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RESEARCH ARTICLE

Assessing Grid Unavailability and Economic Impacts on Hybrid PV Systems: A GUFS-Based Case Study in Dörtyol, Hatay

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Abstract: This study investigated the performance and economic impacts of unplanned power outages on a hybrid photovoltaic (PV) system and determined which region has the least risky outage group according to the Grid Unavailability Feasibility Score (GUFS) method. The study was conducted in 14 different neighborhoods of the selected project area. The initial steps of the study involved compiling data on unplanned power outages via Energy Exchange Istanbul and transferring consumption values from a hybrid system to the PVSyst program. In the hybrid PV system with an installed capacity of 6.05 kWp, economic indicators such as internal rate of return, return on investment, levelized cost of energy, net present value (NPV), and payback period were simulated, while the charge–discharge energies and state of charge (SOC) levels of the batteries and the performance ratios of the PVs were also considered. According to the results, a difference of 16,587.78 USD in NPV was observed when comparing situations with and without power outages. In addition, while the average annual SOC value of batteries used in hybrid systems is 0.589, SOC values have risen to 0.688 in neighborhoods experiencing power outages. According to the results of the GUFS methodology, the Ocaklı neighborhood was the least risky area, while the Altınçağ neighborhood was the riskiest area. This study aims to examine the economic and performance impacts of power outages on people in affected areas.

Keywords: grid unavailability, hybrid PV systems, economic analysis, GUFS method, energy reliability

1. Introduction

Nowadays, electrical energy has penetrated to all points that people can reach. Some examples of energy needs can be a laptop, a motorized machine, a coffee machine, or communication equipment. It should not be forgotten that the continuity of energy is a vital thing today. A short- or long-term cut in energy means that it cannot meet a significant part of energy needs.

The causes of power outages due to weather events are perhaps one of the greatest pieces of evidence of climate change today. Sometimes a flood, sometimes a storm, sometimes wildfires, or even birds changing their migration routes are among the culprits responsible for the vast majority of power outages. If precautions aren't taken, it will be seen that there are more power outages every day. Most importantly, it's crucial to remember that power outages are not just a technical issue; they are a phenomenon that can paralyze the entire society socially and economically.

Power outages can occur at the transmission level as well as at the distribution level, planned or unplanned. The power outage that recently occurred on April 28, 2025, in the Iberian Peninsula occurred as a result of power and frequency fluctuations in the grid due to supply–demand imbalance [1]. According to the information provided by the European Network of Transmission System Operators for Electricity (ENTSO-E), it was reported that the first oscillation affected Spain and Portugal, while the second oscillation reduced the energy flow between France and Spain, causing an inter-area power outage [2]. It was announced that approximately 2200 MW of production was disconnected in the south of Spain, which caused a voltage increase in Spain, and the same voltage increase was experienced in Portugal, and the frequency decreased. It was revealed that the sudden increase in voltage caused the production plants to be disconnected, and serious drops in frequency occurred. After the Iberian Peninsula lost synchronization with the European System, protection devices tripped, and overhead lines between France and Spain were separated[1].

All countries in Europe that have joined ENTSO-E set their frequency levels to 50 Hz. This frequency level should not fall below 47.5 Hz and should not rise above 51.5 Hz [3]. Increases or decreases in frequency occur when there is an imbalance between production and consumption. Naturally, to bring the frequency back to 50 Hz, connected loads may need to be isolated from the system, or power plants may need to be shut down. This explains how power outages occur on a national scale [4–6].

As with this power outage at the transmission level mentioned above, unplanned power outages can also occur at the

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[1] https://www.entsoe.eu/publications/blackout/9-may-2025-iberian-blackout

distribution level. In this study, unplanned power outages at the distribution level were examined. The main reasons for these outages are the end of the life of electrical equipment, breaker and fuse failures, maintenance needs, new electrical connections, relay failures, Supervisory Control and Data Acquisition maneuvers, tree and external factors, adverse weather conditions, fire, transformer failures, voltage drops or increases, and wild animals. These outages are divided into three different categories according to their duration. Those less than 24 h are called short term, those between 24 h and one week are called medium term, and those longer than a week are called long term [7]. Short-term and long-term power outages have different social and economic consequences. In short-term power outages, it is momentarily deprived of power and unable to perform immediate tasks, and its energy reserves gradually deplete [8, 9]. This can be perceived as a more tolerable power outage compared to long-term outages. When it comes to long-term power outages, food gradually starts to spoil, cooking problems arise, water may stop flowing, and hygiene problems can begin to emerge. The social damage from long-term power outages can be far greater than the economic damage [10].

To back up power outages, photovoltaic (PV) coupled batteries, micro wind turbines, micro combined heat and power systems, fuel cells, integrated micro generation systems, and portable generators with various fuel types can be used [11]. These types of backup power tools may be sufficient to solve problems at the micro level, but even micro-level backup power tools may not be a definitive solution in the event of a national blackout.

In this study, in order to see the minimum damage from energy outages, a PV system design with batteries was carried out, and power outages in 14 different neighborhoods of Dörtyol district of Hatay were integrated into PVSyst software annually, and an economic evaluation was made with the performance in the hybrid system and its effects on batteries. The aim of this study is to examine the economic and performance impacts of power outages while identifying, using the Grid Unavailability Feasibility Score (GUFS) methodology, the regions that are least affected and exhibit higher system performance.

The composition begins with a review of studies on power outages in the literature, continues with a description of the hybrid system design and the GUFS methodology, and concludes with economic and performance indicators of the hybrid system.

2. Literature Review

A study in the literature uses long-term power outage data to calculate the duration of these outages using Monte Carlo simulations. After calculating the outage durations, customer damage functions are defined, and the economic losses resulting from power outages are evaluated. The study explains the Monte Carlo method, used in conjunction with the traditional methodology, as follows: In the traditional method, power outage data are first collected, then annual outage durations are calculated, and the impact on each feeder is determined. In the proposed method, outage data are divided into 5-min groups, and a Monte Carlo simulation consisting of 1000 iterations is performed in Excel [12]. Subsequently, outage durations are estimated, and their impact on the feeders is calculated. Although the study states that Monte Carlo simulation is superior to the traditional method, its main focus is on predicting outage durations. This allowed for a comparison between the predicted outage durations and the actual outage durations [12]. In this study, no specific methodology was used. Unplanned power outages were recorded in minute-by-minute outage profiles, which were then integrated into the PVsyst program. Since the outage data were already available on the Energy Exchange Istanbul (EXIST) platform, no predictions were made.

Another study evaluated the direct and indirect economic losses of power outages. This study differs from others in that while the economic losses discussed in the literature are generally direct losses, this study also describes indirect losses [13]. As examples of direct losses, blackouts in the power industry, particularly the 724 MW load loss in the UK on August 28, 2003, and the 8 GW energy loss in Brazil on February 4, 2011, caused approximately $60 million in economic losses [13]. Indirect economic losses are defined in the study as economic losses resulting from the psychological panic caused by the power outage. The authors state that measuring and determining these losses is quite difficult. While the traditional input–output method can calculate indirect losses from inter-industry power outages, another method, Computable General Equilibrium, is also mentioned as a helpful tool in calculating indirect economic losses [13]. In this study, economic losses were calculated not from indirect losses caused by power outages but from the revenue losses that these power outages caused in hybrid systems.

Another study analyzed the methods used to assess the costs of energy outages. These methods are, namely, the proxy method, case studies, indirect analytical methods, customer survey method, marginal cost technique, value of leisure method, simple value-added method, adjusted value-added method, and willingness to pay method [14]. The proxy method generally provides maximum and minimum values and makes some predictions regarding power outage losses. However, it does not consider factors such as outage duration, time, season, and customer type when making these predictions. Case studies are conducted after large and extensive blackouts and consider both direct and indirect losses. Customer survey methods are a way of estimating losses by directly contacting customers after power outages. However, because it requires reaching a large audience to obtain accurate results, it is also an expensive method. The marginal cost technique can be calculated as the costs of activating and using one's own generator systems in the event of an electricity outage. The value of the leisure time method describes the losses customers experience when power outages occur during their leisure time, requiring them to reschedule and carry out certain activities. While the simple value-added method is suitable for agriculture, industry, and commerce, it is not appropriate for estimating local electricity consumption. Overall, the study has separately costed and determined losses for specific moments and situations where power outages occurred [15].

In a study conducted in the literature, the blackout that occurred after the Marmara earthquake in Türkiye was examined, and the load, transmission lines, transformer centers, and the production plants in the Turkish grid in 1999 were modeled and simulated on MATLAB software. Before the earthquake, Hamitabat, Ambarli, Unimar, and Bursa natural gas power plants provided a 1.2 GW power flow between Northwest Anatolia and Mid-Anatolia via transmission lines at a 380 kV voltage level [16]. When the Osmanlıca and Adapazari transformer substations were damaged by the earthquake, the Northwest Anatolia transformer substations were switched off, and the loads in that area were suddenly disconnected. According to the simulation study performed in MATLAB, it was revealed that the voltage level in the event of sudden load loss was between 1.2 and 1.5 per unit levels, and this value reached 2.0 per unit value at 400 kV voltage levels [17]. In contrast, this study analyzes hybrid PV systems rather than focusing on voltage level control and examines the state of charge (SOC) values of the batteries, charge–discharge energies, charge–discharge hours, and the performance ratios of the PV system.

Another study examined the impact of power outages on customers in the Thrace Electricity Distribution Company region in Türkiye [18]. The study used the System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), and Customer Average Interruption Duration Index (CAIDI) as methodologies [18]. The annual evaluation revealed that power outages were less frequent in the spring months and significantly increased in the summer months. SAIDI, SAIFI, and CAIDI are calculated using the following Equation in (1), (2), and (3) [18, 19]. In this study, SAIDI, CAIDI, and SAIFI values were calculated, and results were obtained using the following method. First, the population of Dörtyol, Hatay, was accessed, and the number of electricity subscribers was obtained from the EXIST platform. Since access to subscriber numbers was not possible due to data privacy concerns, estimated electricity subscriber numbers were calculated for each neighborhood, and annual average estimated SAIDI, CAIDI, and SAIFI data were calculated. The results showed similar values to those in the literature, with the lowest and highest SAIDI values calculated as 0.000738 and 0.010492, the CAIDI values as 0.0010 and 0.0076, and the SAIFI values as 0.519 and 6.5. Since these values vary depending on the number of subscribers and power outages, Yeşil neighborhood gave the lowest SAIDI value, while Altınçağ and Yeşil neighborhoods gave the lowest CAIDI and SAIFI values.

$$\text{SAIDI} = \frac{\sum \text{Duration of Outage}}{\sum \text{Number of Consumer}} \tag{1}$$

$$\text{SAIFI} = \frac{\sum \text{Number of Outage}}{\sum \text{Number of Consumer}} \tag{2}$$

$$\text{CAIDI} = \frac{\sum \text{Duration of Outage}}{\sum \text{Number of Outage}} \tag{3}$$

In another study, the damage levels to electrical power equipment were measured for two different earthquake levels in the Marmara Region, which has a high risk of earthquakes [20].

Another study conducted for Iraq provided information on the causes and occurrences of energy outages and discussed strategies for reducing them. The study identified the following as the main causes of power outages: excessive population growth due to overdemand, heavy use of air conditioners, administrative problems, bypassing the national grid, power system failures, and energy shortages. For the management causes of power outages, the use of Internet of Things-based microcontrollers and sensors is recommended. In addition, the use of smart energy meters has been shown to reduce power outages [21].

Another study was conducted in Zambia. The study describes how extreme droughts in Zambia lead to hydroelectric power plants failing, resulting in power outages. The effects of power outages on people have also been examined in many categories. These categories are, namely, the onset of illnesses due to lack of running water, illnesses from uncooked food, household pollution, sleep disorders, depression, malfunction of electronic devices, disruption of social life, generator noise, limitations in temperature control, water shortages, limitations in cooking, risks of working from home and entertainment, and spoiled food, with spoiled food receiving the highest score [22].

Another study examined the performance compliance of Nordex wind farms in Türkiye following a blackout that occurred in 2015 [16]. Field measurements revealed that the blackout caused frequency and voltage imbalances in Türkiye, exceeding limit values. However, Nordex wind turbines were not affected by these changes, as they were programmed in accordance with grid regulations. Frequency fluctuations were corrected, and even in under-voltage situations, reactive power support maintained the voltage level at the desired levels. This study examines a hybrid PV system, a living system, from a techno-economic perspective, rather than focusing on the changes in frequency and voltage levels caused by general power outages.

Another study, while also explaining that power outages harm the social and economic structure, stated that these outages increase especially during the summer months and that each outage, along with its duration, leads to increasing outage costs. The study also noted that early warning systems significantly reduce the costs of power outages [23].

Another study describes a 6-h blackout in Sudan in 2017, resulting in a loss of approximately 10 GWh of energy [24]. At one of the most affected plants, the Khartoum North thermal plant, the shafts of both the high- and low-pressure turbines suffered significant damage. The damage was due to insufficient oil circulation during a blackout [24].

Another study described blackouts in California. In California, where natural events are frequent, hurricanes, earthquakes, and similar natural disasters were cited as natural causes of power outages. According to the Edison Institute, 70% of power outages are due to weather events. One way to reduce power outages was to use smart electricity meters. This opened the way for customers to actively use an early warning system [25].

In another study, reliability indices of power outages caused by vegetation crossover were calculated. According to the results, unplanned power outages at the 33 kV voltage level due to this reason lasted 449 h and 17 min on an annual basis [26].

Another study compared power outages in poor and non-poor counties in China between 2019 and 2021. Natural disasters were presented as the input for the cause of the power outages. As a result, an increase in the frequency and duration of power outages was observed in poor counties by 5.19% and 8.96%, respectively, while in non-poor counties the increases were recorded as 3.80% and 5.34% [27].

According to another study in the literature, Nigeria is another country struggling to access energy. With 84% of its total installed capacity generated from fossil fuels, Nigeria's 3879 MW of transmission capacity is insufficient to provide adequate energy to many users. Approximately 38% of the population is not connected to the national grid [28].

Another study shows that while India has made significant progress in accessing grid electricity, in Africa, according to 2014 data, only 38% of the population has access to electricity [29]. Furthermore, electricity connection fees remain quite high, even when infrastructure is in place [29].

2.1. Relationship with literature

This study is similar in nature to other power outage studies in the literature, but it has a significant distinguishing feature. As is known, power outages can occur as planned or unplanned. Unplanned outages, in particular, are those caused by weather events where the technical team is late in intervening or is notified early. Unplanned power outages, which can affect all countries and for which examples are given in the literature, may have turned into a cascaded outage due to the frequency and voltage exceeding the limit values in the power system. Generally, the recovery and restoration of the electrical system after power outages have been examined, and the extent to which power outages affect people in terms of frequency and duration has been explained in the literature. Furthermore, the literature discusses the direct and indirect economic losses of energy outages. Methods have been developed to estimate these economic losses in monetary terms.

In this study, however, after power outages occur, the performance and economic status of existing systems will be examined, and accordingly, regions less affected by these power outages will be selected using the GUFS method. This will pave the way for future planned outages to be carried out in terms of frequency and duration based on this selection.

3. Research Methodology

3.1. GUFS method

This method was specifically designed for this study. The GUFS, a lengthy methodology, assesses the feasibility of 14 different neighborhoods in the Dörtyol district of Hatay province following power outages. This feasibility scoring considers the number of power outages, the NPV value of the hybrid PV system, the discharge energy of the batteries, and the performance ratio of the PV system. In a ranking system from 1 to 14, areas with the most power outages receive the lowest scores, while those with the fewest outages receive the highest scores. Since the active and intensive use of energy indicates that a system is working well, neighborhoods that yield the highest PV performance rates, experience the most battery discharge, and generate the highest economic return also receive the highest scores. “Neighborhoods in total”, “evaluation criteria”, and “total score” the mathematical formulation of the GUFS method is shown below in (4) and (5).

$$1 \leq X_{ij} \leq 14 \tag{4}$$

$$S_i = \sum_{i=1}^{4} X_{ij} \tag{5}$$

i: Neighborhoods in total, j: evaluation criteria, S_i: total score

The most important features that distinguish the GUFS method from other methods in the literature are its evaluation criteria. Here, while NPV values are used as the basis for economic loss, not only economic losses but also the performance rates affected by energy interruptions are examined. While this method is a feasibility scoring system, its main purpose is to rank regions experiencing power outages and, by examining the performance and economic losses in those regions, to enable planning regarding the duration and frequency of future planned power outages. The GUFS method differs from SAIDI, SAIFI, or CAIDI indices in that it doesn’t just evaluate power outages. It also considers economic losses and performance criteria; therefore, other power outage indices do not offer the same feasibility assessments. The GUFS method also does not apply any normalization. The quantities are ranked internally, and all evaluation criteria are weighted equally. Therefore, they are not multiplied by any weighting factor to achieve the evaluation result.

3.2. Design of the study

The study initially selected Hatay province as the local area. Due to the devastating earthquake in 2023, the region frequently experiences power outages. Dörtyol district of Hatay was chosen as the district where the simulation studies will be conducted, comprising 14 neighborhoods: Kapılı, Sanayi, Özerli, Altınçağ, Yeşil, Karakese, Yeniyurt, Çaylı, Konaklı, Kışlalar, Ocaklı, Yeşilköy, Numuneevler, and Kuzuculu.

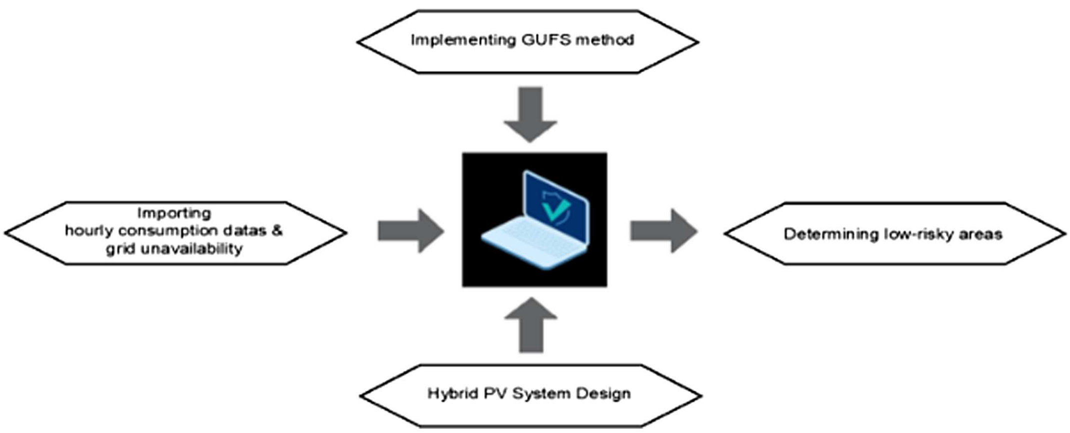
PVSyst was used as the simulation program. Unplanned power outages that occurred in 2024 were fed into this program via EXIST, and a hybrid PV system was designed that is expected to operate together with the consumption data.

Of course, the power outages occurred at different points along different lines for all neighborhoods, and the number of customers affected varied. In this study, it was assumed that there was a single customer in a location where all neighborhoods could experience power outages, and all outages at the neighborhood level were adjusted to the worst-case scenario. Figure 1 shows the stages of the simulation study.

3.2.1. Consumptions

Consumption data were derived by scaling down the consumption values of a workshop operating 24/7. According to these values, the average power requirement is 0.827 kW per h, while the maximum power requirement reaches 1.49 kW per h.

Figure 1
Implementation of the study



Annual consumption data can be seen in Figure 2. Electricity users' energy needs vary depending on the electrical equipment they use, such as air conditioners, and energy consumption can increase or decrease during seasonal changes. For this reason, the consumption amounts shown in Figure 2 are not fixed but variable. As can be seen in Figure 2, the distribution of the customer's annual consumption amounts in watts is shown over 8760 h. According to this graph, energy needs are highest in the summer months, while they are at their minimum in the autumn and spring months. Here, customer consumption data are transferred to the PVSyst program on an hourly basis, and energy supply and consumption amounts are simulated in the program on an hourly basis.

3.2.2. Grid unavailability

According to EXIST data, in the 14 neighborhoods where the study was conducted, the total number of customers affected by power outages was 3,133,503 on an annual basis, while the total duration of outages was 3,157,340.98 h. The neighborhood with the most power outages was Özerli with 536 outages, while the neighborhood with the fewest outages was Kapılı. When customer hours were calculated during the outages, Özerli and Numuneevler neighborhoods had the highest number of outages exceeding 2000 customer hours, while Kışlalar and Yeşil neighborhoods had the fewest outages below 2000 customer hours according to EXIST data. The areas with fewer than 200 customer hours of outages were the Özerli, Sanayi, Yeşilköy, and Çaylı neighborhoods. Figure 3 shows the frequency of outages by neighborhood, based on customer hours. According to the EXIST data. Figure 3 shows the customers affected by power outages and the duration of these outages for 14 neighborhoods. Looking at the graph, it is particularly noticeable that the Numuneevler neighborhood experienced more power outages exceeding 2000 customer-h. The same situation was observed in the Altınçağ neighborhood, clearly demonstrating an increase in the duration of power outages and the number of affected customers. In the Özerli neighborhood, which experienced the most power outages, both short-term and long-term power cuts occurred, affecting a high number of customers. In other neighborhoods, there has been a decrease in the duration of power outages and the number of affected customers, compared to 2000 customer h.

All these unplanned power outages were entered into the PVSyst program on a minute-by-minute basis, and simulation outputs were obtained for each neighborhood. Table 1 provides detailed information about power outages. Table 1 shows the periods and durations of the outages. It also indicates the total percentage of outages, considering an annual total of 8760 h.

3.2.3. Hybrid system

Hybrid systems are energy production mechanisms that utilize multiple inputs. Examples of such systems include solar and wind, solar and battery, wind and battery, solar, wind and battery, and solar and diesel generator systems. In this study, our hybrid system consists of solar energy and batteries. This means

Figure 2
Yearly consumption

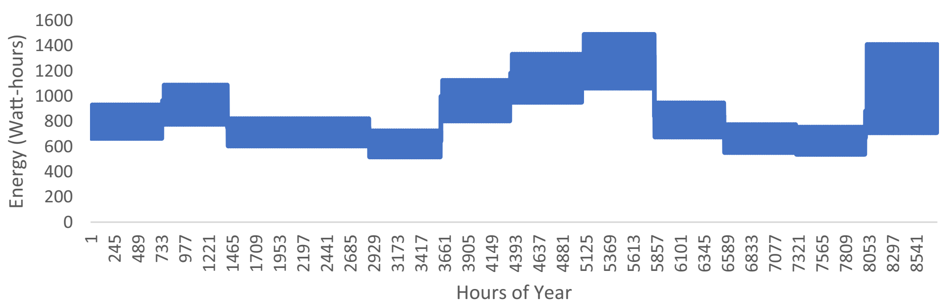


Figure 3
Frequency of outages

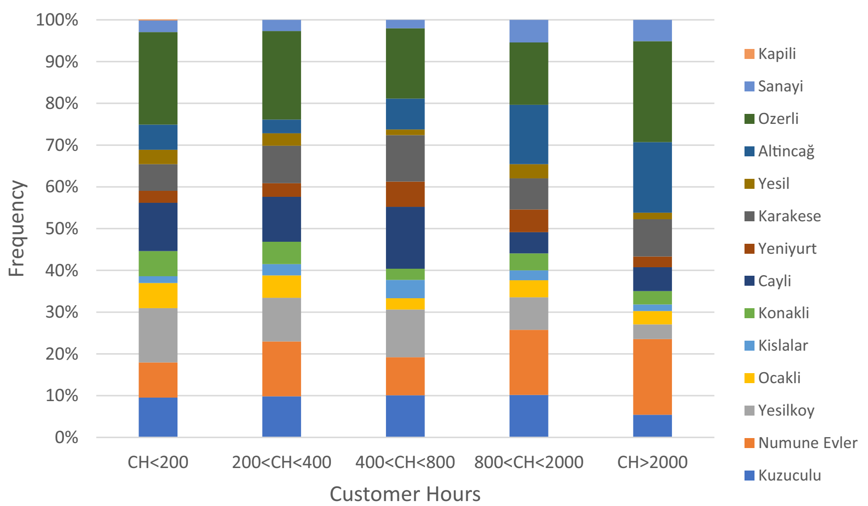


Table 1
Data of outages

Neighborhoods	Periods	Hours	Percent of time
Kapılı	2	13	0.1
Sanayi	76	79	0.9
Özerli	381	402	4.6
Altınçağ	187	108	1.2
Yeşil	71	54	0.6
Karakese	167	215	2.5
Yeniyurt	89	79	0.9
Çaylı	230	181	2.1
Konaklı	13	26	0.3
Kışlalar	54	64	0.7
Ocaklı	118	122	1.4
Yeşilköy	231	221	2.5
Numuneevler	242	219	2.5
Kuzuculu	212	146	1.7

that during the day, when solar energy is available, it will be supplied to the consumer, while at night, consumption will be met by batteries. Furthermore, when battery and solar energy are insufficient, energy will be drawn from the grid. The study was conducted using the PVSyst program. This program was chosen because it allows for the input of energy outage data on a minute-by-minute basis and consumption profiles on an hourly basis, enabling economic and performance evaluations for different load and outage scenarios. Figure 4 shows the power supply and demand status of the PVSyst program. In the first scenario, if the energy produced from solar power exceeds consumption, and the battery's SOC is 0.95 or higher, then there is an energy surplus that will be fed into the grid. If the battery SOC is between 0.20 and 0.95, then the batteries will be charged. In the second scenario, if production is lower than consumption, and the battery SOC is above 0.20, then the batteries will power the load and discharge. In the third scenario, if consumption exceeds production and the battery SOC is below 0.20, then energy will be drawn from the grid to power the load. The PVSyst program determines the energy supply and withdrawal based on the battery SOC values remaining within the specified range and performs the economic analysis accordingly. The program provides excess energy to the grid without distribution fees and taxes, while calculating energy consumed and drawn from the grid with taxes and distribution fees and determining the payback period accordingly. PVSyst program was used in the study because, in addition to its hybrid system feature, it allows for the input of power outages into the program and the performance of an advanced simulation.

The total annual consumption in this study is 7250 kWh. The specific production value of the selected location is 1499 kWh/kWp/year. Accordingly, the required PV power is calculated using the following formula in Equation (6) [30].

$$Power_{PV} = \frac{Consumption\ [kWh]}{Specific\ Production\ \left[\frac{kWh}{kWp}\right]} \tag{6}$$

In this case, it was determined that installing a 4.83 kWp PV system was necessary compared to consumption, and considering the possibility of power outages, it was decided to increase this power to 6.05 kWp. The selected panel is a 605-watt panel from the JA Solar brand. Ten of these panels were connected in series to form a PV string, which was then entered into the PVSyst program. The panels are tilted at 13 degrees and are positioned to face south.

Regarding the inverter selection, the Goodwe GW5000L-DT model was chosen, a 5 kW AC inverter suitable for use with hybrid systems and batteries. With the selected inverter and PV panels, the DC/AC ratio [31] is 1.21, which helps reduce losses caused by overloading the inverter with PV panels. When the batteries are used in the hybrid system, it was found that the Pylontech brand, Rack Phantom X_50 Ah model, was used. The battery voltage is 384 V, and the C10 rating indicates a nominal battery capacity of 51 Ah. The daily energy requirement has been determined as 19.86 kWh, which makes it an extremely suitable design considering the battery capacity and power outages lasting up to 24 h.

The batteries are set to have a maximum charging capacity of 5.2 kW DC and a maximum discharging capacity of 1.6 kW AC. This allows them to successfully handle the maximum power consumption per hour on their own. Horizon data were obtained from the PVSyst program and used in the simulation. The average horizon line for the selected location is 3.3 degrees.

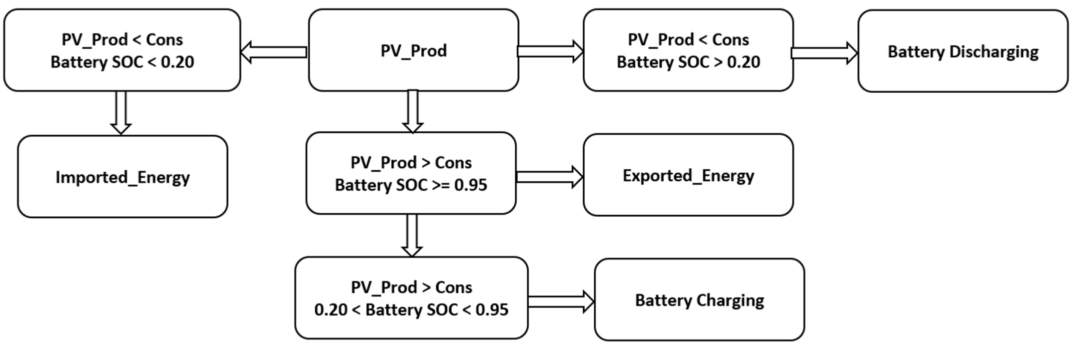
Another issue that needs to be incorporated into the program is charging and discharging strategies. As a charging strategy, the batteries will be charged when there is excess solar energy and will discharge when there is a sudden demand for power.

3.2.4. Economic indicators

3.2.4.1. LCOE

LCOE, the levelized cost of energy, is defined as the ratio of investment cost, operational and maintenance cost, and fuel cost

Figure 4
Working principle of PVSyst



to the amount of energy produced and is calculated using the following formula in Equation (7) [32, 33].

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{\mathrm{It+Mt+Ft}}{(1+r)^t}}{\sum_{t=1}^{n} \frac{\mathrm{Et}}{(1+r)^t}} \tag{7}$$

LCOE: the average lifetime levelized cost of energy generation. It: investment expenditures in the year t; Mt: operations and maintenance expenditures in the year t; Ft: fuel expenditures in the year t; Et: electricity generation in the year t; r: real discount rate, that is, the nominal discount rate adjusted for inflation; n: economic life of the system.

3.2.4.2. IRR

IRR, internal rate of return, refers to the discount value that equates all future returns on an investment to zero. It is calculated using the following formula in Equation (8) [34].

$$\mathrm{IRR} = \sum_{n=1}^{N} \frac{\mathrm{PW[CI}(N)]}{(1+d)^n} = C_0 = 0 \tag{8}$$

PW[CI(N)]: present worth of cash inflows during the project, d: discount rate, N: lifecycle of the project, C_0: total initial investment cost.

3.2.4.3. NPV

NPV, or net present value, is the amount remaining after deducting capital expenditures from all revenues realized at a discount rate over the life of a project and is calculated using the following formula in Equation (9) [35].

$$\mathrm{NPV} = \sum_{\mathrm{i=1}}^{\mathrm{n}} \left(\frac{\mathrm{NCFn}}{(1+\mathrm{r})^{\mathrm{n}}} - I \right) \tag{9}$$

r: market capitalization rate, n: project lifetime, NCF: net cash flow, I: investment outlays.

3.2.4.4. ROI

ROI, or return on investment, is the ratio of the income remaining after deducting all expenses to the initial cost of investment and is calculated using the following formula in Equation (10) [36].

$$\mathrm{ROI} = \frac{\mathrm{NPAT}}{\mathrm{Total\ Assets}} \times 100\% \tag{10}$$

NPAT: Net profit after all costs.

The economic indicators previously prepared for Turkey were used in this study as well. Accordingly, the inflation rate was taken as 39.67%, the discount rate as 25.60%, the annual change in electricity tariff as 45.8%, and the change in feed-in tariff after a 10-year purchase guarantee as 25% [34]. The economic analysis was performed using inputs such as inflation, discount rate, and annual electricity tariffs, and the calculations were made in Turkish Lira. The results are shown at an exchange rate of 44.21 USD/TRY. The initial investment cost of the designed hybrid system is estimated at 4410.76 USD and has been included in the calculations.

4. Results

After all the inputs were entered into the study, the first scenario simulated was one where there was no power outage. When this situation is examined, the system amortizes itself in 4.7 years. The LCOE is 0.13 USD/kWh. The PV system's performance ratio is 79.03%; 44.9% of the energy produced is used from batteries, 55.1% is used directly from solar energy, 2574 kWh of energy is fed into the grid, while 754 kWh of energy is drawn from the grid. When the batteries were examined, the battery efficiency was calculated as 95%, and the amounts of energy charged and discharged were 4118.43 kWh and 3915.19 kWh, respectively. The average annual SOC value was 0.589. When economic indicators are examined, the NPV value is 157,303.86 USD, the IRR value is 64.16%, and the ROI value is 3566.4%. Figure 5 shows the PV production and consumption graph for the initial scenario. Looking at the monthly production–consumption balance in Figure 5, consumption exceeded production in January, February, and December, while production remained higher than consumption in other months. All production figures were calculated via PVSyst software and offset against hourly consumption. Table 2 and Figure 6 list the performance indicators and results of the hybrid system with the GUFS method after power outages. Table 2 shows the charge and discharge energy, total annual charge and discharge times, average annual SOC levels, and PV system performance ratios for the batteries used in the hybrid PV system. Table 3 lists the economic indicators of a hybrid PV system in a simulation conducted after power outages. These indicators include NPV, IRR, ROI, and payback periods. As shown in Table 3, payback periods ranged from 4.8 to 4.9 years, while the average IRR value for the 14 neighborhoods was 62.95%, and the ROI value was 3196.12%. The highest NPV was observed in the Özerli neighborhood, while the lowest NPV was observed in the Kapılı neighborhood. Figure 6 shows the application of the GUFS method and the scores obtained for

Figure 5
Production and consumption graph

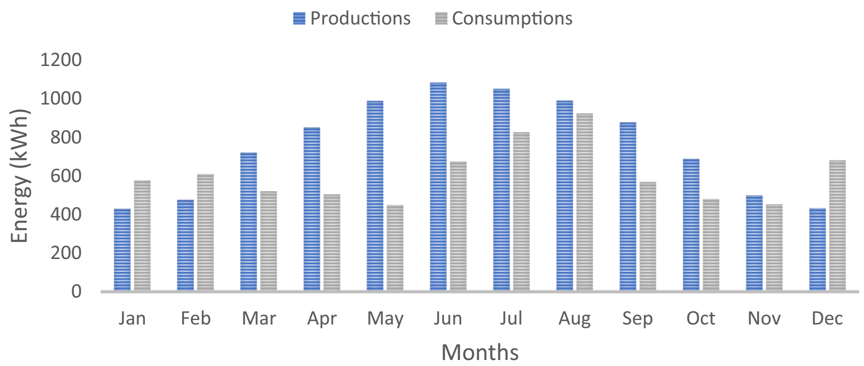


Table 2
Hybrid system performance indicators

Neighborhood	Charged energy (kWh)	Discharged energy (kWh)	Charging hours	Discharging hours	Average SOC	PV PR (%)
Özerli	3381.28	3240.37	1883.03	3696.68	0.682	76.46
Kuzuculu	3351.96	3217.59	1876.11	3651.77	0.687	78.45
Yeşilköy	3362.16	3222.79	1877.41	3660.72	0.686	77.07
Ocaklı	3345.51	3206.22	1867.61	3643.30	0.687	78.92
Çaylı	3354.84	3223.23	1871.74	3662.55	0.685	77.99
Karakese	3354.89	3215.27	1872.04	3647.12	0.685	77.89
Numuneevler	3361.79	3221.88	1875.42	3656.00	0.687	77.15
Sanayi	3342.05	3202.93	1868.72	3629.00	0.688	78.97
Yeniyurt	3341.26	3202.89	1866.81	3629.00	0.688	78.96
Kışlalar	3331.49	3192.82	1863.38	3619.00	0.688	79.39
Konaklı	3332.39	3193.69	1863.76	3617.00	0.688	79.60
Altınçağ	3339.45	3200.45	1867.41	3628.00	0.687	78.90
Yeşil	3335.12	3196.19	1864.49	3620.00	0.687	79.18
Kapılı	3332.63	3193.92	1863.84	3616.00	0.688	79.52

Figure 6
GUFS method results

Neighborhoods	Outages Score	NPV Score	Disc. En. Score	PV PR Score	Total Score	Neighborhoods	Outages Score	NPV Score	Disc. En. Score	PV PR Score	Total Score
Özerli	1	14	14	1	30	Sanayi	10	7	7	10	34
Kuzuculu	5	13	10	6	34	Yeniyurt	9	6	6	9	30
Yeşilköy	3	12	12	2	29	Kışlalar	12	5	1	12	30
Ocaklı	8	11	8	8	35	Konaklı	13	4	2	14	33
Çaylı	4	10	13	5	32	Altınçağ	6	3	5	7	21
Karakese	7	9	9	4	29	Yeşil	11	2	4	11	28
Numuneevler	2	8	11	3	24	Kapılı	14	1	3	13	31

each variable. Here, the Özerli neighborhood, which experienced the highest number of power outages, received the lowest outage score, while the Kapılı neighborhood, which experienced the fewest outages, received the highest outage score. The remaining variables, NPV, battery discharge energy, and PV system performance ratios, showed a direct correlation; in other words, the variable that achieved the highest result received the highest score. Finally, the scores of all variables were summed to obtain the GUFS score, and the Altınçağ and Ocaklı neighborhoods were determined to be the area's most and least at risk as a result of power outages.

When Figure 7 is examined, the areas that scored high using the GUFS method were the Ocaklı, Kuzuculu, Çaylı, Sanayi, and Konaklı neighborhoods. While the Çaylı neighborhood experienced many power outages, the Konaklı neighborhood experienced significantly fewer outages. The scoring that differentiates Çaylı and Konaklı is based on the performance of PV systems, the difference in battery discharge energies, and NPV returns. Although the NPV ranking seems large between Konaklı and Çaylı neighborhoods, a difference of 431.54 USD has emerged over the 25-year project lifespan. The two neighborhoods that received the lowest scores were Altınçağ and Numuneevler neighborhoods. While power outages are more frequent in Numuneevler compared to the Altınçağ neighborhood, the reasons for the seemingly close scores may be due to the higher battery discharge rate in Numuneevler and the better performance of PV systems in the Altınçağ neighborhood. The study shows that PV systems perform poorly in areas with the most frequent power outages. The factors affecting the performance rate can be seen in the following formula in Equation v(11) [37].

$$PR_{PV} = \frac{E_{out} \cdot G_{STC}}{P_0 \cdot H_{POA}} \tag{11}$$

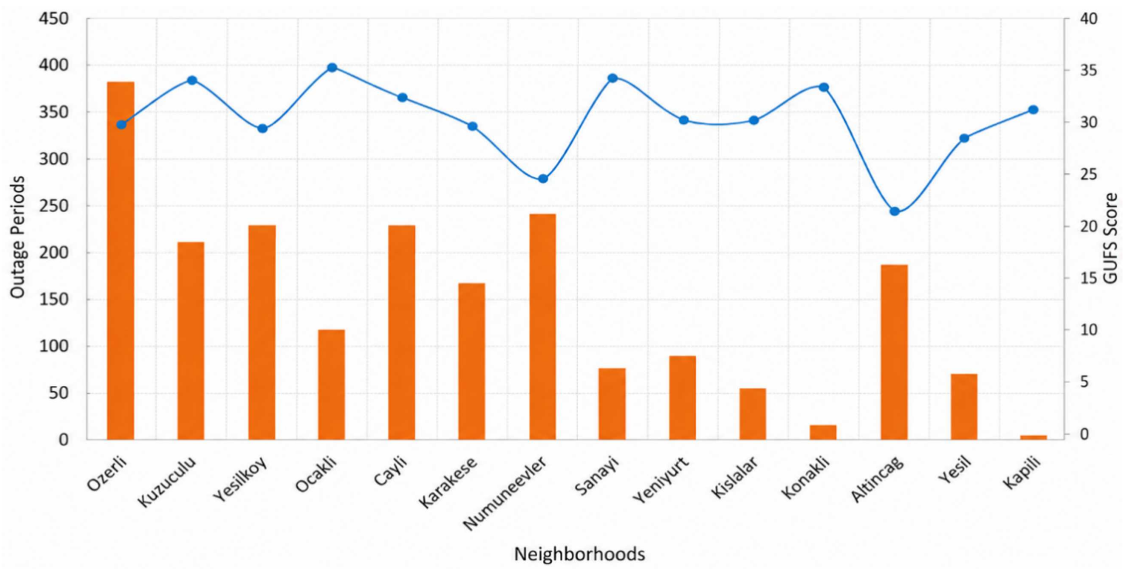
PR_{PV}: PV system performance ratio, E_{out}: output energy of the PV system, G_{STC}: irradiation under standard test conditions (1000 W/m² & 25 °C), P_0: Nominal power of the PV array, H_{POA}: plane of array irradiation.

During a power outage, the hybrid inverter switches to island mode, meaning it cannot convert the total radiation incident on the array plane into energy. While it continues to use some of the

Table 3
Hybrid system economic indicators

Neighborhood	NPV (USD)	IRR (%)	ROI (%)	Payback time (years)
Özerli	141,560.62	62.73	3209.4	4.9
Kuzuculu	141,296.53	62.98	3203.4	4.9
Yeşilköy	141,166.76	62.78	3200.5	4.9
Ocaklı	141,162.31	63.04	3200.4	4.8
Çaylı	141,159.20	62.90	3200.3	4.9
Karakese	141,126.26	62.89	3199.6	4.9
Numuneevler	140,895.87	62.75	3194.4	4.9
Sanayi	140,830.88	63.01	3192.9	4.9
Yeniyurt	140,804.84	63.01	3192.3	4.9
Kışlalar	140,740.45	63.07	3190.8	4.8
Konaklı	140,727.65	63.10	3190.5	4.8
Altınçağ	140,724.74	62.99	3190.5	4.9
Yeşil	140,722.58	63.04	3190.4	4.8
Kapılı	140,716.06	63.08	3190.3	4.8

Figure 7
GUFS—power outage relationship



radiation in the loads, it cannot feed the excess energy back into the grid. This reduces the total PV output, resulting in a decrease in the performance ratio. It has been observed that batteries are used less during power outages. In this situation, PV systems powered critical loads, and battery currents dropped and SOC increased. The PVSyst simulation uses the following Equation in (12) and (13) for battery current and SOC[2].

$$SOC_{end} = SOC_{beg} + \frac{I_{Bat} \cdot D_{Time}}{Cap} \tag{12}$$

$$I_{Bat} = I_{Charge} - I_{Discharge} \tag{13}$$

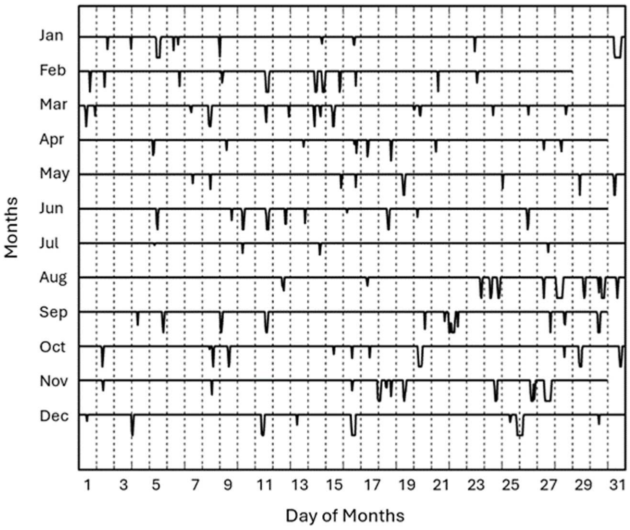
SOC_{end}: SOC at the end of the period, SOC_{beg}: SOC at the beginning of the period, I_{Bat}: battery current [A], D_{Time}: charging/discharging time [h], Cap: battery capacity [Ah], I_{Charge}: battery charging current [A], $I_{Discharge}$: battery discharging current [A].

Looking at the production–consumption graph, it is seen that the customer where the hybrid power plant is installed has a significant electricity demand during the summer months. Consumption needs are more moderate during the spring and winter months. The production–consumption balance is everything in a power system. As seen in Figure 5, the production–consumption balance was more predictable in the autumn and winter months before power outages, and the hybrid system design met the demand. Systems without a production–consumption balance increase capital expenditure (CAPEX) and operational expenditure (OPEX) and therefore generally have longer payback

[2]https://www.pvsyst.com/help/physical-models-used/batteries/battery-use-model.html#internal-operation-current-balance

periods. This is a factor that causes investors to hesitate in solar power plant projects. Looking at the GUFS method in Figure 6, the Ocaklı neighborhood received the highest score, while the Altınçağ neighborhood received the lowest score. Figure 8 shows the annual power outage graph for the Ocaklı neighborhood.

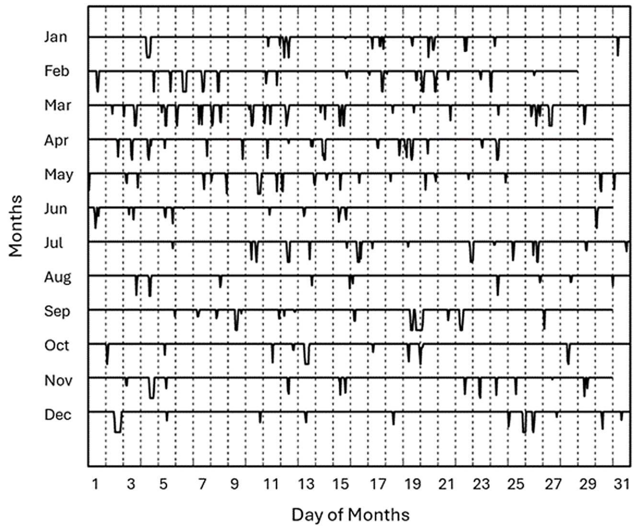
Figure 8
Ocaklı neighborhood power outages



In Figure 8, looking at the Ocaklı neighborhood, the 122 h of power outages that occurred throughout the year took place in 118 separate periods. While the magnitude of power outages varies from time to time, it tends to see longer power cuts toward the end of the month. In this neighborhood where the power outage occurred, there was a 0.11% decrease in PV performance. While it is observed that the SOC values of the batteries generally increased with power outages, the SOC value increased by 9% compared to the period without power outages. In the Ocaklı neighborhood, batteries discharged 20% less during power outages, and the charging energy decreased by the same percentage, thus maintaining a constant battery efficiency. Compared to the situation without power outages, the NPV value in the Ocaklı neighborhood decreased by 16,141.54 USD, and the payback period extended by 1 month. ROI decreased by 10%, while IRR declined by 1.12%. In the GUFS scoring, the Ocaklı neighborhood received an average value in all criteria except NPV. When comparing the Özerli and Ocaklı neighborhoods, which experience the most frequent power outages, in terms of GUFS scoring, the Özerli neighborhood received the highest scores in NPV and battery discharge energy but received the lowest score in the PV system performance ratio metric. When comparing battery discharge energies, a key metric in the GUFS scoring, the Özerli neighborhood discharged 1% more energy than the Ocaklı neighborhood. This situation can be explained by the fact that the duration and frequency of power outages are longer in the Ocaklı neighborhood compared to the other area. In this case, the Ocaklı neighborhood can be described as a less risky area than the Özerli neighborhood in the event of any power outage.

Figure 9 shows power outages in the Altınçağ neighborhood. The Altınçağ neighborhood has the lowest score in the GUFS ranking. Compared to the Ocaklı neighborhood, power outages are spread throughout the year. While the frequency of outages is higher, the duration of outages is shorter than in the

Figure 9
Altınçağ neighborhood power outages



Ocaklı neighborhood. Due to the power outages in the Altınçağ neighborhood, the batteries in the hybrid systems used there discharge less than in the Ocaklı neighborhood. The NPV value, at 140,724.74 USD, is one of the lowest scores in 25 years. The payback period has been extended by two months compared to a scenario where no power outages occurred. The PV performance ratio is moderate. In the Altınçağ neighborhood, the amount of energy needed from the grid is 1477.9 kWh, while in the Ocaklı neighborhood this figure is 1461 kWh, and in the Özerli neighborhood, it is 1421 kWh. Looking at the results, although the Özerli neighborhood has the most outages, the amount of energy needed from the grid is higher in the Altınçağ neighborhood. This raises the question of whether the power outages in the grid occur at night or during the day.

5. Conclusion and Discussion

Firstly, the effect of power outages was directly correlated with a significant increase in SOC values in the batteries. This is shown in Figure 10, in the Özerli neighborhood, where power outages were most frequent.

As seen in Figure 10, a seasonal assessment reveals that the SOC values of the batteries remain the same during periods of power outages and periods without them, especially in the spring months. However, in winter and summer months, the SOC values increase as power outages occur. Figure 11 is sufficiently illustrative to show how these interruptions affect battery SOC values, whether day or night.

During the power outage in the Özerli neighborhood on February 22, the SOC values of the batteries at 9 am were 1.75 times higher than when there was no outage. The SOC values of the batteries before the power outage showed an increase around 3 pm. This increase continued even after the power outage, reaching 1.25 times the level of the batteries in the morning. This suggests that during daytime power outages, batteries tend to discharge more due to the effect of sunlight. When examining the data regarding the power outage that occurred in the Özerli neighborhood on March 9, the results are quite striking this time. In the absence of power outages, the SOC values of the batteries remained stable between 3 am and 7 am. However, during

Figure 10
Özerli neighborhood battery SOC changes

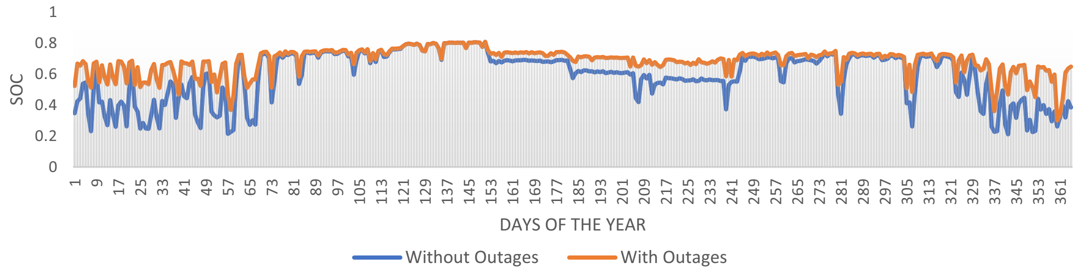
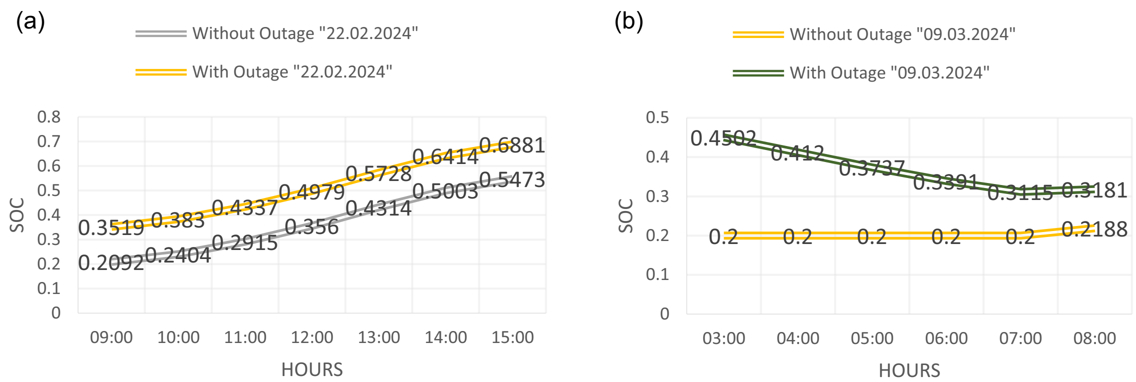


Figure 11
SOC changes in day and night power outages



Özerli neighborhood daytime power outage   Özerli neighborhood nighttime power outage

periods of power outages, the SOC values decreased toward morning, then began to rise again as the day progressed. The reasons why SOC values are higher compared to the situation without power outages can be explained with the following examples:

$$PV_{\text{production}} > \text{Load}_{\text{consumption}}$$

First, if solar energy production exceeds load consumption during a power outage, the batteries remain in charging mode, and the SOC values stay high. Second, if there is no change in solar energy production when the power is cut off, but the load gradually decreases, the SOC value will still remain high. Finally, in a hybrid system, batteries tend to discharge when there is power available from the grid. The hybrid inverter adjusts for this in self-consumption mode because the goal at that moment is to power the loads [38]. Therefore, the SOC value is always low when there is power from the grid. The situation changes completely when the power is cut off. Hybrid inverters start operating in island mode, and the batteries, in order to protect themselves, try to prevent the SOC values from falling below the minimum level via the Battery Management Systems [39]. For this reason, the SOC values are higher compared to their state before the power cut.

In this study, the GUFS system was used to evaluate the suitability of areas experiencing power outages. According to this, the Altınçağ neighborhood received the lowest score, while the Ocaklı neighborhood was the least risky. Considering the duration and frequency of power outages, as well as whether the PV systems were in operation and their consumption values, it was observed that there was a significant decrease in the discharge and charge energy levels of the batteries. Furthermore, the lack of energy sales to the grid due to power outages significantly reduced NPV values and extended payback periods by approximately two months. The aim of applying the GUFS method in this study is to adjust the duration and periods of planned outages in the future based on unplanned outages, so that customers can benefit from this situation with minimum losses. The components used in the method have different characteristics and are suitable for carrying out the necessary evaluations for a hybrid system.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The author declares that he has no conflicts of interest to this work.

Data Availability Statement

Data are available on request from the corresponding author upon reasonable request.

Author Contribution Statement

Cihan Karaman: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration.

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