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Energy Autonomy Scenario for the Island of Mykonos in Greece with Solar Power Plants †

Agathi Nasioula [1,2] and Panagiotis G. Kosmopoulos [2,*]

[1] Department of Physics, Ludwig Maximilian University of Munich (LMU), 80539 München, Germany; agnasioula@gmail.com
[2] Institute for Environmental Research and Sustainable Development, National Observatory of Athens (IERSD/NOA), 15236 Athens, Greece
* Correspondence: pkosmo@noa.gr
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Abstract: Mykonos is one of the fastest growing Greek islands, and it attracts hundreds of thousands of tourists, mainly in the summer months. A consequence of this rapid development is an ever-increasing energy demand. Solar energy exploitation is the topic of this study, and the aim is to provide an energy autonomous solution for Mykonos that covers its electricity needs for the whole year from photovoltaic plants. Data from the Copernicus Atmosphere Monitoring Service and Eumetsat's support to nowcasting and very short-range forecasting were combined with Radiative Transfer Models and the Photovoltaic Geographical Information System in order to quantify the island's expected electricity production and the effect of atmospheric parameters, and this enabled an energy adequacy scenario to be formed and financial analysis to be conducted. The aim of the method proposed in this study is to highlight the opportunity for energy transition for Mykonos as well as the rest of Cyclades islands, and to thereby provide viable and sustainable development.

Keywords: energy autonomy; cloud and aerosol effect; renewables

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1. Introduction

Mykonos is one of the most popular tourist destinations In Greece, and it is an important part of the country's economy. The "island of the winds", as it is often called, is located in the heart of the Cyclades group in the Aegean Archipelago [1]. Defined by Greek legislation and the Regulatory Authority of Energy (RAE) as a Non-Interconnected Island (NII) [2], the island of Mykonos covers an area of 86.125 km^2, and it consists of 9802 permanent residents according to the latest census of 2021 [3]. Until 2020, when a programme of the Independent Power Transmission Operator (ADMIE or IPTO) S.A. connected Cyclades Islands with the National Mainland Interconnected Transmission System, the energy production of Mykonos was to a great extent due to thermal stations that used either heavy or light oil, which causes, as we know, significant environmental damage [4]. Taking into consideration the high solar energy potential of Greece, there is a significant reason to question the sustainability of the interconnection of Cyclades, since the installation of renewable energy sources (RES) and especially of PV technologies seems to be an efficient solution for the prevention of ecological pollution and for the financial growth of the region.

For Mykonos, Earth Observations in terms of solar irradiation and environmental parameters, such as Global Horizontal Irradiation (GHI) under different sky conditions as well as Cloud Optical Thickness (COT) and Aerosol Optical Depth (AOD), were exploited so that the effect of clouds and aerosols on solar irradiation and energy could be quantified. Thus, satellite and model-based data were utilized with the aim of forming an adequate energy scenario. In this paper, Section 2 notes the materials and methods that have been exploited during the study, and Section 3 presents the solar energy planning scenario. Section 4 associates the energy measurements of the scenario with a financial analysis, and, finally, Section 5 outlines the conclusions and points out the significance of such studies for both the island's prosperity and the protection of the environment.

2. Materials and Methods

2.1. Solar Radiation and Energy Simulations

For an accurate quantification of the solar energy potential and the atmospheric parameters, namely, the aerosol and cloud effect, the solar, meteorological, and atmospheric services that Copernicus provides through the Solar radiation Data for Professionals (SoDa Pro) platform were put to use [5]. For the aerosol effect on solar energy, the data of total Aerosol Optical Depth (AOD) at 550 nm were extracted from the Copernicus Atmosphere Monitoring Service (CAMS) to measure the mean of AOD550 in the period between June 2019 and June 2021, and this mean was later converted into the Aerosol Modification Factor (AMF). AOD550 results came from using the data of GHI0 and GHI00. GHI0 stands for the radiation under clear sky conditions, and GHI00 stands for the radiation under clean (from aerosols) and clear (from clouds) sky conditions. In order to determine the Cloud Modification Factor (CMF), the Satellite Application Facility for supporting Nowcasting (SAFNWC) was used, and it exploited the GHI and GHI0 data from SoDa Pros CAMS radiation service for the period between March 2013 and February 2023. Here, the term GHI represents the radiation under all sky conditions, while GHI0, similar to AMF, represents the radiation under clear sky conditions. In order to plan a realistic scenario, the energy losses caused from aerosols and clouds must be taken into consideration and calculated by a formula. The aerosol effect on solar energy, namely, the AMF, due to the ability of aerosols to scatter and absorb the sunlight is given from by Equation (1):

$$\mathrm{AMF} = \mathrm{GHI0}/\mathrm{GHI00} \quad (1)$$

CMF that indicates the cloud scattering, absorption, and reflecting effect is given by Equation (2):

$$\mathrm{CMF} = \mathrm{GHI}/\mathrm{GHI0} \quad (2)$$

Both factors take values between 0 and 1, with 1 indicating no aerosol and no cloud effect, respectively. With the aid of the Photovoltaic Geographical Information System (PVGIS), it was subsequently able to point out and visualize the difference of PVs with and without a latitude-based tilt concerning the in-plane irradiation and the performance of the system [6].

2.2. Financial Analysis

Taking into account that the wholesale electricity price in Greece in December 2022 was on average 276.97 EUR per MWh [7], the financial revenues and losses were measured according to Equations (3) and (4):

$$\text{Revenue (€)} = \text{Energy Production (MWh)} \times \text{Electricity Price (€/MWh)} \quad (3)$$

$$\text{Loss (€)} = (EP_{max} - EP_{actual}) \times \text{Electricity Price (€/MWh)} \quad (4)$$

In Equation (4), EP_{max} stands for the energy production of the PV under "clean from aerosols" and "clear from clouds" sky conditions, and EP_{actual} depicts the actual energy production (i.e., including the atmospheric effects) [8].

3. Results

3.1. Aerosol and Cloud Effect on Solar Radiation

Figure 1 depicts the atmospheric effect, i.e., the aerosol and cloud parameters of each month, into solar radiation. The monthly average of AMF is calculated based on the 3-h observations of AOD, while the monthly measurements of the cloud effect, namely, those of CMF, are based on the 15-min rate of COT according to the periodicity obtained and collocated to the AOD data time steps of 3 h [8]. The graph of CMF has a parabolic curve, according to which CMF increases gradually from January to July, where it reaches its highest rate and then decreases until December. CMF that shows low rates during the winter months and higher rates during the summer months indicates the major effect of clouds on solar energy during winter and their minor effect during summer, and this accords with the climatological conditions of the wider region. AMF presents more unstable values, with its lowest occurring during the spring months, when the aerosols, i.e., dust levels in the atmosphere, reach their peak, and presents its highest during the winter, when low human activity is observed.

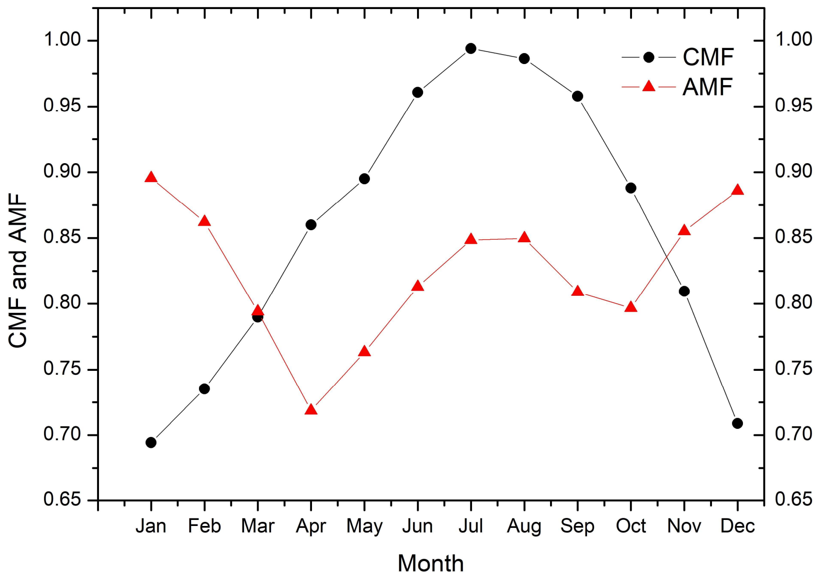


Figure 1. Monthly panel plot for averages of CMF and AMF.

3.2. Energy Planning Scenario

Many studies promote the latitude-based tilts contrary to the optimal tilts for maximum solar energy production, as under bad atmospheric conditions, the performance of latitude-based tilts is more efficient, despite their lower energy production during better weather conditions. The latitude of Mykonos is 37.4° North, so panels with a southern tilt of 37° are appropriate for the coverage of the energy consumption.

Figure 2 depicts the solar irradiation that reaches the horizontal and inclined parts of 37° PV panels. The energy production potential of tilted PV presents a more balanced and stable solution. During the winter months, in which solar energy struggles to cover the island's needs, they have a larger output, and this is contrary to the horizontal ones. The yearly energy potential for the horizontal PV is 1831.13 kWh/m^2, and for the tilted PV at 37°, it is 2036.04 kWh/m^2. The PV system is simulated for the Crystalline Silicon (CS) panel material, with losses of 14%, and with a realistic production rate in the region of 102.97 kWh/m^2 [8].

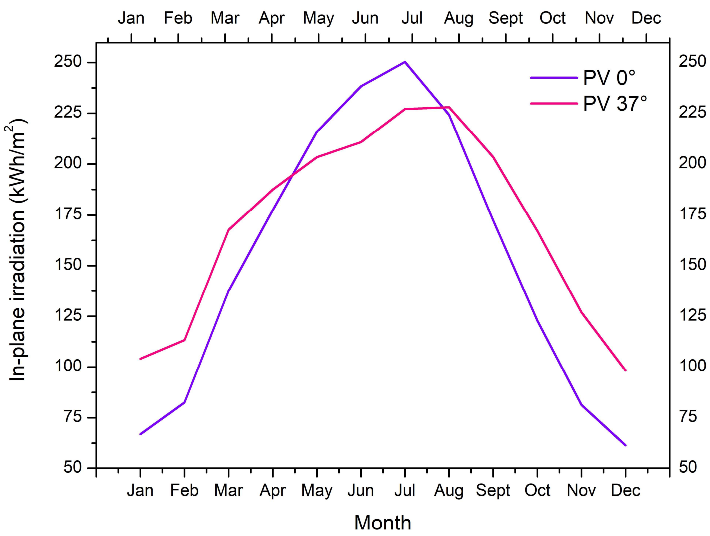


Figure 2. Mean of solar irradiation input to horizontal and tilted at 37° PV panels.

The energy planning scenario was based on the idea that the energetic exigency of the island of Mykonos needs to be fulfilled. The total annual energy consumption of the island is estimated to be 125,500 MWh, which sets this figure as the energy target [4]. Based on the energy output values per month of a PV CS 37° 1 kWp system that has a total 1.63 MWh energy output, an adequate scenario was built prioritizing energy coverage during December, where the lowest PV output is observed. The energy scenario was thus designed with a CS-based 120 MWp PV system.

The scenario of a total CS 120 MWp PV proves to be a sustainable and profitable solution for the energy needs of Mykonos. According to Figure 3, where the energy consumption of the island and the energy production of the PV system for each month are displayed, this scenario not only reaches but also exceeds the energy target, as is clearly shown in Figure 4a. The quite large surplus of electrical energy each month besides August is depicted in Figure 4b, and it shows that the island of Mykonos is able to become autonomous from an energy perspective as well as to benefit financially from the distribution of energy to the rest of the grid.

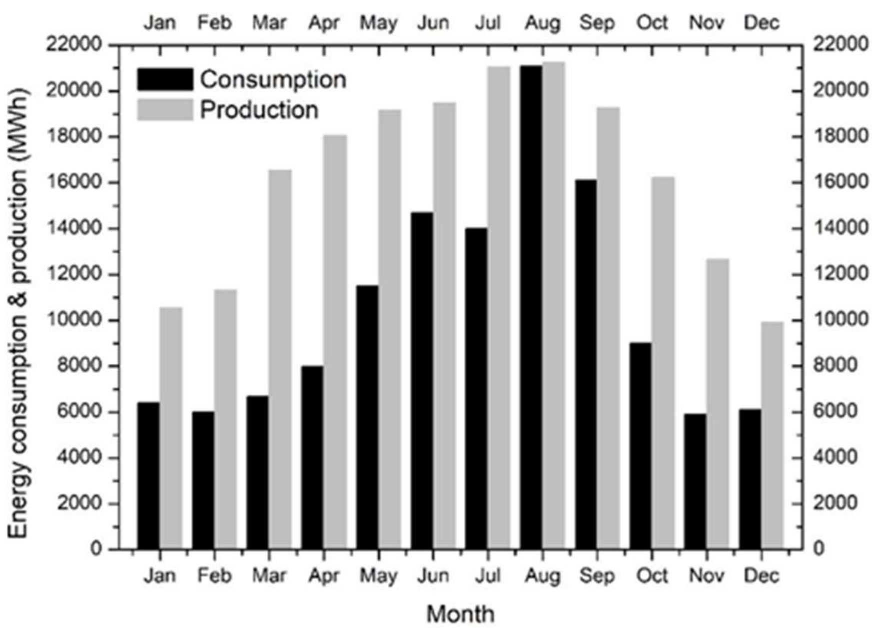
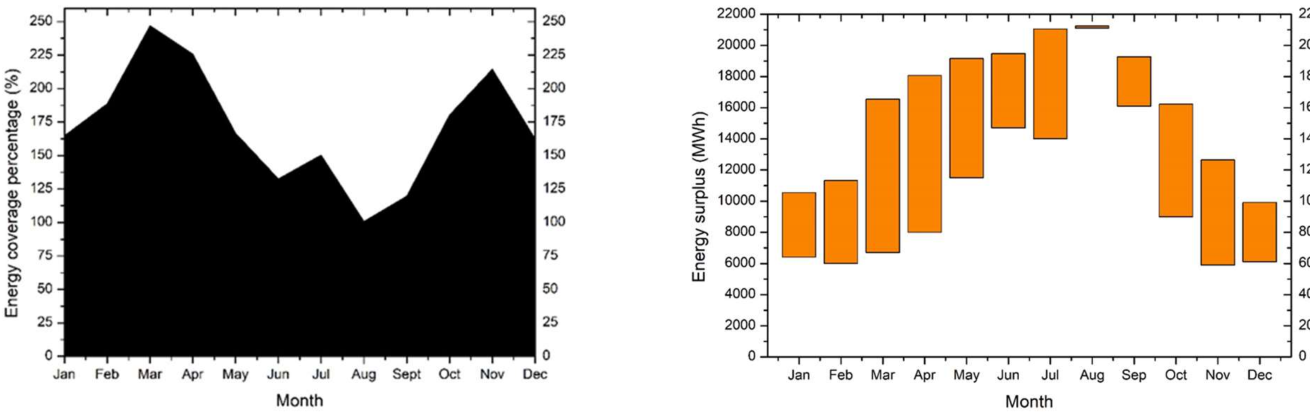


Figure 3. Monthly average consumption and production for the CS 120 MW PV scenario.

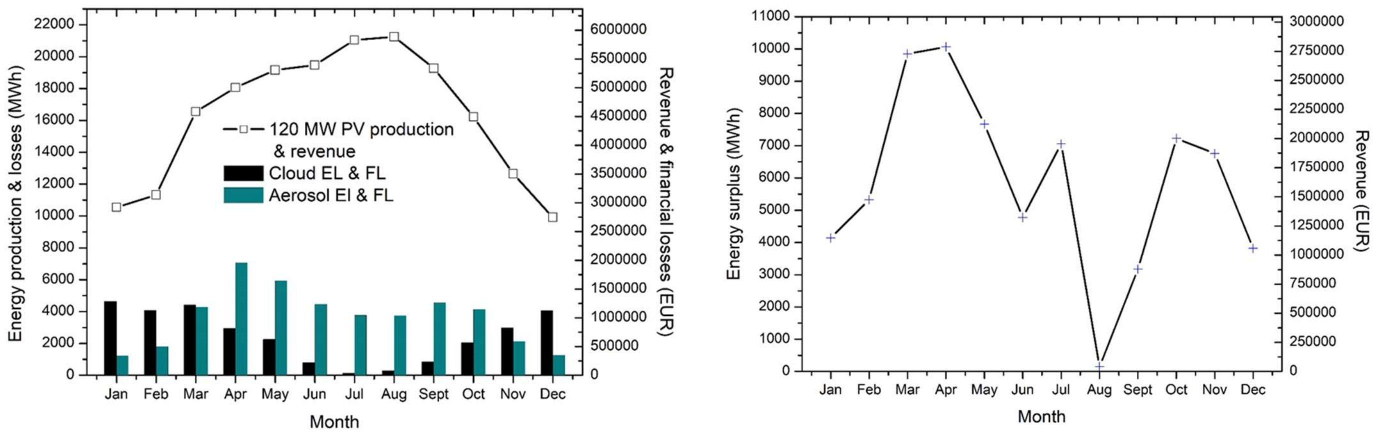


(**a**) (**b**)

Figure 4. Monthly panels plot for (**a**) coverage percentage of the energy target and (**b**) energy surplus from the CS 120 MWp PV scenario.

4. Discussion

Figure 5a associates the energy production of the 120 MWp PV system with the revenue and energy losses due to the atmospheric parameters with financial losses. The scenario produces a total energy of 195,503 MWh, which corresponds to a 54.15 million EUR revenue, and as has already been shown in Figure 3, the financial profit reaches its peak during the summer months, when the effect of the atmospheric parameters is limited. The losses caused from clouds are of the order of 29,465 MWh and 8.16 million EUR concerning energy and financial losses, respectively, with the minimum occurring during summer months, while the effect of aerosols is maximum during spring months and the overall losses are 44,453 MWh and 12.31 million EUR.c.



(**a**) (**b**)

Figure 5. Annual (**a**) financial analysis and (**b**) revenue from the energy surplus of the CS 120 MWp PV system.

The energy surplus from the 120 MWp PV system, which is depicted in Figure 4b, is presented in Figure 5b in relation to the revenue. With its lowest value of 148.4 MWh in August, the annual surplus reaches up to 70,003 MWh, and it provides a total clear profit of 19.39 million EUR to the island. Hence, the financial analysis proves that Mykonos has the potential to become autonomous and stable as far as energy is concerned. Nevertheless, the energy supply during the night or under bad weather conditions has to be taken into consideration, and this makes a storage system a necessity. The most technically possible and easy-to-operate solution that simultaneously provides electrical stability to the island is a lithium battery. For the 120 MW PV system, a 672–720 MWh lithium battery is sufficient [8]. Considering the fact that a lithium battery costs on average 138.71 EUR per kWh [4], the required battery would reach a cost of 93,213,120–99,871,200 EUR [9]. In 2020, the first two phases of a programme that was controlled and operated by the Independent Power Transmission Operator (ADMIE or IPTO) S.A. interconnected Cyclades Islands with the National Mainland Interconnected Transmission System, and it had a budget of 250 million EUR. Mykonos was connected with Syros and Naxos with this infrastructure [10–12]. According to the latest published data, the installation cost per KW is estimated to be nearly 784.40 EUR [13], and so the cost for the CS 120 MWp PV system that is presented in this study, which includes the lithium battery, reaches the sum of 94.13 + 93–100 million EUR, and this is 22.35–25.15% less that the cost of the programme of IPTO. It is therefore of great importance to highlight the significance of both optimum energy planning and decision making for the environment and for the economy as a whole. Nevertheless, even though it is considered an NII, the programme provides the island of Mykonos with the opportunity to exploit the energy surplus mainly during spring and winter in order to develop its tourism and, hence, its economy.

5. Conclusions

As one of the most popular islands of the Cyclades, and, thus, an island with high energy consumption, the goal for Mykonos is energy autonomy and sustainability. The island's energy production from RES and specifically from solar plants is thus a necessity for sustainable prosperity and for further tourism development. Directing the transition of Mykonos, energy planning scenarios were conceptualized, tested, and analyzed that could achieve an appropriate solar plant solution which could fulfill the island's needs. The results obtained by the study were as follows:

- A CS 120 MWp PV system exceeded the energy target during the whole year, and an area of 2,426,748 m^2, namely, 2.8% of the whole island, would be required.
- PV panels with latitude-based tilts produce 10.06% more energy than the horizontal ones, and were thus preferred for the demonstration of the system. The cloud effect on the scenario's energy production was measured to cause a 10.94% loss, while the effect of aerosol was measured to cause a 16.5% loss.
- The calculations used in the financial analysis showed a total system revenue of 54.158 million EUR, followed by a 8.16 and a 12.31 million EUR loss due to clouds and aerosols, respectively. However, there was also a 93–100 million EUR loss due to the lithium battery that would be required.
- The installation of the 120 MW PV system that concludes with the lithium battery that supplies the island with energy during night time or under bad weather conditions costs 22.35–25.15% lower than the programme of IPTO S.A.
- The energy surplus of 70,003 MWh (i.e., 19.39 million EUR) in combination with the interconnection of Mykonos with the rest of the grid provides an opportunity for the island to enhance its economy by distributing energy in excess with the rest of the grid.

The study of the energy transition of Mykonos to renewables shows a reachable and profitable path in the field of energy, and this will encourage more islands and areas around the world to become autonomous. The sustainability that the solar plant system provides is a chance for future economic growth and stability as well as a chance for an active form of environmental protection. Along with the methodology of the study, which spreads awareness of the cloud and aerosol effect on energy plans that result in more stable, consistent, and accurate predictions of energy production, the findings prove the importance and the usefulness of solar plant systems (which must always be accompanied with a proper study of both their operation and their impact) to the prosperous development of the island and the environment.

Author Contributions: P.G.K. designed and conceptualized the idea for this study, and contributed to the methodology, the data curation, the writing of the original draft, and the reviewing and editing process. A.N. contributed to the methodology, the data curation and writing, and the reviewing and editing of the original draft. All authors have read and agreed to the published version of the manuscript.

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