policy implications for small island energy autonomy. Finally, Section 6 concludes with the study's limitations, future work, and the broader applicability of the proposed solutions to other small islands facing similar energy challenges.

2. Methodology

The proposed design aims to establish an optimal system that fulfills the electricity requirements of the selected region and that is feasible for spatial planning, is cost-effective and environmentally friendly with minimal disruption to the area's natural surroundings. The selection of location and the identification of the most suitable scenario or system for the chosen region are primarily guided by a systematic methodological approach, which involves eliminating regions and scenarios that do not meet the specific criteria.

Achieving electrical self-sufficiency through alternative energy sources becomes increasingly challenging, intricate, and cost-intensive as population density increases. In the process of selecting the research area, meteorological, demographic, and tourism-related data for each prospective study location are collected and meticulously examined. Access to sufficient meteorological data from local weather stations is crucial for this selection. Additionally, assessing the wind and solar potential of the area is vital to ensure robust parameters that can support the utilization of photovoltaic systems and wind turbines effectively.

Moreover, it is essential to verify whether the population of the chosen area falls within the prescribed demographic limits to facilitate energy autonomy through renewable sources. Specific emphasis is placed on demographic and tourist-related data, since regions characterized by significant population fluctuations are not suitable for selection. Subsequently, scrutiny is directed towards land use criteria for the area, including geospatial characteristics, to determine the availability of land suitable for the installation of renewable energy generation systems.

After considering all these criteria for the selection of the research area and gathering the requisite data, such as the number and types of buildings and their electricity consumption, the research advances to the subsequent phase. This stage involves the development of alternative scenarios for the electrical coverage of the selected area, utilizing methods of energy generation from renewable sources. The comparison of these scenarios encompasses energy efficiency, installation costs, operational expenses, and maintenance costs, leading to the identification of the most suitable electricity production system for the specific area based on the accumulated energy data.

This section is divided into two primary sections: "General Criteria", which covers the broad methodology for selecting the appropriate regions and designing renewable energy systems, and "Nisyros-Specific Criteria", which focuses on the specific details of the case study for Nisyros Island. These two sections are clearly separated to allow for the application of the methodology in other locations while focusing on the unique characteristics of Nisyros Island.

2.1. General Criteria

2.1.1. Site Selection Criteria

The selection process begins by evaluating regions based on population size, geographic features, and renewable energy potential. The area should have a stable population ranging from 1000 to 3000 residents to ensure a manageable electricity demand. Larger populations or industrial zones lead to complex and costly electricity coverage, while very small populations may not justify large-scale renewable installations. Solar and wind resources must be abundant to ensure the feasibility of photovoltaic and wind turbine systems. Additionally, the availability of land for installation and the legal and environmental suitability of the region are critical for choosing an appropriate study area.

2.1.2. General Demographics

General demographic data, including population size and seasonal fluctuations (e.g., tourism), are analyzed to estimate the area's electricity demand. Building census data and electricity consumption patterns from municipal sources helps to determine the energy needs across different building types, such as residential homes, commercial properties, and public buildings.

2.1.3. Solar and Wind Resource Analysis

Solar radiation and wind speed data are collected from local meteorological stations. These data are crucial for calculating the potential for renewable energy generation. The chosen area must have sufficient solar and wind resources to support photovoltaic systems and wind turbines.

2.1.4. Land Use and Environmental Considerations

Land availability for renewable energy installations is assessed, ensuring that the installation of photovoltaic panels and wind turbines can proceed without disrupting protected areas or violating zoning laws. The region must be suitable for large-scale renewable energy deployment and the project must comply with all relevant environmental regulations.

2.2. Nisyros-Specific Criteria

2.2.1. Demographic Data Analysis

Nisyros island, as illustrated in Figure 1, was selected due to its stable population, ranging from 1000 to 3000 residents, which meets the criteria for ensuring manageable electricity demand. The island experiences seasonal fluctuations, driven by tourism, but these fluctuations remain within limits that do not overly strain the energy system. According to the official census data [53], the population of Nisyros rose from 1008 permanent residents in 2011 to 1048 in 2021. During the peak tourism months (May to September), the number of visitors can increase the population by approximately 10% of the permanent population, as reported by the Port Authority of Nisyros [54]. The data on seasonal tourism helped estimate the island's peak demand during these periods. The results indicate that while there is a notable increase in the population during tourist season, the demand remains within manageable limits for the system.

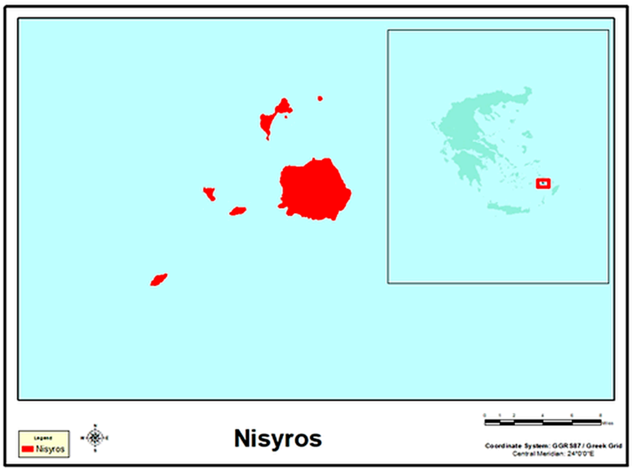

Figure 1. The island of Nisyros and its location in relation to Greece.

2.2.2. Solar and Wind Data

Greece's geographical position offers abundant solar and wind potential. As mentioned previously, solar potential varies across the country, with the highest solar potential found in Eastern Crete and the Dodecanese islands, reaching around 1900 kWh/m^2 or more. Solar intensity peaks around noon, especially during the summer months, due to extended daylight hours. For precise calculations of incident solar radiation on various surfaces, knowledge of solar radiation on a horizontal surface is fundamental [55].

Additionally, Greece ranks among Europe's windiest countries, with most areas experiencing wind speeds between 4 and 10 m/s. Mainland Greece averages 4–6 m/s, with some areas occasionally reaching 7–9 m/s, characterizing Greece as a "windy European territory" [56]. The Aegean islands, particularly the Cyclades and the Dodecanese, exhibit the highest wind potential (8–30 m/s). Given that, wind turbines typically start operating around 3 m/s; suitable locations should maintain average wind speeds of 7 m/s per year or higher. The Dodecanese islands, with their moderate to high wind speeds within the permissible range, emerge as promising sites for wind energy projects.

Nisyros has been selected as a study area because it has both high wind and high solar potential. The wind potential is attributed through the average and maximum wind speed values, while the solar potential, on the other hand, expresses the exploitable solar energy that falls on an area and is influenced by the climatic and geomorphological characteristics of each place, as well as its geographic location. Another meteorological factor that must be studied is temperature, since it plays a significant role in the durability of the renewable energy system materials used, as well as in electricity consumption for heating or cooling. The average and maximum wind speeds from the years 2018 to 2023 in Nisyros Island are presented in Figure 2a,b.

In Figure 2a, it is observed that the average wind speed values in Nisyros range from 0.3 m/s to 4.4 m/s, with an average fluctuation from about 2.0 m/s to 4.0 m/s. It is evident that in the year 2020, there was a sharp decline in the average wind speed values. It is also noted that during the winter months (September–March), Nisyros has higher wind potential. Furthermore, Figure 2b depicts that the maximum wind speed values in Nisyros range from 9.4 m/s to 30.8 m/s, with an average fluctuation from about 9 m/s to 20 m/s.

Additionally, it is evident that the highest wind speed value is observed in the first month of 2019, and is 30.8 m/s. From the curves in the diagram, it appears that from August to April, i.e., in the autumn, winter, and spring months, there is a noticeable increase in wind's potential intensity. Finally, based on Nisyros' wind data, the wind speed values on the island throughout the year fall within the start-up and cut-out speed limits of wind turbines, making Nisyros an island capable of using wind energy for its electrical autonomy.

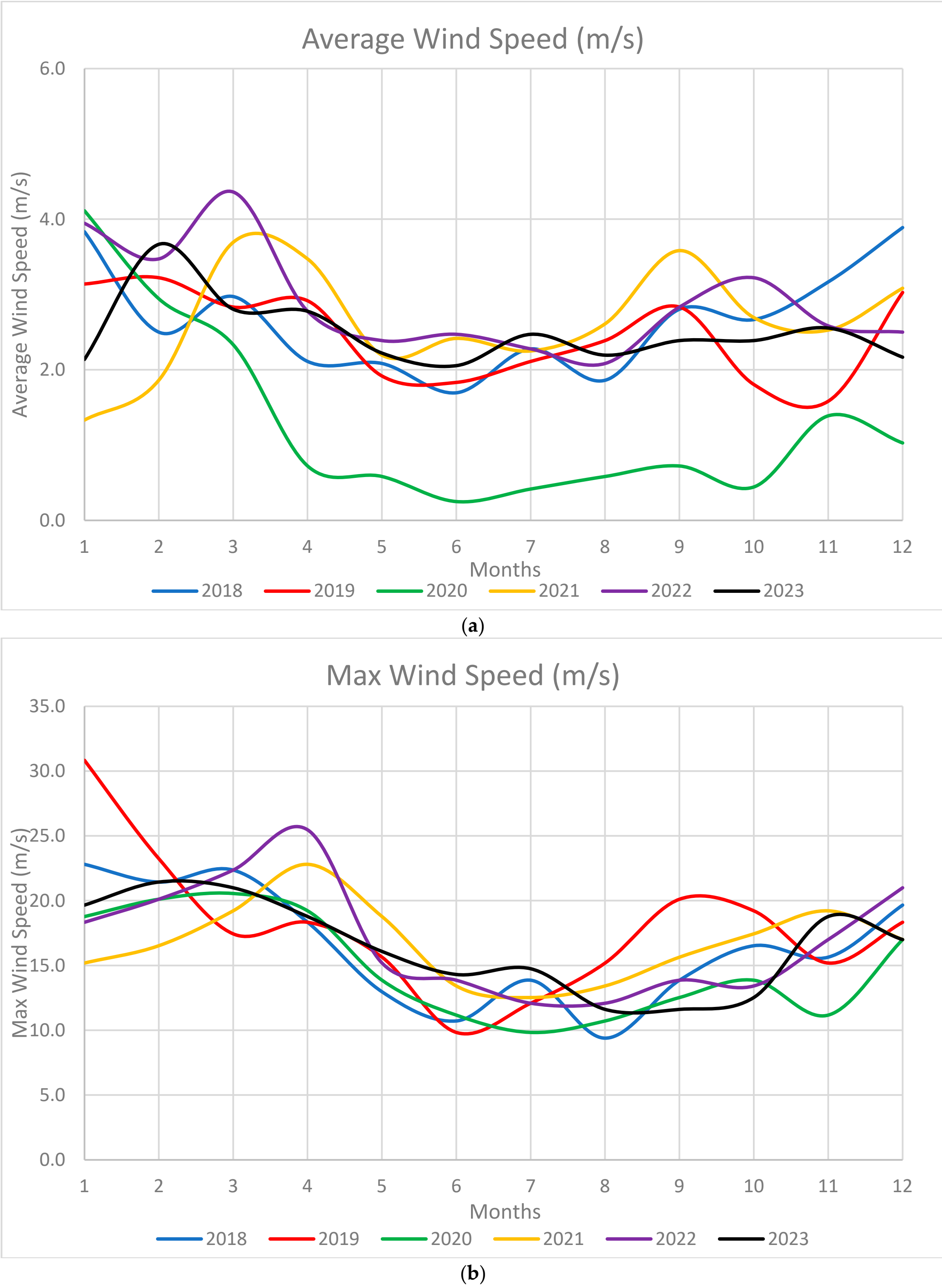

Figure 2. Wind potential in Nisyros Island: (**a**) average wind speed and (**b**) maximum wind speed.

The average temperature values per month for the years 2018–2023 in Nisyros were also studied (Figure 3). Temperature plays an important role in the proper functioning of photovoltaic panels and wind turbines, making it one of the most important factors for renewable energy systems. For this reason, the average temperatures of the place were compared with the durability values of the materials from which wind turbines and photovoltaic panels are made. Specifically, photovoltaic systems operate ideally at an ambient temperature of 25 °C, and much higher temperatures lead to a reduction in system efficiency, as they increase the cell temperature, negatively affecting the conversion of solar energy into electricity. For example, for mono-crystalline PV panels, a temperature increase of 1 °C can lead to power–energy losses of 0.38 to 0.45% [57]. Similarly, the operating temperature range of a wind turbine's electronic system is from −30 °C to 55 °C. Furthermore, the performance of wind turbine batteries is an important factor, operating from 0 °C to 40 °C, with optimal performance at 25 °C. In Greece, where extreme temperatures are not observed, emphasis is placed on battery performance and lifespan, which is temperature dependent. It is noteworthy that at very high temperatures, such as 50 °C, battery life is 4 years, with a simultaneous reduction in performance, whereas at ambient temperatures, battery life can reach 12 years with satisfactory performance [58].

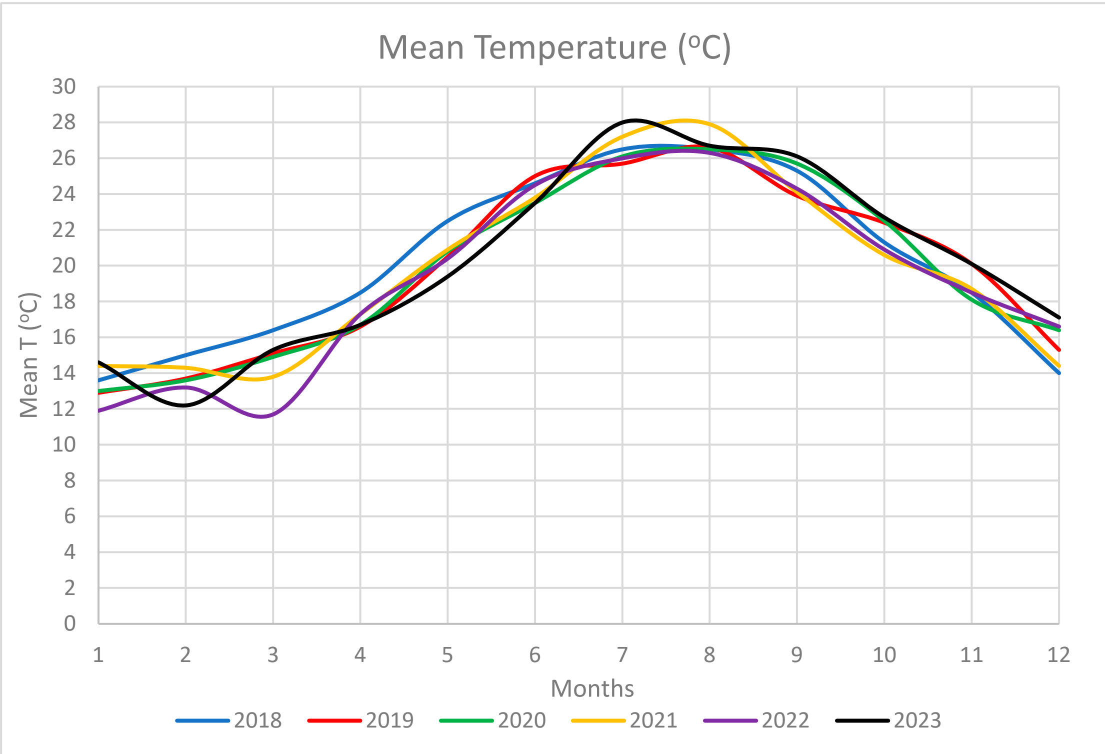

Figure 3. Annual temperature profiles.

In Figure 3, it is observed that the average temperatures in Nisyros range from 11.7 °C in 2022 to 28 °C recorded in 2023 [59]. Generally, it is observed from the curves in the above diagram that the year with the lowest average temperature values was 2022. The temperature increase becomes noticeable from April onwards, with the maximum average temperatures observed in the summer months, July and August, and then a noticeable decrease in temperature. This occurs because in the summer months, the duration of daylight is longer, as, due to Greece's geographic location, the sun emits solar radiation for more hours during the day.

The criterion for selecting the location was to have solar radiation values above the country's average radiation value (1650 kWh/m^2), to optimize the exploitation of solar energy from photovoltaic systems. Nisyros was selected based on the average annual incident solar radiation, which ranges from 1900 to 2000 kWh/m^2 [43].

2.2.3. Electric Load Criteria

The electricity load data for Nisyros were gathered from municipal records, including **building census data** [53] and electricity consumption patterns for various types of buildings. These included residential homes, hotels, restaurants, and other commercial buildings. The analysis of the data helped in determining the energy needs across different building categories, considering the typical electrical appliances used. Table 1 outlines the breakdown of building categories on the island, their respective numbers, and the associated annual consumption in kWh. This load analysis helped estimate the overall electricity demand of the island, which is crucial for designing an energy system that can ensure full coverage throughout the year, including seasonal peaks in demand.

Table 1. Classification of building units on Nisyros and electricity consumption.

Buildings	Numbers	Annual Consumption (kWh)
Permanent residences	467	4,119,622
Vacation homes	311	160,570
Airbnb-type houses	71	114,202
Schools	4	25,953
Hotels	4	68,302
Factories	3	4,400,000
Churches/Monasteries	33	197,100
Hospitals/Clinics *	1	-
Dining establishments	40	1,680,015
Stores/Offices	63	172,523
Municipal lighting	-	175,500
Total consumption		11,113,787

* Collecting electricity consumption data from the provider was not feasible.

2.2.4. Monthly Data Analysis and Annual Electricity Demand Calculations

Monthly variations in energy demand were considered in the analysis. The island experiences fluctuations in demand driven by the tourism season, especially in the summer months. Monthly electricity consumption data were combined with seasonal wind and solar radiation data to calculate the total annual energy production from renewable sources. This process was critical for ensuring that the proposed energy solutions could accommodate these seasonal variations in resource availability. The analysis also considered how to integrate energy storage solutions and backup systems to ensure a stable energy supply during periods of low renewable generation.

2.3. Assumptions and Limitations

To model the renewable energy solutions for Nisyros Island, several key assumptions were made. These include assumptions regarding the solar and wind energy potential of Nisyros and the average wind speeds based on the available meteorological data. Additionally, the study assumes the typical electricity consumption patterns, with seasonal fluctuations in demand driven by tourism. Regarding system efficiency, the analysis assumes that batteries have a lifespan of 5–10 years, turbines will last between 20 and 25 years, and that other components such as inverters and charge controllers would present similar long lifespans. The study also assumes that the costs of components, installation, and labor are based on the current market prices, with potential fluctuations in these costs due to supply chain issues or inflation not being incorporated into the base model. Finally, it is assumed that future energy tariffs and inflation will follow similar trends to the current projections, with modest increases over the 25-year expected lifespan of the system. These assumptions were critical for the modeling process, and help frame the results presented in this study.

This study also has some limitations, including temporal constraints from using monthly data, which may not fully capture short-term fluctuations in energy demand, especially during peak tourist seasons. The meteorological data used for wind and solar potential come from local stations and satellite sources, which may have limited spatial resolution, and could affect accuracy at the island level. Additionally, the model assumes uniform solar and wind conditions across the island, despite natural variations in these resources. Finally, the study excludes advanced energy storage and backup generators, which could enhance system reliability, but were not included, to keep the model straightforward.

The system components—wind turbines, photovoltaic panels, batteries, and inverters—were selected based on Nisyros' local resource availability, cost-effectiveness, and long-term efficiency. Wind turbines were chosen to complement solar energy, ensuring continuous power, while photovoltaic panels efficiently harness solar radiation. Batteries store excess energy for use during off-peak times and inverters convert the stored energy for grid compatibility. This configuration was designed to balance reliability, costs, and sustainability.

Once the general criteria have been applied and a region has been identified, the next phase involves developing renewable energy scenarios, including solar and wind energy solutions. The scenarios are compared in terms of energy efficiency, installation and operational costs, and maintenance requirements to determine the most suitable energy system for the selected area.

3. Proposals—Scenarios for Electricity Coverage by RESs

The study evaluates four scenarios to assess the electricity coverage and self-sufficiency of Nisyros Island. These scenarios stem from two initial exclusive setups: one relying solely on wind turbines and the other on photovoltaic systems. After evaluating their practicality and economic viability, two additional hybrid scenarios are formulated, each combining two distinct renewable energy sources. Thus, the study presents four scenarios to comprehensively explore various renewable energy combinations and their potential applicability for the island's electricity requirements.

The selection of four scenarios is deliberate, based on a comprehensive analysis of feasible and impactful renewable energy combinations for Nisyros Island. Each scenario represents a distinct energy generation approach, aiming to cover the island's electricity demands efficiently. While it is conceivable to create more scenarios by incorporating additional variations or combinations of renewable energy sources, the chosen four scenarios were determined as the most practical, economically viable, and representative of diverse renewable energy solutions for Nisyros' electricity needs. These scenarios were deemed sufficient to capture a range of feasible options without overwhelming complexity in the analysis.

The first scenario entails complete electrical coverage for Nisyros using wind energy via the installation of wind turbines. The second scenario involves meeting the island's energy demands solely through photovoltaic panels installed on the rooftops of both residential and public buildings. The latter two scenarios are hybrid in nature, combining solar and wind energy sources. The first hybrid scenario incorporates a single wind turbine alongside photovoltaic panels, while the second integrates two wind turbines with photovoltaic panels.

The choice of using one or two wind turbines in the hybrid scenarios was based on a balance between cost-effectiveness, spatial limitations, and the island's energy needs. Given Nisyros' moderate electricity demands, adding more turbines would not significantly improve economic feasibility due to high installation costs. While additional turbines could theoretically increase energy production, they would not offer a proportional return on investment. The selected turbine numbers ensure optimal balance between energy supply, investment costs, and environmental impact.

All scenarios are economically assessed by comparing their overall costs, which include the purchasing cost of necessary equipment and materials, installation expenses, maintenance costs, and the cost of replacements. Ultimately, preference is given to the scenario that is more cost-effective while being feasible and capable of achieving electrical autonomy for Nisyros Island, with minimal disruption to and intervention in the island's natural landscape.

For each scenario, hourly power balances were analyzed to ensure that the energy production aligned with the island's consumption patterns throughout the year, including peak tourist seasons. For the wind turbine scenarios, the number of turbines was based on energy output calculations considering the wind data, ensuring an optimal balance between cost and required energy supply. In the photovoltaic-based scenarios, rooftop space limitations were considered, with centralized PV farms explored as an alternative, to reduce logistical challenges and enhance efficiency. Additionally, system stability in transitioning to a 100% inverter-based configuration was addressed by integrating battery storage and appropriate inverters, which helped to manage fluctuations and maintain continuous energy supply. Each scenario was also evaluated in terms of its long-term sustainability, operational cost, and reliability, ensuring the optimal solution for Nisyros' energy needs.

3.1. First Scenario: Complete Electrical Coverage Using Wind Turbines (WTs)

The research reveals that an electrical coverage system relying solely on wind turbines is the most economically advantageous option. Thus, this study could serve as a valuable tool for the implementation of similar energy production systems in isolated regions with comparable characteristics, and even in the same area under investigation.

This scenario aims to achieve complete electrical coverage for Nisyros through the installation of wind turbines on the island's mainland area. The objective is to identify the most cost-effective wind energy system for achieving complete electrical coverage. It involves exploring various wind turbine configurations, considering factors such as turbine size, design, and placement, to determine the optimal solution for harnessing wind energy. Based on the annual electrical consumption of Nisyros, the required number of wind turbines in this scenario is determined to be three. The economic analysis of this scenario is crucial, including equipment procurement costs and total replacement costs over the 25-year project implementation period, as detailed in Tables 2 and 3, respectively.

Table 2. First scenario for the complete electrical coverage of Nisyros with wind turbines (WTs) and the cost in €.

Components	Description	Quantity	Cost per Unit (€)	Total Cost for 3 WTs (€)
WT [60]	PW60–900 kW (25-year lifespan)	3	700,000	2,100,000
Stabilizer [61]	10 KVA (10-year lifespan)	9	421.80	37,962

Table 2. *Cont.*

Components	Description	Quantity	Cost per Unit (€)	Total Cost for 3 WTs (€)
Rectifier [62]	Three Phase 400 VAC 12/24 V 0~1666 A (6-year lifespan)	13,500	921.77	12,443,895
Charge Controller [63]	60 A MPPT Solar Charge Controller (4.5-year lifespan)	330	161.99	534,567
Battery [64]	$LiFePO_4$ Battery Smart 24 V 200 Ah (5-year lifespan)	609	2436.83	1,484,029
Inverter [65]	24/5000 24 V 5000 W (10-year lifespan)	609	2319.95	1,412,850
Installation Cost (€)				18,013,303

Table 3. Overall cost with the calculation of replacement cost for the first scenario.

Components	Number of Replacements in 25 Years	Cost for Replacement (€)
WTs	0	0
Stabilizers	2	75,924
Rectifiers	4	49,775,580
Batteries	5	7,420,145
Inverters	2	2,825,700
Charge Controllers	6	3,207,402
Installation cost		18,013,303
Total Replacement cost (€)		81,318,054

3.2. Second Scenario—Complete Electrical Coverage of Nisyros Through Photovoltaic Panels (PVs)

In this scenario, the objective is to achieve complete electrical coverage of Nisyros through the installation of photovoltaic panels on building rooftops. The choice of rooftop installation was made to minimize land use on the island, considering its overall protected areas. The proposed photovoltaic panels are static, devoid of solar trackers at their base. This decision is due to the cost-intensive nature of procuring and installing solar trackers. Moreover, trackers have significant weight and require more space since they are mounted at the base of the photovoltaic panels, resulting in fewer panels per rooftop. To implement this scenario, photovoltaic panels capable of converting solar energy into electrical power are necessary.

Additionally, the use of batteries is imperative to facilitate electricity storage for utilization during periods of solar insufficiency, such as nighttime or overcast days. Equally important is the employment of charge controllers to prevent complete battery discharge and overcharging. Finally, inverters are required to convert the direct current (DC) generated by the panels and batteries into alternating current (AC) compatible with the grid.

This scenario highlights the crucial components: photovoltaic panels, batteries for electrical storage, charge controllers to regulate battery charging, and inverters for DC to AC conversion, all integral for achieving sustainable energy generation and storage on Nisyros. Table 4 reflects the equipment procurement cost for the complete electricity self-sufficiency of Nisyros, while Table 5 calculates the total replacement cost over the 25-year project implementation.

In Scenario 2, the total number of photovoltaic panels required is estimated at 11,545. Given that there are approximately 1000 buildings on the island, each building would need to accommodate around 12 panels. A preliminary calculation suggests that this may require an estimated 23,000 square meters of rooftop space. While some buildings may have sufficient rooftop area, especially those that are single-family residences, others with multiple residences, or smaller roofs may present challenges for installation. In light of this, the creation of centralized photovoltaic farms is considered a viable alternative. PV farms would reduce the logistical challenges associated with rooftop installations and may also result in cost reductions due to economies of scale. Additionally, centralized PV farms could simplify the approval process, as building owners may be less inclined to participate in rooftop installations.

Table 4. Second scenario for the complete electrical coverage of Nisyros with photovoltaics (PVs) and the cost in €.

Components	Description	Quantity	Cost per Unit (€)	Total Cost for PVs (€)
PV panel [66]	500 W Poly Solar Panel (25-year lifespan)	11,545	139.16	1,606,602
Charge Controller	60 A MPPT (4.5-year lifespan)	46,180	161.99	7,480,698
Battery [67]	12 V 15 Ah Lead Battery Acid VRLA AGM (5-year lifespan)	46,180	34.95	1,613,991
Inverter [68]	24 V 600 W (10-year lifespan)	23,090	257.99	5,956,989
Installation Cost (€)				16,658,280

Table 5. Overall cost with the calculation of replacement cost for the second scenario.

Components	Number of Replacements in 25 Years	Cost for Replacement (€)
PVs	0	0
Batteries	5	8,069,955
Inverters	2	11,913,978
Charge Controllers	6	44,884,188
	Installation cost	16,658,280
	Total Replacement cost (€)	81,526,401

3.3. Third Scenario—Hybrid Scenario of Electrical Coverage for Nisyros Utilizing Photovoltaic Panels and One Wind Turbine

In this scenario, the goal is to achieve complete electrical coverage for Nisyros by integrating photovoltaic panels with a single wind turbine. This approach aims to meet the island's electricity demand, totaling 11,113,787 kWh/y, ensuring a precise comparison among scenarios. The wind turbine models, photovoltaic panels, voltage stabilizers, and rectifiers utilized in the initial wind turbine scenario will be retained. Similarly, the charge controllers and batteries from the wind turbine scenario will be utilized, with the inverter model from the photovoltaic panel scenario incorporated. The same MPPT-type charge controller employed in the previous scenarios will also be used. Table 6 outlines the equipment procurement costs for achieving Nisyros' electrical self-sufficiency, while Table 7 computes the total replacement expenses over the 25-year project duration.

Table 6. Third scenario for the complete electrical coverage of Nisyros with photovoltaics (PVs) and one wind turbine and the cost in €.

Components	Description	Quantity	Cost per Unit (€)	Total Cost for Hybrid 1 (€)
WT	PW60–900 kW (25-year lifespan)	1	700,000	700,000
Stabilizer	10 KVA (10-year lifespan)	3	421.80	1265
Rectifier	Three Phase 400 VAC 12/24 V 0~1666 A (6-year lifespan)	4500	921.77	4,147,965
PV panel	500 W Poly Solar Panel (25-year lifespan)	7697	139.16	1,071,114
Charge Controller	60 A MPPT (4.5-year lifespan)	7807	161.99	1,264,655

Table 6. *Cont.*

Components	Description	Quantity	Cost per Unit (€)	Total Cost for Hybrid 1 (€)
Battery	LiFePO4 Battery Smart 24 V 200 Ah Lithium Battery (5-year lifespan)	15,597	2436.83	38,007,237
Inverter	24 V 600 W (10-year lifespan)	16,902	257.99	4,360,546
Installation Cost (€)				49,552,782

Table 7. Overall cost with the calculation of replacement cost for the third scenario.

Components	Number of Replacements in 25 Years	Cost for Replacement (€)
WTs	0	0
PVs	0	0
Stabilizers	2	2.53
Rectifiers	4	16,591,860
Batteries	5	190,036,185
Inverters	2	8,721,092
Charge Controllers	6	7,587,930
Installation cost		49,552,782
Total Replacement cost (€)		272,492,379

3.4. Fourth Scenario—Hybrid Scenario of Electrical Coverage for Nisyros Utilizing Photovoltaic Panels and Two Wind Turbines

In this latest hybrid scenario, the objective of achieving full electrical coverage for Nisyros remains, by combining photovoltaic panels with two wind turbines. Consistency with the preceding hybrid scenario is maintained by employing the same models for essential components. This includes identical wind turbines, photovoltaic panels, voltage stabilizers, and rectifiers for the wind turbines, as well as consistent charge controllers, batteries, and inverters. The methodology for determining the quantity of components required remains unchanged from the previous hybrid scenario. Table 8 illustrates the procurement costs of the equipment necessary for Nisyros' electrical self-sufficiency, while Table 9 calculates the total replacement costs over the 25-year project duration.

Table 8. Fourth scenario for the complete electrical coverage of Nisyros with photovoltaics (PVs) and two wind turbines and the cost in €.

Components	Description	Quantity	Cost per Unit (€)	Total Cost for Hybrid 2 (€)
WT	PW60–900 kW (25-year lifespan)	2	700,000	1,400,000
Stabilizer	10 KVA (10-year lifespan)	6	421.80	25,308
Rectifier	Three Phase 400 VAC 12/24 V 0~1666 A (6-year lifespan)	9000	921.77	8,295,930
PV panel	500 W Poly Solar Panel (25-year lifespan)	3849	139.16	5,356,684
Charge Controller	60 A MPPT (4.5-year lifespan)	4069	161.99	659,137
Battery	LiFePO4 Battery Smart 24 V 200 Ah Lithium Battery (5-year lifespan)	8104	2436.83	19,748,070
Inverter	24 V 600 W (10-year lifespan)	10,714	257.99	2,764,105
Installation Cost (€)				38,249,234

While renewable energy plays a crucial role in achieving electrical autonomy, energy efficiency improvements can further reduce the overall electricity demand on Nisyros. Measures such as enhancing building insulation, installing energy-efficient appliances, and implementing smart grid technologies can help lower electrical consumption. In addition, public awareness campaigns aimed at encouraging energy-saving behaviors, such as reducing peak demand during high-consumption periods, can also contribute. By integrating energy efficiency measures, the reliance on renewable energy systems is reduced, optimizing the use of resources and improving the overall sustainability of the island's energy system.

Table 9. Overall cost with the calculation of replacement cost for the fourth scenario.

Components	Number of Replacements in 25 Years	Cost for Replacement (€)
WTs	0	0
PVs	0	0
Stabilizers	2	50,616
Rectifiers	4	33,183,720
Batteries	5	98,740,350
Inverters	2	5,528,210
Charge Controllers	6	3,954,822
Installation cost		38,249,234
Total Replacement cost (€)		179,706,952

The battery storage requirement in this scenario poses a significant logistical challenge, particularly in determining whether individual battery units will be housed within each residence or if a centralized storage facility will be utilized. Individual battery systems, while offering greater autonomy to each residence, may present issues in terms of space, cost, and maintenance for individual homeowners. On the other hand, larger centralized storage facilities could be strategically located on the island, reducing overall costs, improving maintenance efficiency, and providing a more streamlined approach to electricity storage. Centralized storage would also simplify electrical distribution and offer greater control over managing excess electricity produced by the photovoltaic panels.

4. Electricity and Economic Comparison of the Four Scenarios

Upon completing the scenarios, it is crucial to conduct a comprehensive comparison of them to determine the most cost-effective option. Economically, the cost of electricity production is compared with conventional methods, excluding wind turbines and photovoltaic panels, which are renewable energy production techniques.

In terms of electricity production comparison of the scenarios, the primary objective was to ensure sufficient electricity coverage for Nisyros. The total consumption of Nisyros, as derived from Table 3, is 11,113,787 kWh/year. However, this figure is expected to be higher due to unaccounted-for electricity requirements for the operation of industrial facilities and the health center on the island. Additionally, the observed exponential population growth, particularly during the tourism influx in summer, suggests a potential increase in consumption.

- **First scenario—Wind Power:** Assuming a consistent wind resource, this scenario utilizes three 900 kW wind turbines, collectively generating 14,664,240 kWh/year. This approach provides a surplus of electricity to accommodate potential consumption increases;
- **Second scenario—Solar Power:** To achieve a comparable electricity output of 14,664,459 kWh/year solely through solar panels, this scenario employs 11,545 500 W photovoltaic panels. This assumes optimal sunlight conditions throughout the year, which may not always be the case;
- **Third scenario—Hybrid Approach:** This scenario combines wind and solar power to leverage the strengths of both technologies. One 900 kW wind turbine generates 4,888,080 kWh/year, while 7697 500 W photovoltaic panels contribute an additional 9,776,729.4 kWh/year, resulting in a total output of 14,664,809 kWh/year. This ap-

proach assumes a balance between wind and solar resources to compensate for potential fluctuations in either;
- **Fourth scenario—Optimized Hybrid:** This scenario refines the hybrid approach, utilizing two 900 kW wind turbines (generating a combined 9,776,160 kWh/year) alongside 3849 500 W photovoltaic panels (contributing 4,888,999.8 kWh/year) for a total output of 14,665,160 kWh/year. This assumes a stronger emphasis on wind power due to its cost-effectiveness (as identified in the study), while maintaining some solar contribution for diversification.

All scenarios appear to exceed the calculated electricity consumption of Nisyros, leaving room for an increase in the specified energy value. In conclusion, the fourth scenario, utilizing two wind turbines and photovoltaic panels, generates the most electricity compared to the others. Following closely is the third scenario with one wind turbine and photovoltaic panels. Subsequently, in descending order, are the second and first scenarios, relying solely on photovoltaic panels and wind turbines, respectively. Table 10 presents the comparison of the four scenarios, in terms of electricity produced as well as in terms of costs.

Table 10. Energy and economic comparison of the four scenarios for Nisyros Island.

Scenarios	Energy Source	Total Energy Output (kWh/y)	Coverage of the Electricity Loads (%)	Installation Cost (€)	Overall Cost (€)
First Scenario	WT only	14,664,240	131.95	18,013,303	81,318,054
Second Scenario	PV only	14,664,459	131.95	16,658,280	81,526,401
Third Scenario	Hybrid wind and solar	14,664,809	131.95	49,552,782	272,492,379
Fourth Scenario	Optimized hybrid	14,665,160	131.96	38,249,234	179,706,952

The generated electricity, according to Table 10, is approximately 30% more than what the permanent residents of the island need. The oversizing was carried out to also accommodate the island's tourist activities during the summer months.

5. Discussion and Results

The four scenarios proposed for Nisyros' electricity coverage, leveraging the island's abundant solar and wind resources, represent a comprehensive solution that aligns with environmentally friendly practices. These scenarios aim to propel Nisyros toward electricity self-sufficiency while minimizing its carbon footprint. Utilizing renewable energy sources (RESs) for electricity production not only presents a sustainable option, but also offers economic advantages for the island.

Selecting an efficient, cost-effective, and environmentally conscious electricity production system is crucial in the face of energy crises and climate change. Although the initial investment in RES systems can be substantial, these projects prove to be economically viable in the long run, especially when compared to the higher electricity costs from conventional sources such as the Public Power Corporation (DEI). Moreover, the unpredictability of conventional electricity costs influenced by global economic and political factors underscores the stability offered by RES investments.

From an economic standpoint, the optimal scenario for Nisyros involves installing just three wind turbines, minimizing environmental disruption by positioning them near existing road networks and away from residential areas. This approach eliminates the need for road expansions and reduces installation costs while preserving the island's natural landscape. Among the hybrid scenarios, the one integrating 2 wind turbines and 3849 photovoltaic panels emerges as a viable option, despite its slightly higher cost.

However, a cost–benefit analysis favors wind turbines over photovoltaic panels in terms of cost-effectiveness.

Furthermore, hybrid scenarios benefit from the diversity of RESs, ensuring electricity production even on days with fluctuating weather conditions. For instance, when there is insufficient wind but abundant sunshine, electricity generation from photovoltaic panels can compensate, either by storing excess electricity or supplying it directly to the grid. However, challenges such as obtaining consent for installing photovoltaic panels on rooftops highlight the feasibility of wind turbine installations.

This study employs a combination of actual and approximate data to estimate Nisyros' electricity consumption, due to data limitations. Despite minor deviations, the results provide realistic scenarios, indicating that relying solely on photovoltaic panels is more costly than exclusively using wind turbines. Hybrid scenarios, particularly those incorporating more wind turbines, are anticipated to offer cost savings compared to those with fewer turbines. Thus, while this approach combines accurate and approximate data, the methodology employed serves as a valuable tool for assessing electricity autonomy in different locations.

Finally, a comparison between the most economical scenario and the existing situation is essential. Taking into account various factors affecting electricity tariffs and charges, including transmission and distribution fees, Public Service Obligation (PSO) services, and miscellaneous levies, provides a more comprehensive understanding of consumer costs. By excluding certain charges from the final calculations, the focus remains on the core electricity consumption aspects, allowing for a clearer assessment of potential savings and benefits.

The average electricity tariff for 2023 in Greece, estimated at 0.231 €/kWh [46], was considered in projections assuming price stability over a 25-year period. This value, however, constitutes approximately 46% of the total amount paid to the provider. Within the invoice, charges are allocated for the transmission system, the distribution system, Public Service Obligation (PSO) services, miscellaneous fees, special emission reduction levy, interest, stamps, Hellenic Broadcasting Corporation (ERT) fee, municipal charges, etc. The final price, inclusive of all additional charges borne by the consumer, amounts to approximately 0.502 €/kWh, presuming this price is consistent across all consumption types in calculations for the island of Nisyros, solely using household billing data. The final calculations were performed after excluding VAT, supply company charges, regulated fees, and charges for municipality, public television, etc. As presented in Table 11, the following results were obtained.

Table 11. Comparison between the most economical scenario and the zero scenario.

Scenarios	Consumption per Year (kwh/h)	Electricity Price per Year (€/kwh)	Overall Cost for 25 Years (€)
First Scenario	14,664,240	-	81,318,054
Second Scenario	14,664,459	-	81,526,401
Third Scenario	14,664,809	-	272,492,379
Fourth Scenario	14,665,160	-	179,706,952
Zero scenario	11,113,787	0.502	139,478,027

This study has provided valuable insights into the feasibility of achieving energy autonomy on Nisyros through the use of renewable energy sources. It is important to acknowledge that the analysis relied primarily on monthly and annual data. This approach does not fully capture the short-term variations in energy supply and demand that occur on a daily or hourly basis. Renewable energy sources like solar and wind are inherently intermittent, and their availability does not always align with energy consumption patterns. A more detailed analysis, incorporating a higher temporal resolution (e.g., hourly or daily data), would provide a clearer understanding of whether the proposed systems can meet real-time demands. This future work could also explore the role of energy storage solutions and backup energy sources to ensure system reliability during periods of low solar or wind activity. Addressing these factors in future research would enhance the robustness of the proposed systems and improve the reliability of energy supply.

6. Conclusions

This study evaluated the feasibility of achieving electricity autonomy for Nisyros Island, Greece, through renewable energy sources (RESs). Four scenarios were assessed, including standalone wind and photovoltaic systems and hybrid configurations, focusing on economic viability and environmental sustainability.

The key findings emphasize the economic advantage of wind-based scenarios, with a three wind turbine setup identified as the most cost-effective option. Hybrid configurations, particularly those incorporating additional wind turbines, also demonstrated financial attractiveness and resilience, offering flexibility to address fluctuations in renewable energy availability. These findings highlight wind energy's viability for island communities with similar geographical and demographic characteristics.

The study's broader implications extend to other islands with limited access to mainland grids, offering a replicable model for integrating RESs tailored to local resources. By transitioning to hybrid systems, islands can reduce dependence on fossil fuels, lower carbon footprints, and create resilient energy infrastructures. Notably, the analysis shows that maintaining the current energy state would result in higher cumulative costs over 25 years compared to RES-based scenarios, underscoring the economic necessity of transitioning to renewables.

In conclusion, this study demonstrates that achieving energy independence for Nisyros Island is feasible and economically viable through RESs, particularly wind-based and hybrid systems. Further research should focus on optimizing renewable energy integration, detailed wind assessments, incorporating real-time consumption data, and exploring advanced energy storage solutions. This study supports the transition of island communities like Nisyros towards sustainable energy independence, aligning with the European Union's climate goals.

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