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Research article

Wind based hybrid systems for increased RES penetration in isolated grids: The case study of Anafi (Greece)

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Abstract: The dependence of the Non-Interconnected Islands on diesel power stations increases the cost of producing electricity in comparison to the mainland. This study focuses on the green energy transition of Non-Interconnected Islands, and Anafi was selected as a characteristic case. The average cost of electricity production from thermal units in Anafi was estimated to be 539 €/MWh with a peak load of 0.55 MW. Two different green energy transition scenarios are proposed for Anafi that include the addition of PV panels plus a wind turbine (scenario 1) or PV panels plus a battery (scenario 2) that would operate along the conventional diesel engines and utilized the software RETScreen program for the design and the analysis of these two proposed hybrid systems. In scenario 1, the renewable systems produced 2793 MWh, while in scenario 2 this value was simulated to be 995.51 MWh. In both proposed scenarios there is a significant penetration from Renewable Energy Sources from 68.2% (scenario 2) to 90.3% (scenario 1). In addition, in both cases there is a significant reduction in carbon dioxide emissions from 80%–95% in comparison to the baseline case which produces 2543 tons of CO_2 annually. The cost of the proposed installations has been calculated to be 5.2 m € and 5.6 m € for scenarios 1 and 2, while the net present value (NPV) of the project becomes positive from the sixth year and the eleventh year respectively. The earnings of a green transition project of this nature can be allocated for the maintenance of the island's own project, as well as for the financing of new similar projects on other islands. The expected result of this work is the proposal of a system that will largely cover the energy needs of the island, reduce the cost of production per kilowatt hour and will contribute to the green energy transition of the other Non-Interconnected Islands.

Keywords: green energy transition; energy analysis; energy storage; energy economics; green islands

1. Introduction

To date, most of electricity's global demand is met by burning fossil fuels such as oil, coal and gas. In line with the European Green Deal and the EU's 2050 targets for mitigating climate change, every EU member state must aim to reduce greenhouse gas emissions to achieve climate neutrality [1]. The long-term strategy for 2050 complements the Greek National Plan for Energy and Climate (ESEK), which is the basic strategy plan of Greece for issues related to energy transition and climate adaptation [2]. One of the main goals of the existing ESEK for 2030 is to reduce greenhouse gas emissions by 42% compared to 1990 and more than 56% compared to 2005 emissions [2]. In this framework, a major goal is the elimination of the energy isolation of non-interconnected Greek islands by 2032, either through their interconnection with the mainland or through the integration Renewable Energy Sources (RES). Several islands are already moving in this direction, such as Agios Efstratios, Tilos and Ikaria. Specifically, in the Agios Efstratios, the penetration of RES is attempted to exceed 85%, while in other small islands 60%. In this way, as well as by interconnecting the rest islands, will lead to the withdrawal of conventional stations to achieve a 77% reduction in oil use by 2030 compared to 2020 [3]. The policies that support green transition aim to counter the obstacle of high energy production process in non-interconnected islands, along with reducing the carbon footprint of the energy production sector.

With the purpose to dive deeper in the updates of green energy transition in Greek islands, Tilos island is a flagship case and has been presented by Kaldellis, 2021 [4]. Tilos is in the southeastern part of the Aegean Sea with a total area of about 63 km^2 and with mountainous and rocky terrain. According to the 2021 census, its permanent population amounts to 745 inhabitants, with an annual consumption of electricity of about 3.2 GWh and an annual peak demand of about 1 MW. The island is powered by a 20 kV submarine cable that connects it to Kos diesel power station, crossing Nisyros [5]. Tilos island was the area of development for the Project T.I.L.O.S. (Technology Innovation for the Local Scale, Optimum Integration of Battery Energy Storage) of the European research program, HORIZON2020, which has as its main goal the coverage of the energy needs of the island by maximizing the use of renewable energy sources [6]. The T.I.L.O.S. hybrid station, which has been in operation for three years, consists of a 800 kW medium power wind turbine, a 160 kWp photovoltaic station, inverters with a rated power of 20 kW, a built-in energy storage system with 800 kW/2.88 MWh Battery Energy Storage System (BESS) and a backup diesel generator with a power of 1.45 MW as well as additional small-scale photovoltaic installations [4]. TILOS is a project of integrated energy autonomy in order to find solutions for the electrification of unconnected islands, leading to the achievement of European goals for clean energy and mitigation of greenhouse gases by 2050. The T.I.L.O.S. facility is one of the most innovative islands microgrids in all of Europe and will set an example for the rest of the islands around the world, so that they can be transformed into green islands with clean energy free of greenhouse gas emissions and reduce costs of production of electrical power [7].

Another flagship project in the overall framework of Greek green energy transition is the Astypalea project, where the Hellenic Republic in collaboration with the Volkswagen Group aim to make Astypalea the first 'Smart and Sustainable Island'. The goal is to transform the transport system by switching to electric vehicles, including a service that will provide shared electric vehicles throughout the year with the scope of replacing conventional commercial vehicles with electric ones, and at the same time creating integrated charging infrastructures. The above will be done in conjunction with the conversion of the island, through the exploitation of RES, into an energy autonomous one, to cover the additional electricity needs that will arise from the use of electric vehicles.

In this way, the goal of zero emissions by 2030 will be achieved, also in the transport sector [8]. In respect of green energy transition, there are other ongoing projects in Greece like Chalki, Symi and Kastelorizo which are projected to be smart/green islands [9]. In addition, there are other non-interconnected islands that should accelerate their green energy transition, due to the fact that they will not be interconnected in the next decade. Such cases are the islands Anafi, Sifnos, Donousa and Gavdos [9]. Dimou and Vakalis [10] presented the first total energy green transition plan for the island of Ag. Efstratios with RES penetration that exceeded 85%. The proposed set-up included a wind turbine, PV panels and a battery and the authors highlighted the low penetration of PV and the high cost of batteries. As seen in the project of Ag. Efstratios [10], the high RES penetration can be limited by several factors and is dependent on the applied technological solutions but also to weather related constraints. On the one hand, the utilization of PV panels is clearly related to the hours of sunlight and the energy demand curve. On the other hand, wind-based solutions are subjected to the wind speed at a given moment in relation to the energy demand. Therefore, the assessment of wind potential has been in the center of attention, with Ouarda and Charron [11] highlighting that the probability density function is usually "fitted to short-term observed local wind speed data". The authors developed two-component mixture models in order to incorporate homogeneous and heterogeneous mixture distributions and incorporated statistical analysis in order to optimize their algorithm. Similarly, Mazzeo et al. [12] applied unimodal and bimodal truncated normal in order to model the extreme wind speed conditions.

There are several similarities between the characteristics of Anafi and Agios Efstratios, where the project Ai Stratis—Green island has been proposed. Both have populations of similar size, high wind potential, and are powered solely by conventional diesel engines. Therefore, Anafi could be another island that will go towards the green transition. This study focuses on the renewable technological installations, the detailed energy demand curves and the detailed yearly weather conditions for the assessment of RES penetration in green island microgrids. The study utilizes the Weibull probability density function for the calculation of the wind speed as developed by Hiester and Pennell [13] and the Klein/Theilacker algorithm for the calculation of solar radiation as presented by Duffie and Beckman [14]. The aim of this paper is to highlight the wind-based renewable energy transition as a pathway to mitigate high cost of electricity generation in the Non-Interconnected Islands and seek green energy transition solutions with lower economic and environmental costs. By using different energy analysis scenarios, the case of Anafi is presented and analyzed for a potential energy transition. The expected result is the proposal of a system that will largely cover the energy needs of the island and at the same time will significantly reduce the cost of production per kilowatt hour.

2. Materials and methods

2.1. Anafi—energy demand and climate information

Anafi was chosen as the place of study, since it is a small island, not interconnected with the mainland network and with a low population that does not fluctuate significantly throughout the year. It was also chosen because of the high wind potential that exists on the island. Anafi is a small island, with a somewhat triangular shape that belongs to the Cyclades complex of the Aegean Sea, is located east of Thira, at the southeastern tip of the Cyclades and is 155 nautical miles from Piraeus. It consists of three settlements in the town of Anafi, Kleisidi and Agios Nikolaos or Gialos. According to the 2021 census it is an island with a small population of 257 inhabitants, while its area is about 39 km^2. In the east of the island there is a peninsula, while in the south of Anafi there are small uninhabited islets, Ftena, Pachia, and Makria. The island has a mountainous character with the highest height being found on Vigla mountain with 579 m. In addition, it has an intense coastal division, with the length of its coasts reaching 32.4 km, without large bays [15]. Solar radiation data were retrieved from the software RETScreen-presented in the following subsection—which has incorporated the NASA climate database. Data for the wind potential were retrieved from via the Geographical Map of RAE [16], Figure 1 presents the solar radiation and Figure 2 presents the average annual wind speed on the island.

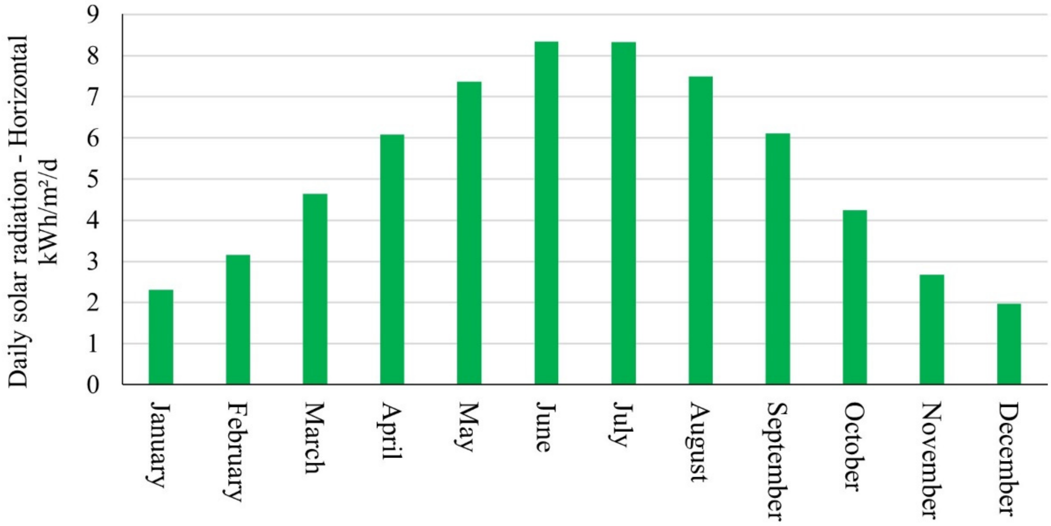

Figure 1. Monthly horizontal solar radiation of Anafi (source: RETScreen database).

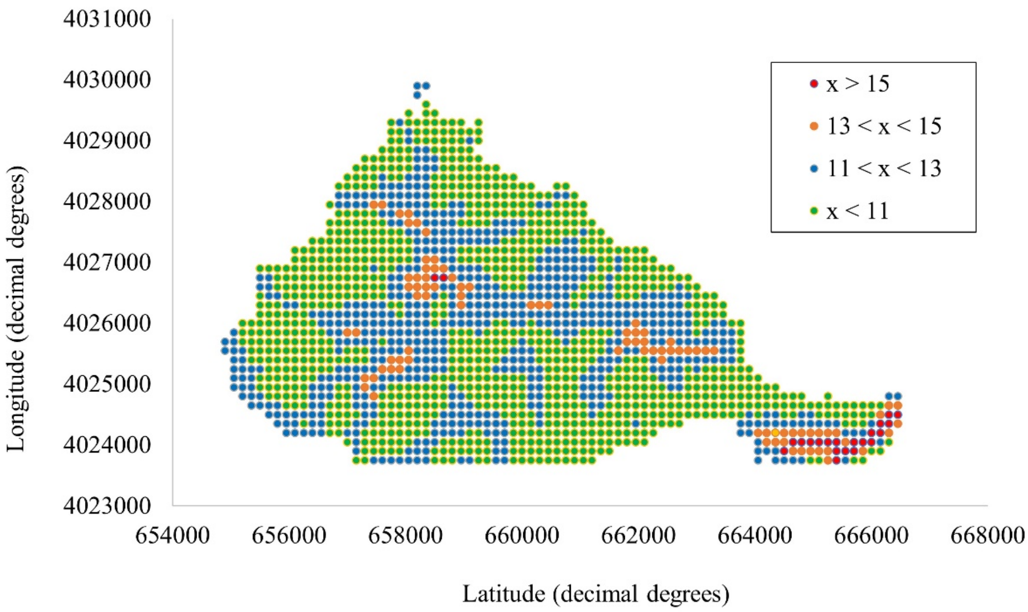

Figure 2. Average annual wind speed on Anafi island [17].

Anafi is one of the Non-Interconnected Islands (NII), and specifically belongs to the group of ‘small’ NIIs whose annual peak demand does not exceed 10 MW. To date, Anafi has not been connected to the mainland electricity grid but is planned to be connected within the framework of the 4th Phase interconnection of the Cyclades, through submarine cables between the Santorini-Anafi islands (Network Development Plan 2021–2025, 2020). The energy needs of its inhabitants are covered by a local power station, which includes five internal combustion engines with a total nominal power of 1.1 MW. According to the Production Data Sheets of the HEDNO [18] of NIIs that are presented in Table 1, in the last 5 years the annual peak demand ranged from 0.59 MW for the year 2017 to 0.55 MW in the year 2021. Regarding the required energy of thermal units of the island, in 2021 it fluctuated from 77.93 MWh in the month of April with a maximum price of 278.03 MWh for the month of August.

Table 1. Electricity generation and cost on Anafi for the year 2021.

Year	Month	Energy of thermal units (MWh)	Average cost of production (€/MWh)	Average variable cost (€/MWh)
2021	December	82,73	493,46	309,01
2021	November	78,98	497,99	304,79
2021	October	86,56	444,78	283,01
2021	September	137,35	787,26	300,45
2021	August	278,03	184,66	121,35
2021	July	205,42	325,47	237,67
2021	June	120,6	944,02	251,31
2021	May	80,23	387,44	252,45
2021	April	77,93	650,14	260,29
2021	March	84,98	612,66	248,06
2021	February	80,53	623,07	245,81
2021	January	88,82	583,84	241,79

As seen in Table 1, the average cost of production of conventional units in Anafi for the months of January to August 2021, is approximately 539 €/MWh, with the highest price meeting in June at 944.02 €/MWh and the smallest in August with 184.66 €/MWh. The average variable production cost of conventional units of the island, is approximately 232 €/MWh with the lowest price being observed again in August (121.35 €/MWh) and the highest in April (260.29 €/MWh). It should be stated that the participation of renewable energy systems (RES) in electricity production is zero.

2.2. Software and methods of analysis

The energy analysis was implemented by means of RETScreen, a free software that has been developed in Excel environment and aims to evaluate the production of energy from potential projects with renewable energy sources and it can provide information about the emissions, the economics, and the risk of the specific project [19]. It is a useful tool in decision making and for assessing the viability of future RES projects, but also to find additional solutions for profitable energy production [19]. The Energy analysis part evaluates the generated energy from the proposed energy system. Cost Analysis calculates the initial and annual costs for the proposed project are estimated. Emission Analysis assesses the mitigated greenhouse gas emissions due to the development of RES. Financial Analysis, calculates the net present value of the project and assess the overall economic sustainability of the project.

This present study analyzed and compared two different scenarios for energy production on Anafi from one or more renewable energy sources, conventional energy sources and storage systems. In the first scenario the hybrid system used consists of a wind turbine with a nominal power of 330 kW, a photovoltaic station with a total rated power of 150 kW and a 537-kW backup diesel generator, in a manner that would resemble the energy generation set-up of Ag. Efstratios. In this scenario a wind turbine was used as the basic electric charge system, photovoltaic as the intermediate electric charge system, while a backup diesel generator was used as the peak electric charge system. More specifically, a wind turbine from the manufacturer Enercon, model Enercon 33–50 m, electric power 330 kW and with a turbine was used. The technical characteristics of the wind turbine selected are the following: pylon height 50 m, rotor diameter per turbine 33 m and scan area per turbine 876 m^2. As an intermediate electric charge system, solar energy was selected using photovoltaics. More specifically, 1000 units of monocrystalline photovoltaics of the manufacturer Canadian Solar, model mono-Si-CS4A 150 W, with a total electric power of 150 kW and a power factor of 23% were used. Finally, a conventional energy source, a backup oil generator, model D2842-1103, was selected as the peak electric charge system by the manufacturer MAN Group. Then the price of the fuel is required, at which the price of 1.2 €/L was registered.

The second scenario utilized PV panels, a battery storage system and conventional energy source, i.e., a backup diesel generator. In this scenario, 2500 units of monocrystalline photovoltaics from the manufacturer Sunpower, model mono-Si-SPR-210-BLK and a total electric power of 525 kW were used. The PV station will cover a total area of 3.11 km^2. The photovoltaics will be placed at an angle of 28 degrees setting the azimuth 0°, because it is preferable that their orientation is towards the equator. The efficiency of the photovoltaic system will be 16.9%. An energy storage system with Li-ion battery packs was preferred as the storage system. The battery packs will have 0.2 days of autonomy, 24 V voltage, 85% efficiency, maximum discharge depth of the battery that can be withdrawn repeatedly without abnormal loss of battery life 60%, charge controller efficiency 95% and power 45000 Ah. 'Environmental' was chosen as the temperature control method, considering that the battery will be in an uninsulated shed. A backup diesel generator was chosen as the state-of-the-art electric charge system. The model chosen here is Turbion, from the manufacturer Entropic Energy. Then the price of fuel entered was 1.2 €/L. In summary, the hybrid system used in Scenario 2 consists of a photovoltaic station with a total rated power of 525 kW, a Li-ion storage batteries or similar features 1.8 MWh, a backup diesel generator power 250 kW.

Continuing, in the next spreadsheet, in the Cost Analysis, the initial and annual costs for the proposed project were estimated. To carry out these estimates, the costs of the study, the development, the engineering of the project, as well as the costs for the power generation systems, their transmission, operation and maintenance and their spare parts were recorded. Due to the similar size and the population of Anafi with Agios Efstratios, recent financial data were used from the environmental impact study of the project Hybrid System for Production of Electricity and Thermal Energy from RES on the island of Agios Efstratios [21]. Completing the first scenario, the financial parameters were entered so that the financial analysis of the project could be calculated. It was therefore considered that the rolling tax on fuel costs is 3%, the inflation price 1.5%, the reduction rate 1% and the life of the project is 25 years. The amount of the project grant is 1.000.000 €, with 50% interest arrears, 1% loan interest rate for 25 years.

3. Results

The basic case of a power generation system was calculated by converting the monthly energy of thermal units (MWh) taken from Table 2. The peak load of the system (0.55 MW) was then calculated towards the maximum average monthly average (278 MWh = 374 kW), which represents the percentage that the peak electricity load exceeds the maximum monthly average power load during the twelve months. This percentage is 29%.

Table 2. Data on demand and production of electricity in Anafi.

Year	Month	Maximum annual point of demand (MW)	Energy of thermal units (MWh)
2021	December	0,55	82,73
2021	November	0,55	78,98
2021	October	0,55	86,56
2021	September	0,55	137,35
2021	August	0,55	278,03
2021	July	0,55	205,42
2021	June	0,55	120,6
2021	May	0,55	80,23
2021	April	0,55	77,93
2021	March	0,55	84,98
2021	February	0,55	80,53
2021	January	0,55	88,82

In scenario 1, the wind energy was set to be the main system, solar as the intermediate electric charge system and a conventional energy source as the conventional peak charge system. The energy produced by the basic load, the wind turbine, amounts to 1920 MWh, the energy produced by photovoltaics is 873 MWh, while the energy produced by the backup generator is 3124 MWh if it operates nominally. The percentage of electricity delivered to the load from each energy source is also calculated. More specifically, 86.4% is delivered through the wind turbine and 3.9% through photovoltaics. It should be mentioned that the operation of PV panels overlaps with the operation the wind turbine, which is the base system, but the PV produced electricity assists significantly to cover the mid-day peak demands with green energy. This result is comparable with the results that were published in a relevant study of Ag. Efstratios [10]. In this case, therefore, it is necessary to have a peak load supply system which is designed to cover the electricity consumption that has not already been covered by the main power system. This can happen when the installed capacity is not enough or to cover scheduled shutdowns. For this reason, a conventional diesel engine has been selected as the peak cargo supply system, which covers the remaining 9.7%. The results are presented in Table 3.

Table 3. Elements of electricity generated and delivered to the load in Scenario 1.

	Wind	Solar	Diesel	Total
(MWh) Electricity generated	1920	873	3124	5917
(MWh) Electricity delivered to load	1224	55	137	1416
(%) Electricity generated	68,4	31,1	111,3	210,8
(%) Electricity delivered to load	86,4	3,9	9,7	100

In Scenario 2, according to calculations in RETScreen, the electricity delivered to the load from the photovoltaics is 995.51 MWh, while the percentage of electricity delivered to the load for the proposed case of electricity use of the power system is 68.2%. And in this scenario, it is necessary to have a peak load supply system. In this scenario a diesel engine, model Turbion was used, and the electricity delivered was 464.5 MWh, and it covers 31.8% as presented in Table 4. These results highlight the ability to install battery-backed systems with lower nominal capacity than non-battery-backed systems in order to support the same load. Nonetheless, a significant parameter that need to be assessed is the RES penetration of such systems.

Table 4. Elements of electricity generated and delivered to the load in Scenario 2.

	Solar	Diesel	Total
Electricity generated (MWh)	1481,04	705,84	2186,88
Electricity delivered to load (MWh)	995,51	465,50	1461,01
(%) Electricity generated	108,90	51,90	160,80
(%) Electricity delivered to load	68,20	31,80	100,00

Summarizing, in the first proposed scenario the penetration from RES amounts to approximately 90.3%, while in the second proposed scenario 68.2%, as presented in Figure 3. The higher penetration rate from RES, highlights that wind-based hybrid systems can be used for increased RES penetration in isolated grids in order to promote the efficient green transition. In the second scenario, the total share of RES in electricity production is lower, as is the percentage of electricity produced. This makes sense because the main system is photovoltaics using a battery. While the power of the photovoltaic exceeds the average electricity demand, it does not have the ability to meet the peak demand where it ends up being covered by the conventional engine. In this scenario, however, there is less excess energy, due to the correct dimensioning of the photovoltaic and the battery. Thus, the percentage of excess electricity produced in the first scenario is much higher than in the second. This excess energy could be exploited by other projects, such as hydrogen production systems, for electrolysis, for charging electric cars or for the conversion of the port of Anafi into a green port [21].

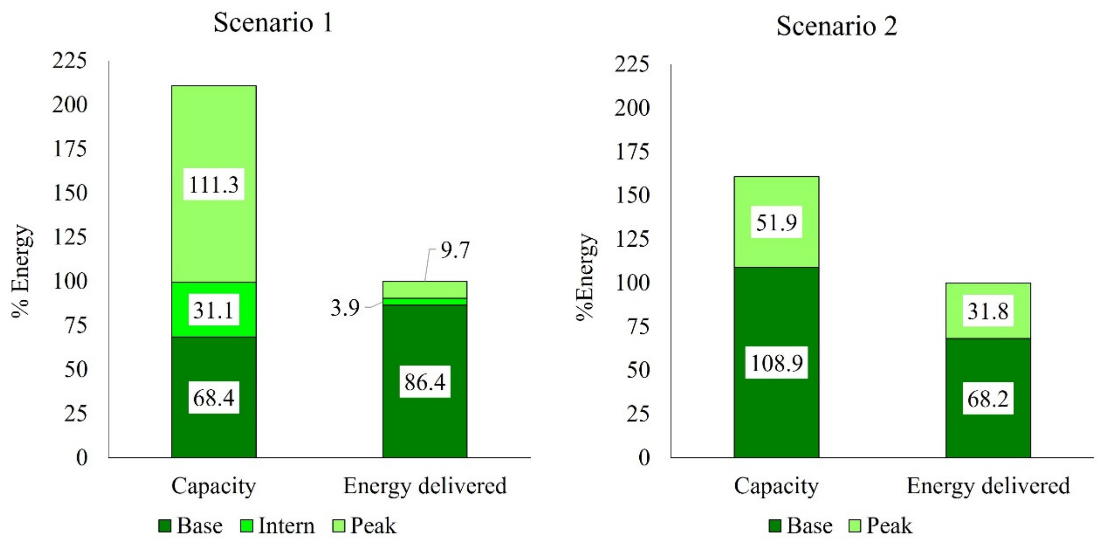

Figure 3. Energy produced and delivered by source type for both analyzed scenarios.

Regarding the greenhouse gas emissions in the first scenario, that is, taking advantage of wind, solar and a conventional energy source, there is a reduction of CO_2 of about 95%. With the basic power system, it is estimated that 2051 tons of CO_2 are produced, while in the proposed scenario only 95.9 tons of CO_2, so there has been an annual reduction of emissions of 1956 tons of CO_2. By removing the wind energy and adding a battery storage system (Scenario 2), a drop of about 80% in CO_2 is observed. More specifically, with the basic power system it is estimated that 2543 tons of CO_2 are produced, while in the proposed scenario only 520.9 tons of CO_2, so there has been an annual reduction of CO_2 emissions of 2022 tons of CO_2.

RETScreen calculated the total annual cost for each scenario, which represents the annual costs related to the operation, maintenance, and financing of the project. It is essentially the sum of the savings or operating and maintenance costs, the fuel costs for the proposed case and the debt payments. The total annual cost includes the repayment of the "capital" of the debt. In the first case, it was estimated by the program that the initial cost amounts to 5.205.720 €, of which 1% concerns the cost of the study, 2.9% the cost of development, 1.9% of the engineering of the project, 60.4% of the costs for the electricity generation systems and finally 33.8% of the costs of their transportation, spare parts, etc. In the second case it was estimated by the program that the initial cost amounts to 5.631.600 € of which 1.8% concerns the cost of the study, 2.7% the cost of development, 1.8% of its engineering, 57.2% of the costs for the electricity generation systems and finally 36.6% of the costs of their transportation, spare parts, etc. Figure 4 presents the net present value (NPV) of the two scenarios and the payback times of each scenario. It is shown that the wind-based system has a much faster payback time, i.e., 6 years in comparison to 11 years, but has an overall lower net present value with 11.13 million € vs 12.28 million € and this can be attributed to the role of the relatively big sized battery that allows the integration of a smaller diesel engine in order to meet the peak demand.

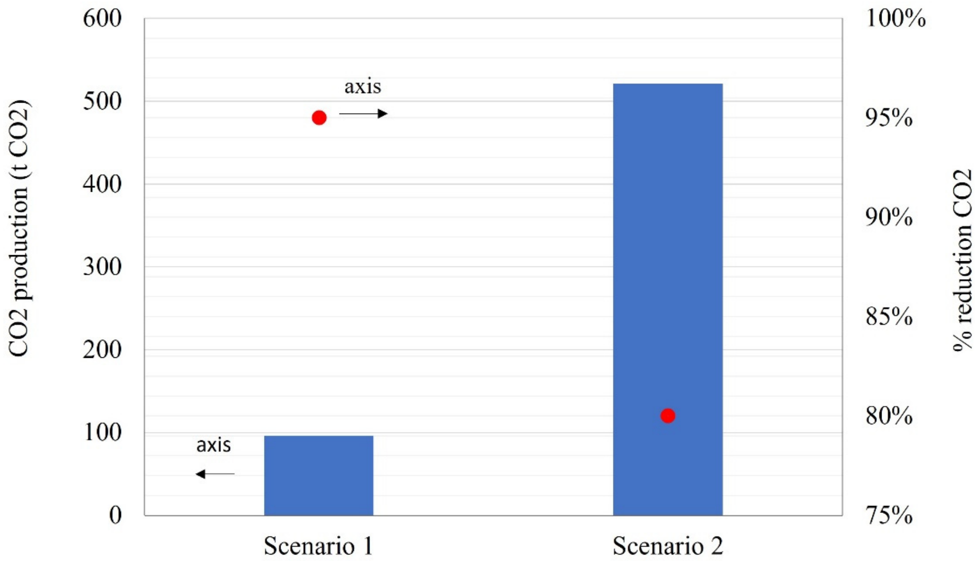

Figure 4. Reduction of emissions for both analyzed scenarios.

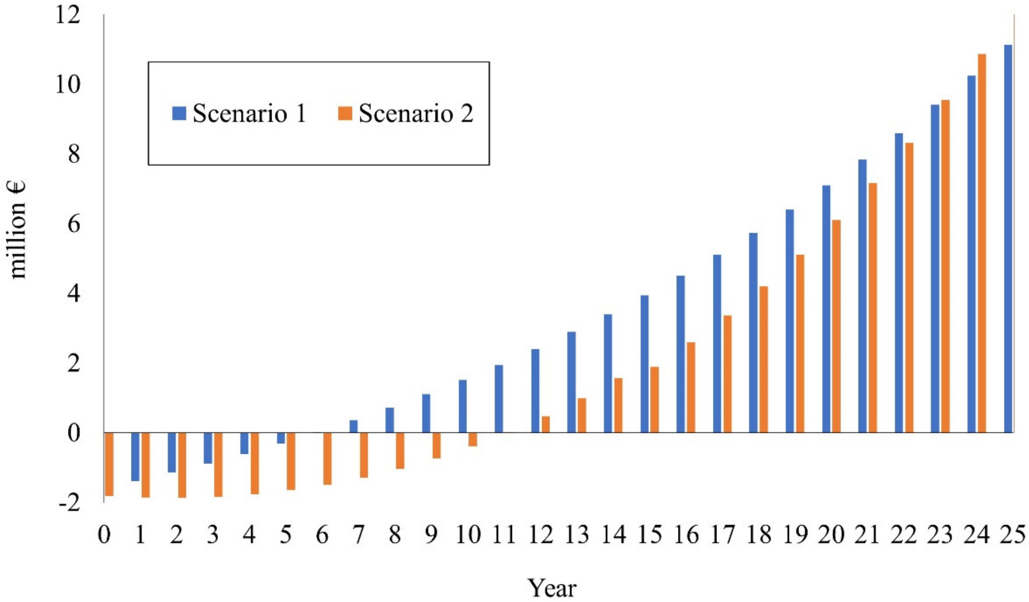

Figure 5. NPV for both analyzed scenarios.

From the sixth year onwards, it is observed that there is the possibility of revenues that can be used for the maintenance of the island's project itself, as well as for the financing of new similar projects on other islands, in order to contribute to their own green energy transition. Thus, initially, through state subsidies, sustainable, low-risk projects can be financed that will lead to the energy transition of the NIIs, which will then contribute to the islands themselves in order to achieve a rolling green transition of the remaining NIIs. This will also lead to a reduction in the greenhouse gas emissions of such islands, as shown in both scenarios, and consequently to the achievement of the goals set at national and European level. An issue that needs to be in the center of the conversation is that wind power seems to be the most efficient renewable energy system in respect of penetration, efficiency and payback time [10]. Nonetheless, photovoltaic panels have far greater acceptance when compared to other RES. More specifically, according to a research study that took place in regions of France, Germany and Switzerland in 2019, resulted in more than 85% of respondents being in favor of solar energy [22]. Thus, the pathway of efficient green energy transition should include a systematic effort to inform the public about the positive aspects of RES with low social acceptance like wind power.

4. Conclusions

In order to achieve the goals of the Greek National Energy and Climate Plan, the Long-Term Strategy 2050—LTS and the European Green Deal, regarding the reduction of greenhouse gas emissions, the green transition of the NIIs in the coming years is necessary. Through this work, two systems using RES were proposed to meet the energy needs of Anafi and to reduce its energy production costs. Using RETScreen as analysis software, it is observed that with the existing conditions, government programs and grants, in a small NII (annual demand peak <10 MW) through a relatively low self-financing it is possible to create hybrid stations where the penetration of RES can exceed 90%. This percentage is very important as it exceeds the penetration of 85% that has been set as a target in the case of Agios Efstratios, where it is a model of a green island. Finally, the green transition of the NIIs can be done more directly with the contribution of the inhabitants of the island, through the energy communities. With the help of state funding and by investing in green systems themselves, through the installation of photovoltaic panels on the roofs of their homes, or through their participation in an energy community, they can contribute to the more direct penetration of RES, the decoupling from fossil fuels and the reduction of electricity generation costs.

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Conflict of interest

The authors declare no conflict of interest.

Author contributions

A.O.: Writing—Original Draft, Investigation, Methodology, Validation, Data Curation, Formal Analysis; S. V.: Supervision, Visualization, Conceptualization, Methodology, Project administration, Validation, Writing—Original Draft, Writing—Review & Editing, Resources.

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