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RESEARCH ARTICLE / ARAŞTIRMA MAKALESI

Assessment of Off-Grid Photovoltaic System Feasibility: A Dual Simulation Approach for Economic Viability and Performance in the Mediterranean Region

Şebeke Dışı Fotovoltaik Sistem Olanaklılığının Değerlendirilmesi: Akdeniz Bölgesinde Ekonomik Uygulanabilirlik ve Performans için Çift Simülasyon Yaklaşımı

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Abstract

This study investigates the feasibility and economic viability of off-grid photovoltaic systems in the Mediterranean region, specifically focusing on a detached house located in Üçoluk Plateau, Antalya Province. The research employs dual simulation software, PVSyst and Homer Pro, to model and analyze the PV system's performance and cost effectiveness. The designed system incorporates a PV panel, battery storage, and an inverter, facilitating energy generation and storage to enhance reliability during periods of low solar radiation. The findings underscore the importance of energy storage solutions in off-grid applications and demonstrate that the proposed system can significantly reduce energy costs while minimizing greenhouse gas emissions. Overall, this study advocates for the adoption of PV systems as a sustainable and economically advantageous energy source in regions with high solar potential, highlighting their role in promoting renewable energy initiatives and supporting environmental sustainability goals.

Keywords: *Off-Grid Photovoltaic Systems, Electricity For Remote Area, Simulation Software, Cost Analysis, Battery Storage Units*

Öz

Bu çalışma, Akdeniz bölgesindeki şebeke dışı fotovoltaik sistemlerin fizibilitesini ve ekonomik uygulanabilirliğini incelemekte olup, özellikle Antalya ili Üçoluk Yaylası'nda bulunan müstakil bir eve odaklanmaktadır. Araştırmada, PV sisteminin performansını ve maliyet etkinliğini modellemek ve analiz etmek için PVSyst ve Homer Pro olmak üzere çift simülasyon yazılımı kullanılmaktadır. Tasarlanan sistemde, elektrik enerjisi üretimi için PV paneller, üretilen DC akımlı elektriğin depolanması için batarya üniteleri ve AC elektriğe çevrilmesi için inverterler kullanılmıştır. Bulgular, şebeke dışı uygulamalarda enerji depolama çözümlerinin önemini vurgulamakta ve önerilen sistemin enerji maliyetlerini önemli ölçüde azaltırken sera gazı emisyonlarını en aza indirebileceğini göstermektedir. Genel olarak, bu çalışma, yüksek güneş potansiyeline sahip bölgelerde PV sistemlerinin sürdürülebilir ve ekonomik olarak avantajlı bir enerji kaynağı olarak benimsenmesini savunmakta, yenilenebilir enerji girişimlerini teşvik etmedeki ve çevresel sürdürülebilirlik hedeflerini desteklemedeki rollerini öne çıkarmaktadır.

Anahtar Kelimeler: *Şebeke Dışı Fotovoltaik Sistemler, Uzak Bölgeler Için Elektrik, Simülasyon Yazılımlar, Maliyet Analizi, Batarya Depolama Üniteleri*

1. Introduction

The high solar potential in the Mediterranean region has led to increased interest in photovoltaic (PV) energy in this area. This focus on PV energy is driving countries to implement policies that support renewable energy sources. Annually, the Earth receives an immense amount of solar energy (120,000 TW) that easily surpasses the global energy demand (around 15 TW) [1]. Thanks to technological innovations, cost reductions, and government support, solar energy production is expanding rapidly worldwide [2].

As a developing country, Turkey faces a unique energy challenge [3]. Electricity demand is rising faster than the global average (5% annually in Turkey versus 3% globally between 2000 and 2019) [4]. With only 56.4% of its energy needs met by domestic sources, Turkey relies heavily on imports, raising economic and security concerns. Sustainable development requires strategic energy planning and well-defined targets. In 2020, Turkey's installed capacity reached 95,890 MW, with a significant portion (53.4%) generated from renewable energy sources [5].

Turkey's advantageous geographic location makes it highly suitable for large-scale solar energy development [6-8]. Traditionally, solar energy in Turkey has been used primarily for heating, but recent technological advances have triggered a boom in solar electricity production. As photovoltaic technology becomes more affordable, there has been rapid growth in large-scale photovoltaic solar power plants across Turkey [9, 10].

In the literature, many studies focus on the feasibility and sustainability analysis of PV systems. The sizing of a PV system depends on weather data (solar radiation and ambient temperature) and local electricity demand. Analytical [11-12],

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numerical [13,14], and heuristic [15,16] optimization methods have been used in studies for sizing PV systems. Commercial software such as HOMER (Hybrid Renewable Energy Optimization Model) or RETScreen is used for optimal sizing of renewable energy sources [17-19]. Kaundinya et al. examined the feasibility of grid-connected and off-grid PV systems. They found that feasibility analysis is limited to annual life-cycle costs; however, off-grid PV systems have a more significant impact on greenhouse gas emissions [20]. Roy and Kabir discussed the feasibility of an off-grid PV system. They found that electricity cost depends on daily load demand and generator power capacity. For medium-sized generators (3-5 kW), a PV system provides lower electricity costs for low load demand (0.4-8 kWh) compared to gasoline-diesel generators, but the latter offers lower costs for high load demand (14 kWh) [21]. Bhayo et al. evaluated an off-grid PV-battery system for rural households, finding that excess electricity generated could be used for water pumping applications. For a daily load demand of 3.2 kWh, the PV and battery sizes were determined as 2.44 kWp and 3.55 kWh, respectively. The PV system produced around 9.807 kWh/day, enabling water pumping of 363 m^3/day with the excess energy [22]. Rezk et al. conducted a performance evaluation of a PV-battery-diesel generator system for irrigation applications in remote areas. They determined that PV-battery systems have a 69.74% lower electricity cost than diesel generator systems, significantly reducing CO_2 emissions by approximately 86,511 kg/year [23]. Das and Zaman performed a performance analysis of an independent PV-diesel-battery system with a daily load demand of 350 kWh. The HOMER simulation tool was used for techno-economic analysis, with three dispatch strategies: load following, cycle charging, and combined dispatch. The load-following strategy resulted in 40-50% lower CO_2 emissions than the other two strategies [24]. Odou et al. performed a techno-economic analysis of a hybrid PV-diesel-battery system for off-grid communities, finding that the hybrid system was more economically feasible than grid extension in certain locations [25].

Battery energy storage is an effective medium for storing excess electricity in off-grid PV systems. Both lithium-ion and lead-acid batteries have proven useful for energy storage in renewable energy systems [26]. Parra et al. conducted a study comparing lead-acid and lithium-ion batteries for meeting electricity needs in off-grid communities. They found that considering the levelized cost of electricity, lithium-ion batteries are more preferable than lead-acid batteries [27].

According to the literature, photovoltaic solar energy systems offer a significant application area for remote load applications. The operating performance and cost of such systems vary based on factors such as the availability of solar resources at the location, energy storage methods, and load demand. Most existing studies focus on large power applications and have not adequately addressed the use of solar energy systems for small load applications.

In this study, a PV system for a rural residence was scaled and modeled using the demo versions of PVSyst and Homer Pro, while the cost analysis was simulated using Homer Pro. The designed system was found capable of meeting all monthly energy needs of a 3-bedroom detached house located in Üçoluk Plateau, Antalya, except in January and December."

2. Solar Radiation Data of Üçoluk Plateau

Evaluating the solar energy potential of a region relies on accurate information about the area's solar radiation profile, which can be obtained through long-term solar radiation measurements and analysis. Knowing the solar irradiance of a region is vital for assessing the feasibility of various solar energy applications, including thermal engineering, agriculture, and electricity generation. Such data serves as a fundamental prerequisite for designing solar energy conversion systems, performing cost-effective analyses, and optimizing efficiency. Additionally, obtaining daily, monthly, and annual solar radiation values enable a reliable prediction of the long-term performance of solar energy systems.

Traditionally, determining the solar radiation capacity of an area has relied on several theoretical models, which give considerable weight to estimated global solar radiation data [28]. Research efforts in Turkey have focused on solar energy modeling and prediction techniques [29-31]. Many studies on Turkey's solar energy potential are based on the Solar Energy Potential Atlas (GEPA) compiled by the Ministry of Energy and Natural Resources [32]. Although GEPA has been revised multiple times, there is approximately a 10% discrepancy between its solar radiation values and real-world measurements. Additionally, one limitation of GEPA is that it provides global solar radiation values only for horizontal surfaces. According to GEPA, Turkey's global solar radiation and sunlight hours are illustrated in Figures 1 and 2, respectively.

Figure 1. Global solar radiation in Turkey [32].

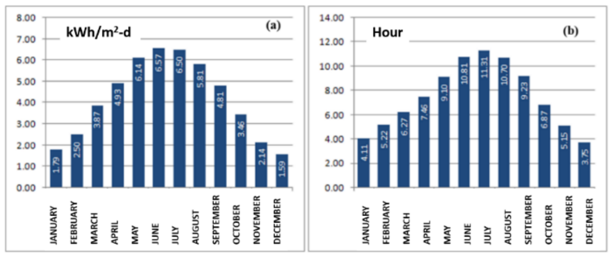

Figure 2: (a) Monthly average daily global solar radiation in Turkey, **(b)** Sunlight duration [32].

This paper presents a study on the optimal sizing of an off-grid photovoltaic power system with battery storage. The research aims to provide a simplified and effective methodology for determining component sizes for off-grid photovoltaic solar energy systems used in regions without access to the national electricity grid. Detailed mathematical analysis and numerical calculations derived from case study data are presented to aid in the sizing of off-grid photovoltaic power systems. This approach is designed to be easily applicable by PV system designers and users, allowing them to adapt the methodology to their specific site data. The case study location selected for this study is a mountain house in Üçoluk Plateau, located in Kemer district, Antalya Province, shown in Figure 3.

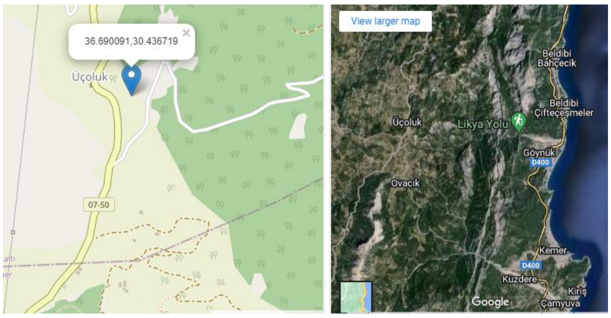

Figure 3: Üçoluk Plateau, Kemer, Antalya, Turkey [33].

The total solar radiation for Antalya Province is provided in Figure 4, and monthly global solar radiation and sunlight duration in Kemer are shown in Figure 5.

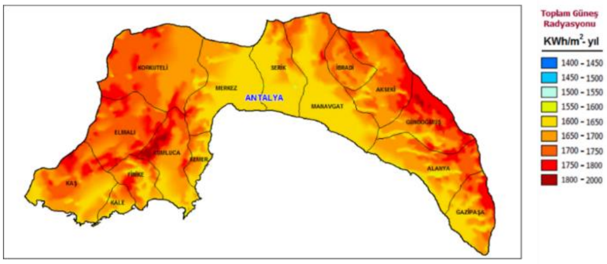

Figure 4: Total solar radiation in Antalya Province [32].

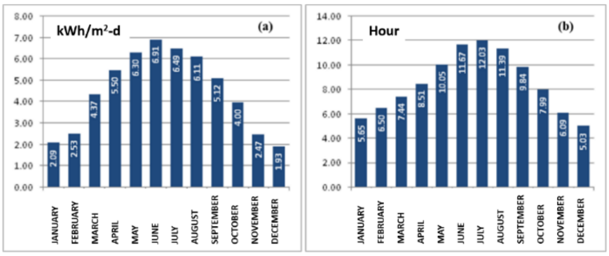

Figure 5: (a) Monthly average daily global solar radiation in Kemer, Antalya, Turkey, (b) Sunlight duration [32].

According to the data, the highest solar radiation in Kemer, where Üçoluk Plateau is located, occurs in June, with an average daily value of 6.91 kWh/m^2, and the longest sunlight duration is in July, with an average of 12.03 hours per day. Observing the solar potential map shown in Figure 4, it is evident that the values for Üçoluk Plateau are above average.

3. PV System Modeling and Sizing of System Components

3.1. Site and determination of electricity consumption

To use in system simulation software, necessary data must be created, including the location of the structure and its electricity consumption. In this study, the electricity consumption of a house located in Üçoluk Plateau within Antalya Province was considered. Üçoluk Plateau is a location outside of electrical transmission lines [33].

To obtain real energy data for buildings in rural areas of Antalya, contact was made with the electricity distribution company Akdeniz Elektrik Dağıtım A.Ş. The monthly electricity consumption amounts for 2023 are shown in Table 1.

Table 1: Average Monthly Electricity Consumption of a Household in the Plateau Region for 2023 [26] .

Month	Consumption (kWh)
January	1864.44
February	1883.03
March	1311.38
April	924.02
May	472.26
June	215.42
July	151.77
August	149.47
September	178.68
October	342.37
November	977.897
December	1580.66

When examining Table 1, it can be seen that consumption reaches its peak during the heating season (January-March and December) and is approximately three times the average in transitional months (April and November), which is likely due to the use of electricity for climate control. Considering that the 3-bedroom house being simulated uses air conditioning in the rooms and living room, possible electricity consumption was calculated for scenarios with and without air conditioning.

Based on the highest consumption month (February) in Table 1, the maximum average daily consumption was calculated as 67.25 kWh (1,883 kWh/28 days). For the months without air conditioning (May-October), the highest consumption month (May) showed a maximum daily average consumption of 15.23 kWh (472 kWh/31 days). These figures were used to create the consumption scenario shown in Table 2.

Table 2: Estimated Electricity Consumption of a 3-Bedroom House.

Usage Area	Hours	Quantity	Power (W)	Hourly Consumption (W)	Daily Consumption (W)
Television	12	1	100	100	1200
Light Bulb	6	6	20	120	720
Refrigerator	24	1	55	55	1320
Washing	3	1	400	400	1200
Dishwasher	2	1	100	1000	2000
Satellite	12	1	30	30	360
Computer	5	2	100	200	1000
Iron	2	1	100	1000	2000
Electric	3	1	100	1000	3000
Air	12	4	100	4000	48000
Vacuum	3	1	300	300	900
Total (With	84	20	500	8205	61700
Total	72	16	400	4205	13700

According to the scenario in Table 2, hourly load approximately doubles with air conditioning, meaning the inverter power must also double. The daily load in the air-conditioned scenario reaches about five times the non-air-conditioned design, indicating that the battery capacity and panel power of the system would also need to be increased fivefold.

Since the study location is an off-grid area, where initial investment costs play a critical role in system selection, it is estimated that the system's payback period would be much shorter if heating is done without electricity. Therefore, the system will be designed based on the electricity consumption scenario without air conditioning.

3.2. System Design Using Simulation Software

Once the coordinates of the location and energy consumption amounts are determined, system design can be carried out using simulation software. In this study, the Homer Pro and PVSyst programs were used for simulations. After conducting simulations with these programs, mathematical formulas were used to find the required capacities of system components, and the results were compared with the software outputs.

3.2.1. System Design with Homer Pro Program

The selected coordinates and monthly average daily energy consumption values were entered into the program. Homer Pro retrieves meteorological data for the specified coordinates from NASA's database. The PV panel, inverter, and battery components used in the system were selected in the program as shown in Figure 6, and the simulation was started.

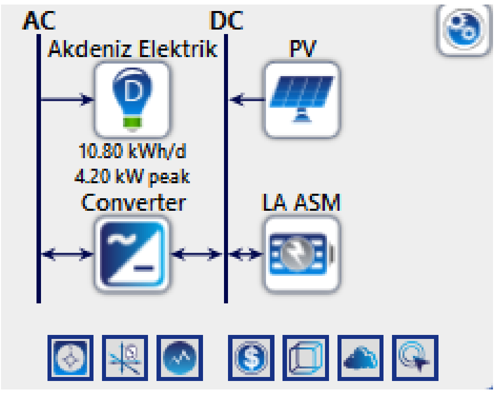

Figure 6: Selecting System Components in Homer Pro.

Based on the cost values for pre-loaded system components in Homer Pro, the program ran 372 simulations with the data entered, of which 140 were found feasible. The most efficient solution was reported as a 9.98 kW PV panel, 66 kW battery, and 5.85 kW inverter.

3.2.2. System Design with PVSyst Program

After entering the selected coordinates, the meteorological data specific to the location was sourced from the PVGIS TMY 5.2 database. Unlike Homer Pro, energy consumption was entered for each device on an hourly basis.

The slope angle, azimuth angle, and horizon line of the PV panel placement site were entered into the program. The azimuth angle was determined using Google Earth Pro, and the horizon line was determined using the website www.suncalc.org.

The collected data was processed into a 3D model in the PVSyst program, as shown in Figure 7. Simulation results indicated that a 9.304 kW PV panel, 1345 Ah battery, and 5.00 kW inverter were required.

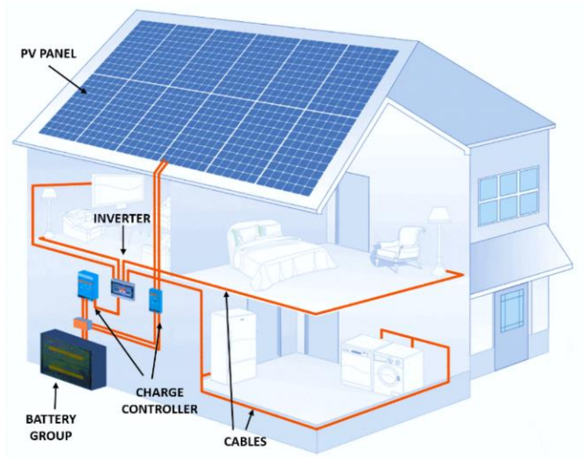

Figure 7: Placement of Structure and PV Panels.

3.3. Sizing of Photovoltaic Array

To determine the necessary PV capacity based on daily electricity consumption, Equation 1 is used [35].

$$P_{PV} = \frac{P_{load}}{PSH \, . \, \eta_{sys}} \tag{1}$$

In this equation; P_{load}, represents total energy demand, PSH, is Peak Sun Hour, η_{sys}, is system efficiency.

System efficiency is calculated with Equation 2.

$$\eta_{sys} = \eta_{rbat} \times \eta_{inv} \times \eta_{rect} \tag{2}$$

For the proposed system, η_{rbat}, battery round-trip efficiency (ratio of energy entering and withdrawing from the battery) (0,85), η_{inv}, inverter efficiency (0,90) and η_{rect}, rectifier efficiency (0,85). For this study, the battery round-trip efficiency was calculated as 0.65. This results in a required PV capacity of 4.70 kW according to Equation 1.

Homer Pro suggests a panel capacity of 9.98 kW, while PVSyst suggests 9.4 kW. The difference arises because the software aims to meet energy demand for all days of the year.

If Equation (1) was based on December's PSH value of 1.93 kWh/m^2, the required PV capacity would be 10.92 kW.

Figure 8 shows the global radiation on the panels and the effective energy produced by the 9.4 kW PV panel array in December. According to Figure 8, energy demand cannot be met on December 18. To address cloudy weather, PVSyst sets the number of autonomy days to 4, so energy was only unavailable on 8 days, as shown in Figure 9.

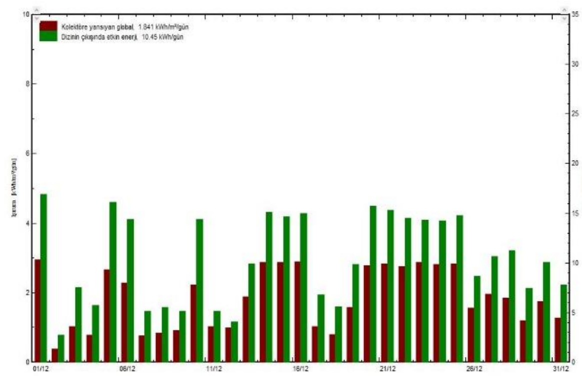

Figure 8: Radiation Reflected to Collector in December and Produced Effective Energy.

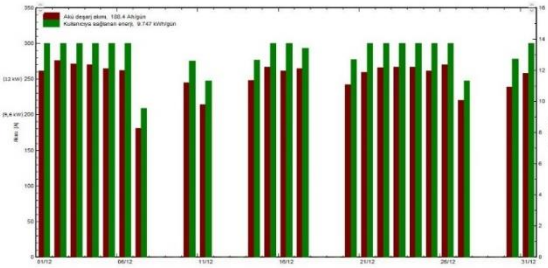

Figure 9: Relation Between Supplied Energy and Battery Discharge Current in December.

3.4. Determining Inverter Power

Inverter power is determined with Equation 3.

$$\text{Inverter power } (W) = \frac{\text{Hourly consumption x Safety factor}}{\text{Inverter efficiency}} \quad (3)$$

Assuming a safety factor of 1.25 and an inverter efficiency of 0.9, the inverter power requirement is 5,840 W. Homer Pro and PVSyst suggest an inverter capacity of 5.84 kW and 5.00 kW, respectively.

3.5. Determining Battery Capacity

Battery capacity is calculated using Equation 4 with data in Table 3.

Table 3: Battery parameters.

Parameter	Value
Total Energy Demand	13.700 W
Battery Efficiency	0,95
D.O.D (Depth of Discharge)	0,85
Nominal Battery Voltage	48 V
Number of Autonomous Days	4

$$B_S = \frac{E_d}{U \times \text{DoD} \times \eta_B} \times d \quad (4)$$

Where, B_S, is battery capacity (Ah), E_d, is total energy demand (W), U, is nominal battery voltage (V), DoD is depth of discharge, η_B, is battery efficiency, and d is the number of autonomy days.

When substituting Table 3 values into Eq. (4), the required battery capacity is determined as 1,413.82 Ah. Homer Pro recommends 1,375 Ah, and PVSyst suggests 1,400 Ah.

4. Cost Analysis

4.1 Calculating System Costs

The cost calculation for the system was conducted using the "Economics" module in the Homer Pro software. The software comes with default values for parameters like nominal discount rate, expected inflation rate (in USD), and project lifespan, which are pre-loaded according to the region settings in Windows.

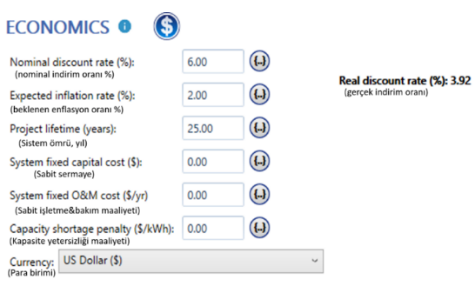

Figure 10: Values Used in Cost Calculation in Homer Pro.

In Figure 10, the nominal discount rate, expected inflation rate, and project lifespan can be manually entered, while the real discount rate is calculated using Equation 5.

$$i = \frac{i' - \text{f}}{1 + \text{f}} \quad (5)$$

Where, i is the real discount rate, i' is the nominal discount rate, and f is the expected inflation rate . i is found as 3.92%.

The initial investment cost of the system components, replacement cost, annual operation, and maintenance expenses, as well as economic lifespan values, are pre-loaded into the system. Since these values may vary in different regions, the software recommends verifying these values.

As part of the study, it was noted that the PV panel and inverter prices in the software were higher than Turkish market prices, so these values were updated.

4.2. System Cost Calculation Using Homer Pro

The initial costing by Homer Pro is shown in Table 4.

Table 4: Cost Estimation with Default Pricing in Homer Pro .

Component	Capital ($)	Replacement ($)	O&M ($)	Salvage ($)	Total ($)
Generic 1 kWh Lead Acid (ASM)	19800.00	10401.00	10396.58	3831.54	36766.05
Generic flat plate PV	24961.53	0.00	1572.82	0.00	26534.35
System converter	1755.20	985.69	0.00	223.65	2517.25
System	46516.73	11386.70	11969.40	4055.18	65817.65

Homer Pro estimates panel costs at 2500 USD per kW, battery costs at 300 USD per kW, and inverter costs at 300 USD per kW. After revising these prices based on market research—160 USD for a 470 W panel and 180 USD per kW for the inverter—the results shown in Table 5 were obtained.

Table 5: Cost Estimation with Updated Prices in Homer Pro

Component	Capital ($)	Replacement ($)	O&M ($)	Salvage ($)	Total ($)
Generic 1 kWh Lead Acid (ASM)	19500.00	10243.41	10239.06	3773.48	36208.99
System converter	1051.20	590.34	0.00	133.94	1507.59
Torges 470 W Monocrystalline	3200.00	0.00	3150.48	0.00	6350.48
System	23751.20	10833.75	13389.54	3907.43	44067.06

It was observed that the updated cost values were approximately 32% lower than the default costs provided by the software.

4.2.1 Calculation of System Component Costs

When the market prices of the system components are entered into Homer Pro, the software generates a cost table, as shown in Table 5. This section examines how these values are calculated using formulas.

4.2.1.1 Battery Cost Calculation

For 65 batteries with a capacity of 1 kW, the software calculated an initial investment cost of 19,500 USD, a replacement cost of 10,243.41 USD, an operation and maintenance cost of 10,239.06 USD (10 USD/year per unit), and a salvage value of 3,773.48 USD. The battery lifespan is reported as 16.75 years.

These values are calculated as net present values using the formulas below.

The annual operation and maintenance cost for 65 batteries is calculated as 650 USD/year.

The system has a lifespan of 25 years, and the net present value of this recurring cost over the project lifespan is calculated using the discount factor formula in Equation 6.

$$f_d = \frac{1}{(1+i)^N} \tag{6}$$

f_d, is the discount factor, i, is the real discount rate [%], N, is the number of years.

The discount factor for year 1 is 0.96, giving a cost of 625.48 USD for year 1, and for year 2, the discount factor is 0.93, with a cost of 601.89 USD.

The total discounted operation and maintenance cost, calculated by summing the values for all years, is 10,240.75 USD, as shown in Figure 11.

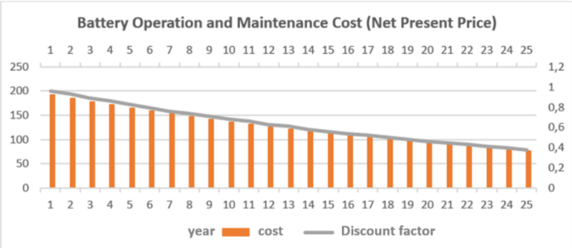

Figure 11: Calculation of Battery Operation and Maintenance Cost.

The battery lifespan is given as 16.75 years (16 years and 9 months). The discount factor for this replacement period is 0.5251, and the replacement cost is calculated using Equation 7:

$$C_{rep} = f_d \times \text{Initial Capita} \tag{7}$$

The replacement cost is 10,240.57 USD.

The salvage value of the battery is calculated using Equation 8:

$$S = C_{rep} \frac{R_{rem}}{R_{comp}} \tag{8}$$

Remaining life of the component, R_{rem}, is calculated using Equation 9:

$$R_{rem} = R_{comp} - (R_{proj} - R_{rep}) \tag{9}$$

S, Salvage cost (USD), C_{rep}, replacement cost (USD), R_{comp}, component lifespan (16,75 yrs.), R_{proj}, Project lifespan (25 yrs.), R_{rep}, replacement period (16,75 yrs.). For the above values, R_{rem} is 8.5 years and S is 9,895.52 USD.

In this case, the salvage value for the battery is calculated as 3,760.29 USD after adjusting for the 25-year project lifespan.

4.2.1.2 Inverter Cost Calculation

For an inverter with a capacity of 5.84 kW, the software calculated an initial investment cost of 1,051.20 USD, a replacement cost of 590.34 USD, and a salvage value of 133.94 USD.

The inverter lifespan is 15 years, and the discount factor for this replacement period is 0.56, resulting in a replacement cost of 590.47 USD.

The salvage value of the inverter is calculated using Equation 8. The remaining lifespan is determined to be 5 years, and the salvage value is calculated as 350.40 USD, which, after discounting, yields a net present value of 133.15 USD.

4.2.1.3 PV Panel Cost Calculation

The initial investment cost for 20 PV panels with a capacity of 0.47 kW each is 3,200 USD. The annual operation and maintenance cost is 3,150.48 USD (10 USD/year per panel). Since PV panels have a 25-year lifespan, there is no replacement or salvage value.

The annual operation and maintenance cost for the PV panels is calculated as 200 USD/year.

The net present value of this recurring cost over the project lifespan is shown in Figure 12.

Figure 12: Calculation of PV Panel Operation and Maintenance Cost.

By summing the present values across all years, the total is 3,151.00 USD.

4.2.2 Calculation of Levelized Cost of Energy (LCOE)

The Levelized Cost of Energy (LCOE) is calculated using Equation 10:

$$LCOE = \frac{C_{ann,tot}}{E_{served}} \tag{10}$$

Where, $C_{ann,tot}$, is the total annual cost of the system (USD/yrs.), E_{served} is the total energy provided (kWh/year). In this study, E_{served} is calculated as 3942 kWh.

The total annual cost $C_{ann,tot}$ is calculated using Equation 11:

$$C_{ann,tot} = CRF(i, R_{proj}) \times C_{NPC,tot} \tag{11}$$

Where, $CRF(i, R_{proj})$ is the capital recovery factor calculated in Equation 12:

$$CRF(i, N) = \frac{i.(1+i)^N}{((1+i)^N)-1} \tag{12}$$

The capital recovery factor CRF is 0.06347. Using this, $C_{ann,tot}$ is 2,791.024 USD, giving a levelized cost of energy 0.7080 USD/KWh.

5. Economic Feasibility

To improve economic feasibility, it is recommended that surplus energy, generated when the battery is full, be used for secondary needs such as greenhouse heating.

In PVSyst, the unused energy due to a fully charged battery, E_{unused}, 7153 kWh, while the energy provided to the user E_{user}, is 4782.9 kWh.

If the unused energy is utilized for greenhouse electricity needs, the total energy provided would be 11.935,9 kWh reducing the levelized cost of energy to 0,2338 USD.

This represents a 67% reduction in energy costs, significantly increasing the feasibility of this type of system.

6. Results and Conclusions

In this study, we explore the outcomes of our simulations and their broader implications for implementing off-grid photovoltaic systems in the Mediterranean region. The results from both PVSyst and Homer Pro offer valuable insights into the system's performance under varying conditions.

The simulations demonstrate that the off-grid photovoltaic system operates efficiently throughout the year, effectively meeting energy demands even during periods of low sunlight. This reliability is essential for households in remote areas where access to conventional energy sources may be limited. The inclusion of battery storage is particularly significant, as it allows surplus energy generated on sunny days to be stored for use during cloudy periods or at night, thereby enhancing overall energy security.

Economically, our analysis suggests that investing in an off-grid PV system can lead to substantial long-term savings on energy costs. While the initial investment may appear considerable, the reduction in reliance on traditional energy sources and the potential for lower utility bills make this a financially sound choice over time. As technology continues to advance and prices for solar components decrease, the attractiveness of such systems is likely to improve even further.

The environmental advantages of adopting photovoltaic systems are noteworthy. By harnessing solar energy, households can significantly lower their carbon footprint and contribute to global efforts to combat climate change. Our findings indicate that widespread adoption of these systems in the Mediterranean region could play a crucial role in promoting renewable energy initiatives and supporting sustainable development goals.

In summary, the results of this study underscore the practicality and benefits of off-grid photovoltaic systems for residential use in the Mediterranean region. By combining reliable energy generation with economic savings and positive environmental impacts, these systems present a compelling case for individuals and communities looking to embrace renewable energy solutions. As we move toward a more sustainable future, off-grid PV systems emerge as a viable option for enhancing energy independence and fostering ecological responsibility.

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