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RESEARCH ARTICLE

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Techno-Economic Analysis of Hybrid Photovoltaic Systems with Integration of Electrical Vehicles

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Abstract: With the decrease in fossil resources and the increase in oil prices, countries that direct the development of today's technology want to sustain their increasing energy needs with clean and renewable energy sources. When energy is almost a new value, we are coming to times when the load flows on the producer and consumer side are constantly changing and unpredictable with the integration of renewable energy plants and electric vehicles (EV). In the face of this unexpected energy flow, minimizing energy consumption costs and providing the highest benefit and income in this energy cycle are among the main reasons for carrying out this study. This study shows the technological and economic examination of hybrid systems with the integration of electric vehicles charged at different periods in terms of household consumption using PVSyst software. The study examines eight different night- and day-charging behaviors of electric vehicles. As a result, the rates of benefiting from the hybrid systems are revealed in the PVSyst software. The study examines the charging status, charge-discharge energies, and hours of lithium-ion batteries in the hybrid solar energy system, along with the hybrid system's performance. Economic indicators such as internal rate of return (IRR), net present value (NPV), levelized cost of energy (LCOE), payback time, and return on investment (ROI) are analyzed in the study. According to the results, vehicles charged during the daytime generate more income than vehicles charged at night. The highest income was obtained by case 1, with 80% SOC and 3,287,567 TRY NPV, and the lowest income was obtained by case 8, with 20% SOC and 2,549,651 TRY NPV. Another interesting finding is that even if EVs start charging at night at 80% SOC, they provide more profit than vehicles start being charged during the day at 20% SOC.

Keywords: electrical vehicles, batteries, Li-ion, photovoltaic systems, hybrid systems, SOC

1. Introduction

The increasing energy demand and the harmful effects of fossil resources on the environment lead people to use cleaner and renewable energy sources [1, 2]. Undoubtedly, solar and wind power plants, known as the cleanest energy sources today, cover a significant portion of the total installed power with the increasing installation speed. Naturally, the excessive use of these clean energy sources affects and directs consumers' energy management mechanisms. For example, solar energy can be only used during the day. At the same time, the amount of energy varies throughout the day and appears as an intermittent and decreasing energy source depending on the cloudiness of the weather. When looking at wind energy, the air temperature change in the area where the power plant will be installed must be high for wind to form. Wind energy is a type of energy that can be accessed at night compared to solar energy. The continuation of the use of fossil-based production plants, which are basic production plants and plants with a certain inertia, is due to unintermittent energy production. Voltage fluctuations [3], supply-demand imbalances [4], and deviations in system frequency [5] can be seen as the disadvantages of intermittent energy to consumers [6]. Despite intermittent energy production, solar energy has made significant progress in the energy race with its predictability with calculation methods, design capability in desired dimensions, low operating costs, suitability for distributed production models, considerable reduction of carbon dioxide emissions, low maintenance costs, grid support, and energy independence [7, 8]. These characteristic features of solar energy have led to the widespread use of hybrid power plants and energy storage systems. Hybrid systems such as photovoltaic (PV)-wind-battery, PV-diesel-battery, and PV-wind-diesel, which are used primarily in areas suitable for off-grid design, have gained a prominent place in the literature. PV or wind power plants with batteries in places with a grid increase the total system efficiency, ensure continuity of energy supply, and provide users with a large amount of profit with peak shaving and time-shifting strategies [9, 10].

Batteries used widely in hybrid systems, from phones to electric vehicles, laptops to small household appliances, and their usage methods will be the research subject in the next 10 years. The batteries commonly used as energy storage systems are sodium sulfur (NaS), lead-acid, lithium, and flow batteries [11]. Lithium-ion batteries, among the most advanced battery technologies, account for a significant portion of the battery market due to their high energy density and fast charging capacity. Although the prices of these batteries are still considered high, it is anticipated that the cost will be around 62 USD per kWh by 2030 [12].

The transportation sector is at the top of the list of industries that harm the environment the most, with a rate of 25% [13, 14]. For this reason, the production and sale of electric vehicles with incentives by the government and the establishment of charging stations will be of great importance in reducing carbon emissions. China, in particular,

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has announced that all vehicles it will sell by 2035 will be electric vehicles in its long-term goals. When it is looked at the 2023 data, while the electric vehicle stock in Europe is 15 million, this figure is over 20 million in China. Again, China ranked first in charging stations, with 1,385,000 public charging stations, followed by Europe with 253,000 [13, 15]. The main types of electric vehicles are as follows: battery electrical vehicles (BEV), hybrid electrical vehicles (HEV), plug-in hybrid electrical vehicles (PHEV), fuel cell electric vehicles (FCEV), and extended-range electric vehicles (ER-EV) [16, 17].

According to Strategy and PwC's report, in December 2023, electric vehicle sales in Turkey were 169,310 units and took a 17.5% market share. In China, America, Japan, Germany, and England, these figures are 10,297,590, 2,584,688, 1,556,267, 1,364,523, and 1,057,066, respectively. As a result of this increasing pace of electric vehicle sales, consumers are informed about vehicles and learn how to charge their cars in the most appropriate and economical ways. The International Electrotechnical Commission (IEC) has determined four different modes (IEC 62196 and IEC 61851) for alternative current (AC) and direct current (DC) charging conditions [18].

These modes can be defined as follows:

- Mode-1: AC, 1/3 phase, 1 phase maximum power: 3.8 kW, 3 phase maximum power: 7.6 kW
- Mode-2: AC, 1/3 phase, 1 phase maximum power: 7.6 kW, 3 phase maximum power: 15.3 kW
- Mode-3: AC, 1/3 phase, 1 phase maximum power: 60 kW, 3 phase maximum power: 120 kW
- Mode 4: DC—maximum power is more than 150 kW.

Electric vehicle charger installations are divided into two: on-board [19] and off-board chargers [20, 21]. There are also four different charging methods [22]:

- Constant current (CC) charging method

In this method, the battery is charged with a constant current throughout the charging period.

- Constant voltage (CV) charging method

The charging current is constant until the battery voltage reaches a certain point. The voltage is kept constant when the predetermined threshold value is reached and the charging current is reduced.

- Constant current-constant voltage (CC-CV) charging method

This method is a combination of both constant current and constant voltage methods.

- Multistage constant current (MCC) charging method

In this method, the charging current is reduced in steps, and the electric vehicle is charged.

- Pulse charging (PC) charging method

In this method, the batteries are charged as high-current intermittent pulses.

- Trickle charging (TC) method

This charging method charges the batteries with a very low current value.

With the rapid introduction of EVs to the market, some problems will arise in the current electricity systems. The most important of these problems is the increase in energy demand amounts. The distribution and transmission lines in the current electricity system are established according to the peak demand amounts projected for the needs of the consumers. With the integration of electric vehicles into the system, there will be significant increases in peak demand amounts, and even power losses and voltage drops in transmission or distribution lines will increase. Solar power plants, which are renewable energy sources currently available in the electricity system, cause serious consumption that needs to be met in a short time in the evening due to duck curves [23, 24], meeting this need with the inclusion of electric vehicles in the system will be challenging for system operators. This study investigated when electric vehicles should be charged in electricity infrastructure with such technical difficulties and how much profit consumers will gain after charging.

In this study, the distribution of demand consumption of electric vehicles is designed to be charged at different time intervals during the day and night. The aim is to provide maximum profit by putting less load on the existing electrical system. As a result, there will be more money input with the net metering [25]. A more efficient hybrid system for consumers' accounts using solar power plants in their homes will be used.

This study examines the economic and technological results of photovoltaic hybrid systems used in households, along with the integration of electric vehicles into the grid. The starting and focus point of the study is to obtain the economic return and performance results of the hybrid system by charging the electric vehicles of a household at different periods and SOC values.

The second part gives examples of similar studies on hybrid systems. The third part explains the charging method of electric vehicles and how consumption is shaped, which parameters are used when performing economic analysis, consumption changes after integrating electric vehicles into consumption values, and equipment used in simulation and simulation logic. In the fourth part, simulation outputs, and the fifth part, the result, similarities, and differences with the studies in the literature are explained.

2. Literature Review

It was designed and used a hybrid photovoltaic system as a backup in a study for Kandi in Benin. The electrical equipment used to create the consumption model in the hybrid system is as follows: Interior and exterior lighting, laptops, brewers, printers, air conditioners, electric strike alarm, PA system, fan, and camera. It was envisaged that this electrical equipment would be used at certain time intervals, and the total consumption amount was calculated. After the consumptions were determined, the hybrid system was examined in six cases. In the first case, Benin Electricity Company (SBEE) supplies brewers, electrical outlets, and air conditioners; in the second case, mini central station supplies lamps, sockets, and stirrers; and SBEE operates air conditioners; in the third case, mini power station supplies all equipment; in the fourth case, backup system supplies lamps, sockets, and stirrers in case of power outage caused by SBEE; in the fifth case, backup system supplies all equipment; in the sixth case, mini power station supplies all equipment; and at the same time batteries are charged by PV modules and grid. After determining the battery and PV module capacities, the system was simulated using RETScreen software. Daily electricity consumption of all equipment was calculated as 393.173 kWh. Consumption needs were realized for all cases between 07.00 am and 07.00 pm. The values of inflation rate, discount rate, project lifetime, debt ratio, interest rate on debt, price of exported electricity, cost of operation, and maintenance entered as input to the RETScreen program are 4.3%, 4.25%, 20, 0.1%, 4%, 0.26 USD, and 709 USD, respectively. As for system components, the highest battery capacity was 14,627 Ah in case-3, the highest consumption amounts were 393.173 kWh in cases 3 and 6, and the highest PV capacity was 134 kWp in case-3. According to the financial analysis results, NPV values for cases 2, 3, and 6 were positive, while they were negative for the other cases. The shortest payback period was 5.1 years in case 6, and the most extended payback period was in case 5 [26]. Another study investigated the optimum hybrid PV-battery system connected to the grid. The study created an algorithm to reduce voltage changes and minimize the cost of the smart grid, consisting of variable loads, photovoltaic modules, and energy storage systems. Considering the cost, a genetic algorithm (GA) and fuzzy logic-based controller were used to create the optimum PV-battery system. With the algorithm combined with the fuzzy logic controller, the cost was reduced by 4%, and a 17% reduction in voltage changes occurred [27].

In another study, a PV/wind turbine (WT)/diesel-based hybrid system with a battery storage system was designed for the off-grid region of Rafsanjan, Iran. The optimal system design was achieved with the swarm optimization algorithm inspired by the social behavior of animals. The study was carried out for different cases; the cases are as follows: PV/WT/diesel/battery, PV/diesel/battery, WT/diesel/battery, and diesel generator alone. The study was evaluated in terms of cost and carbon dioxide emissions. According to the results, the case with only a diesel generator gave the best result in terms of cost and emissions. Considering the increasing diesel fuel prices, it was concluded that PV/diesel/battery systems will soon be more economical and less environmentally harmful [28]. In another study, a techno-economic analysis was conducted for a hybrid system in the Diyala region, Iraq. The system's peak power is 5 kWp, and the system uses eight batteries with 150 Ah capacity and 12 Volt voltage level, 18 units of 355-watt polycrystalline PV modules, and a 5-kW smart inverter. The NPV value was calculated as an economic analysis, and the payback period was found. The system's total cost is 5,360 USD; the PV panel and battery costs are 2,520 USD and 1,440 USD, respectively. An annual cost of 335 USD was added as the operating cost, the yearly interest rate is 4% in USD, and the annual inflation for operation and maintenance is 0.057%. The battery life is estimated at 5 years. The lowest load consumption occurred in winter, and the highest energy demand was in summer. The months when the most and least energy is injected into the grid are winter and summer. The payback period was calculated as 10 years, and the performance ratio was found to be 66% [29].

The details of another study simulated in MATLAB are as follows: A system consisting of an electric vehicle, PV modules, a battery, and a grid is established. In this system, the energy required for charging electric vehicles is stored in batteries when the electricity tariff is low. Later, this energy is used to charge electric vehicles when the feed-in tariff is high. The logical algorithm controlling the battery system is designed as follows: The system initially charges the battery with the available energy via a DC-DC converter and feeds the DC loads. If the battery SOC value falls below 20% and the current DC load power exceeds the available power, the system is charged via the power grid. When the feed-in tariff is high, and the battery SOC value reaches 30%, charging from the grid is stopped. In periods with a low feed-in tariff, charging starts independently and continues until the battery SOC value reaches 100% [30].

In another study conducted in Greece, a hybrid system was designed with lead-acid batteries and PV modules. The total economic and unit costs per energy are calculated in the first stage. At the same time, real-time 1-year data are collected for the designed system. As a result of the study conducted for two different scenarios, the cost per unit of energy is 0.55 to 0.62 euros and 0.42 to 0.46 euros, respectively. At the end of the study, it was revealed that more research is needed to reduce the cost of the battery design further [31].

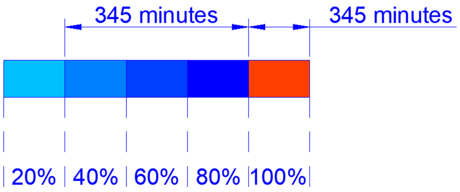
A stand-alone hybrid PV system study conducted in Madhya Pradesh, India, aimed to meet a health center's daily energy needs. The simulation was performed in HOMER software. Two scenarios, PV-diesel-battery and diesel-battery cases, were compared in terms of cost and carbon dioxide emissions. The installed hybrid system used 6 battery groups with 12 V, 100 Ah capacity, 7 units of 250-watt polycrystalline PV modules, and a 1 kW diesel generator. The total initial investment cost of the PV-diesel-battery system was 2,418 USD, while the cost of the diesel battery case was 879 USD. While the PV-diesel-battery system released 2,100 kg of carbon dioxide emissions per year, this figure increased to 3,913 kg in the diesel-battery case. In the PV-diesel-battery system, 70% of the energy requirement is provided by PV modules, while the diesel generator meets 30%. The payback period is calculated as 9.9 years [32].

Another study where real data were transferred to the simulation program was carried out for Moi University, Kenya. The software used was HOMER. In the measurements made with the PCE-360 power analyzer, the peak power of the university was determined as 60 kW. The temperature and radiation data between 2017 and 2022 were collected by the university's weather station and compared with the National Aeronautics and Space Administration's (NASA) database. 4 different scenarios consisting of grid, grid/battery, grid/PV, grid/PV/battery cases were economically examined. While the lowest LCOE value was 8.78 KSH in the grid/PV case, the highest LCOE value was 22 KSH in the grid/battery case. According to the results, the most optimal hybrid system emerged in the PV/grid case. Integrating batteries into the hybrid system increases the LCOE value [33]. In a case study conducted in the Muhanga district of Rwanda, a techno-economic analysis was performed on the PVSOL program. In a grid-connected hybrid system, PV modules were coupled with battery groups. The load requirement of the hybrid system was 82.34 MWh per year, while the peak power it could reach was 30.4 kW. The designed hybrid system consisted of a 57.33 kWp PV plant and 89.2 kWh energy capacity batteries. According to the results, the return on investment rate was 9.14%, and the payback period was 9.65 years [34]. A hybrid solar and wind energy system is being created to power the Nigerian mobile base transceiver station (BTS). Techno-economic analysis and system modeling were performed using the HOMER program. PV-diesel-battery and PV-wind-diesel-battery systems were compared with stand-alone diesel generators. The design consisted of 64 units of Trojan Battery, 10 kW of PV capacity, and a 5.5 kW diesel generator, which emerged as the most economical system, with a cost of 69,811 USD and an LCOE of 0.409. In addition, this system reduced annual carbon dioxide emissions by 16.4 tons compared to the stand-alone diesel system [35].

3. Methodology

The entire study was done by applying advanced simulation techniques in PVSyst software. First, household consumptions were grouped month by month as night-day peak in a 1-year electricity bill. Then, total daytime consumption was converted to average hourly consumption in a monthly bill. The same process was used for night and peak tariff periods, which were repeated monthly. Daytime, nighttime, and peak tariff periods are 11, 8, and 5 hours, respectively.

Figure 1
EV battery charging lots



$$\mathrm{A_{hd}} = \frac{\mathrm{T_{dm}}}{11 \times \mathrm{d_m}} \tag{1}$$

$$\mathrm{A_{hp}} = \frac{\mathrm{T_{pm}}}{5 \times \mathrm{d_m}} \tag{2}$$

$$\mathrm{A_{hn}} = \frac{\mathrm{T_{nm}}}{8 \times \mathrm{d_m}} \tag{3}$$

where $\mathrm{A_{hd}}$: average hourly consumption in kWh in a day timeframe, $\mathrm{A_{hp}}$: average hourly consumption in kWh in peak timeframe, $\mathrm{A_{hn}}$: average hourly consumption in kWh in the night timeframe, $\mathrm{T_{dm}}$: monthly total consumption in kWh in a day timeframe, $\mathrm{T_{pm}}$: monthly total consumption in kWh in peak timeframe, $\mathrm{T_{nm}}$: monthly total consumption in kWh in the night timeframe, $\mathrm{d_m}$: total days of the month.

In the study, EV integration and consumptions are calculated as follows: As seen in Figure 1, when the electric vehicle used in the study is charged with an AC charger with a power of 11 kW, it will be charged from 20% to 80% in 345 min. In this case, it will cover three units of equal distance. It will also charge from 80% to 100% in 345 min, but the EV battery will cover 1 unit of distance in this case. The electric vehicle can cover less distance in the same period because the AC charger reduces its power when the battery reaches 80% charge level and charges the battery with less current.

As shown in Table 1, after integrating the EVs, the consumptions were added to the hourly household consumptions when EVs were charged at different SOC values day and night. These consumptions were imported into the PVSyst program on an annual hourly basis. The AC charger with a power rating of 11 kW charges EV batteries until they reach the 80% charge level, after which the power decreases by 66%. This period continues, so every charging day during the year, and EVs are charged.

$$X = \mathrm{Ch_P} \times t \tag{4}$$

where X: EV battery lot distance, $\mathrm{Ch_P}$: AC charger power, t: charge time for lot distance

In the PVSyst program, the production and consumption data for the hybrid solar power plant are subjected to an energy flow. The energy drawn from the Li-ion batteries and the battery discharge current are formed after this consumption and production balance. The software calculates the SOC values of the batteries at the time of discharge according to the formula[1] below.

$$\mathrm{SOC_e} = \mathrm{SOC_b} + \frac{\mathrm{I_B} \times \mathrm{D_T}}{\mathrm{C}} \tag{5}$$

where $\mathrm{SOC_e}$: end of the SOC, $\mathrm{SOC_b}$: the beginning of the SOC, $\mathrm{I_B}$: battery charge/discharge current [A], $\mathrm{D_T}$: charge/discharge time in hours, C: capacity [Ah]

The stored energy in the batteries is also calculated by the program using the formula below.

$$\mathrm{SOC_E} = (\mathrm{SOC_e} - \mathrm{SOC_b}) \times C \times \mathrm{V_B} \tag{6}$$

where $\mathrm{SOC_E}$: SOC energy balance [Wh], $\mathrm{V_B}$: battery voltage [Volt], $\mathrm{SOC_e}$: end of the SOC, $\mathrm{SOC_b}$: the beginning of the SOC, C: capacity [Ah]

In the PVSyst program, it is necessary to make some assumptions about using the hybrid system. These assumptions are the batteries' maximum charge cut-off SOC value, the minimum discharge cut-off SOC value, the maximum charge power, and the maximum discharge power. Before integrating electric vehicles into the system, the average consumption was 0.83 kW per hour. Accordingly, the maximum battery discharge power is selected as 3 kW. The maximum charging power is selected at 5.4 kW for charging the batteries. The batteries will stop charging when they reach 0.95 SOC, and the minimum discharge SOC value will be 0.20. Another assumption made in the hybrid system is that the energy drawn from the grid is not from renewable energy sources. Table 2 in the hybrid system performance results displays this energy originating from fossil resources.

The steps of this study are as follows: First, a sample house's annual consumption values are compiled hourly. Then, the charging needs of EVs with different SOC values in various periods were added to these hourly variable consumptions, and the consumptions were recalculated. According to the new consumption, simulations were carried out for eight different cases on PVSyst, considering the day-and-night charging situations of the hybrid system consisting of PV and batteries. The simulations resulted in calculating NPV, IRR, ROI, payback time, and LCOE values necessary for economic analysis, along with technical examinations of the hybrid system and its batteries' efficiency. Figure 2 shows the basic schematic of the hybrid system and EV. As seen here, electric vehicles are integrated into household consumption; the network and consumption equipment are connected to the grid connection end of the inverter, the photovoltaic modules are connected in series to the PV point of the inverter, and the batteries are connected to the battery connection point. Figure 3 shows the steps of the PVSyst simulation. As seen here, consumption data was first entered into the simulation, then the hybrid system design was implemented, and simulation outputs were obtained from the software.

3.1. Economic inputs of the study

Figures 4, 5, and 6 data were obtained from the website of the Central Bank of the Republic of Turkey and the Energy Market Regulatory Authority. Figure 4 shows electricity prices for residential buildings in Turkey for the last 13 years. According to these figures, the average increase in electricity prices, including taxes, for 13 years is 25%, and the average for the last 5 years is 45.80%.

Figure 5 shows Turkey's inflation and interest rates in the last thirteen years. According to these figures, the inflation average of the previous thirteen years is 22%, and the average of the last five years is 39.67%, while the interest rates are 19% and 25.6%, respectively.

In the study, the life of the project is 25 years, inflation is 39.67%, the interest rate is 25.60%, the capital investment is 555,000 TRY, the annual change in the tariff is 45.8%, and the decrease in the tariff after the purchase guarantee is integrated into the program as 25%.

A study conducted on consumers using solar power plants at different times and tariffs showed that the three-time variable

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[1] PVSyst SA, "State of charge (SOC)," https://www.pvsyst.com/help/physical-models-used/batteries/battery-model/state-of-charge.html.

Table 1
Household consumption with the integration of EV

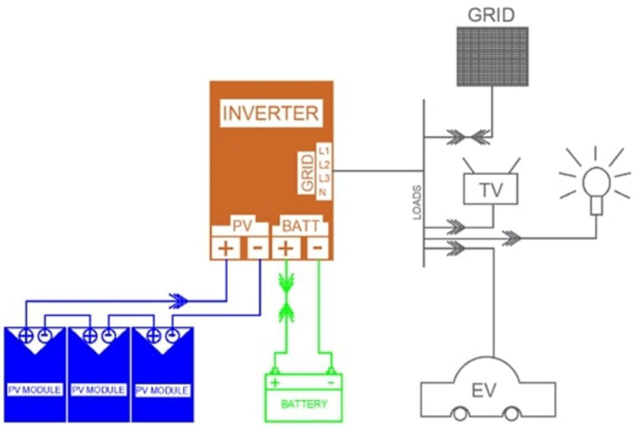
Months	0.80 SOC DT (kWh)	0.80 SOC NT (kWh)	0.60 SOC DT (kWh)	0.60 SOC NT (kWh)	0.40 SOC DT (kWh)	0.40 SOC NT (kWh)	0.20 SOC DT (kWh)	0.20 SOC NT (kWh)
January	583	583	561	561	517	517	517	517
February	537	537	537	537	493	493	581	581
March	592	592	592	592	570	556	592	592
April	898	898	920	912	832	846	920	898
May	1,139	1,139	1,117	1,124	1,073	1,073	1,073	1,095
June	1,323	1,323	1,345	1,345	1,323	1,309	1,345	1,345
July	2,214	2,214	2,214	2,207	2,126	2,141	2,214	2,214
August	1,232	1,232	1,210	1,217	1,166	1,166	1,254	1,254
September	645	645	667	667	645	645	667	667
October	696	696	696	688	608	608	696	674
November	683	683	661	668	617	617	617	639
December	750	750	772	772	750	750	772	772
Total	11,291	11,291	11,292	11,290	10,720	10,721	11,248	11,248

DT: daytime, NT: nighttime

Table 2
Hybrid system performance result

Cases	LC [kWh]	FG [kWh]	RG [kWh]	HSEP [%]	REC [%]	PV_PR [%]
case-1	11,291	4,395	8,866	85.14	66.85	84.37
case-2	11,291	6,071	8,866	75.59	59.35	84.05
case-3	11,292	5,224	8,866	80.14	62.92	84.33
case-4	11,290	6,103	8,866	75.42	59.22	83.87
case-5	10,720	5,061	8,866	76.97	63.66	84.22
case-6	10,721	5,545	8,866	74.39	61.52	83.82
case-7	11,248	5,622	8,866	77.63	61.19	84.15
case-8	11,248	6,077	8,866	75.27	59.33	83.81

Figure 2
Schematic of hybrid system with EV



electricity tariff is more advantageous than the single-time tariff after the solar systems are integrated [36]. For this reason, in this study, the feed-in tariff is taken as a three-time electricity tariff, and the daily variation is shown in Figure 6. As seen here, electricity prices are highest during peak hours, and the cheapest tariff is at night.

LCOE is defined as the cost of energy produced throughout the power plant's life, including operation and maintenance costs.

NPV: It is the sum of all future cash flows over the life of the investment and discounted to present value.

IRR: The discount rate equates the net present value of any investment you have made and the cash flows you receive regularly in the future to zero.

ROI: It is a performance measure used to evaluate the efficiency of an investment. ROI, expressed as the return on investment, return on investment, or profitability of investment, indicates the rate of return an investment provides.

The formulas in (7), (8), (9), and (10) below show how to calculate LCOE [36], NPV [36], IRR [37], and ROI [38].

$$LCOE = \frac{\mathrm{PW[CO(N)]}}{\mathrm{E_{PV}} \sum_{\mathrm{n=1}}^{\mathrm{N}} \frac{(1-\mathrm{r_d})^{\mathrm{n}}}{(1+\mathrm{d})^{\mathrm{n}}}} \tag{7}$$

where PW[CO(N)]: present worth of cash outflows during the project, which can be operational costs of photovoltaic systems during their lifetime N: lifecycle of the PV system, which is 25 years r_d: annual degradation rate of PV system, which is 0.7 % per year in average for 25 years d: discount rate, E_{PV}: energy produced for the year.

$$NPV = PW[\mathrm{CI(N)}] - PW[\mathrm{CO(N)}] \tag{8}$$

PW[CO(N)] represents the current value of cash outflows during the project, while PW[CI(N)] represents the current value of cash inflows during the project.

$$IRR = \sum_{\mathrm{n=1}}^{\mathrm{N}} \frac{\mathrm{PW[CI(N)]}}{(1+\mathrm{d})^{\mathrm{n}}} = \mathrm{C_0} = 0 \tag{9}$$

where PW[CI(N)]: present worth of cash inflows during the project, which can be taken as money inputs to customers regarding the net metering N: lifecycle of the PV system, d: discount rate, C_0: total initial investment cost.

$$ROI = \frac{\mathrm{N_P}}{\mathrm{C_0}} \times 100 \tag{10}$$

C_0 is the total initial investment cost, *and* N_P is the net profit.

Figure 3
Steps of PVSyst simulation

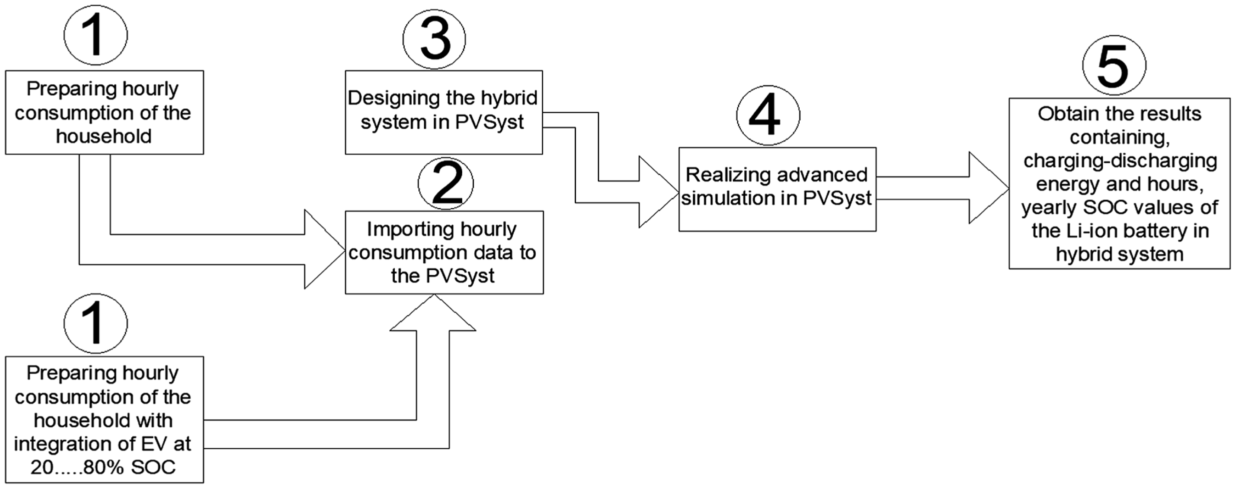


Figure 4
Household electricity tariff of Türkiye

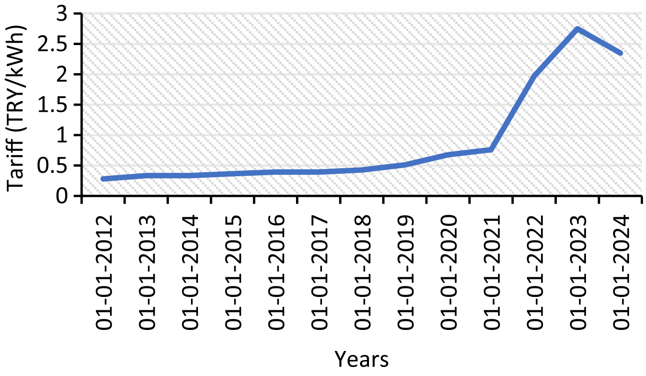
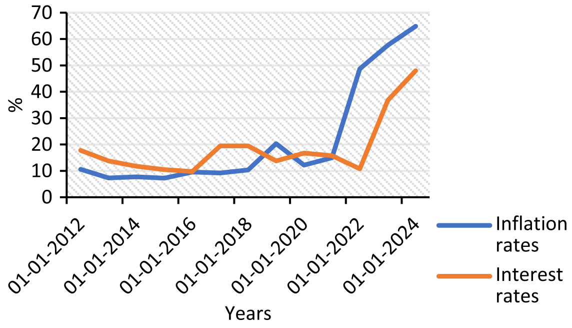


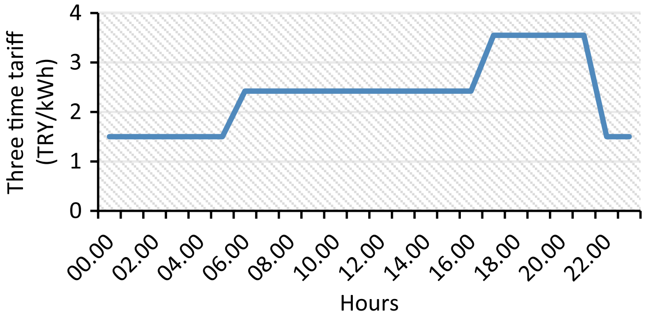
Figure 5
Inflation and interest rates of Türkiye



3.2. Consumptions of the cases

The annual variable consumptions of the house are shown in Figure 7. Accordingly, while the energy needs increase significantly in the summer, electricity consumption is at a minimum in the spring and winter months. Table 1 shows the consumption amounts in kWh after electric vehicles are integrated.

Figure 6
Daily three-time tariff variation for the first January of 2024



In this study, the charging times of the vehicle were determined by considering the data of the long-range version of the TOGG electric vehicle, which is Turkey's automobile brand. TOGG has a range of 523 km and a battery capacity of 88.5 kWh. TOGG, which has an AC and DC charging feature, must be charged for 345 min to increase its battery from 20% SOC to 80% SOC in case of 11 kW slow AC charging. It needs to be charged for another 345 min to reach 100% from 80%. To prevent the batteries from overcharging during charging, electric vehicle manufacturers reduce the current values by maintaining the voltage after 80% SOC, and thus, the batteries are charged with lower currents, similar to the CC-CV charging mode. In this study, the charging of the electric vehicle at different SOC values and different intervals during the day and night was investigated. Figures 8, 9, 10, and 11 show the charging powers and time intervals of the electric vehicle. In Figure 8, electric vehicles are charged four times in the period shown, while in Figure 9, they are charged twice, and in Figures 10 and 11, they are charged once each. As can be seen from the figures, the charging frequency shows a decreasing trend. While the lowest power consumption is shown in Figure 8, in Figures 9, 10, and 11, the peak levels and hours of these consumptions have been increased to provide the energy needed by electric vehicles.

Figure 7
Household yearly consumption

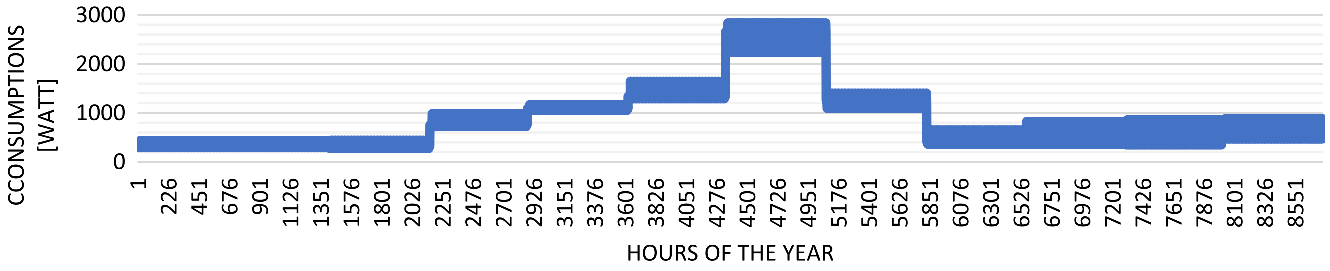


Figure 8
80% SOC of EV charging intervals

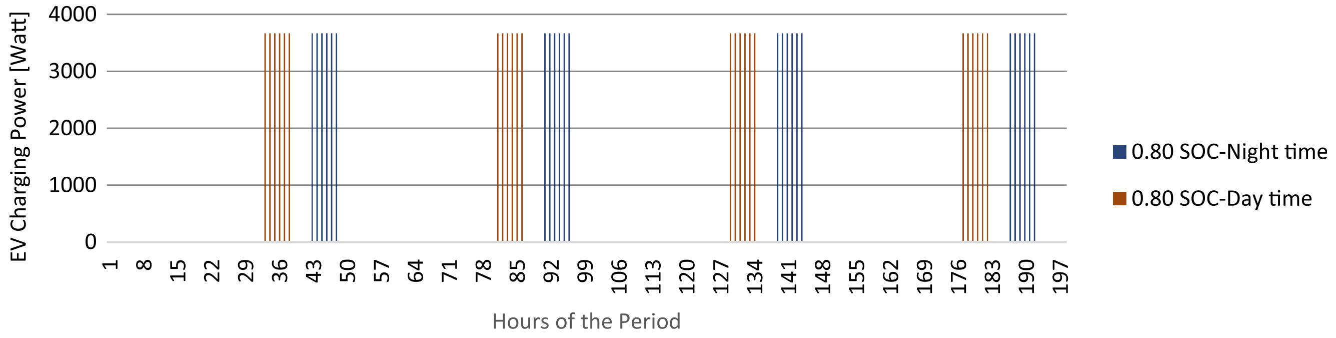


Figure 9
60% SOC of EV charging intervals

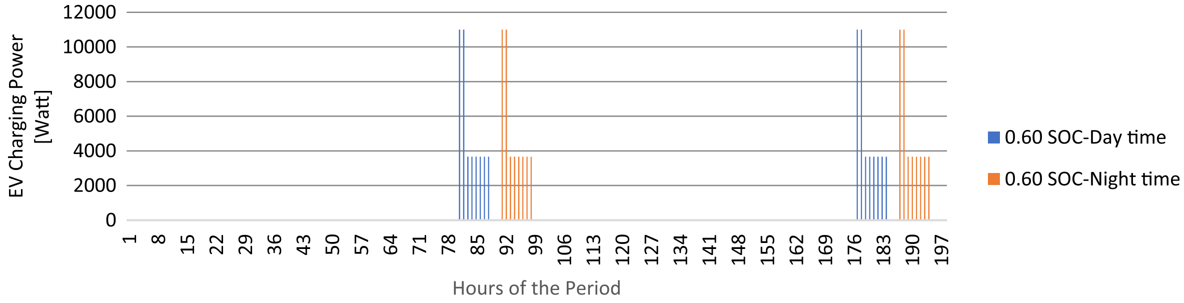


Figure 10
40% SOC of EV charging intervals

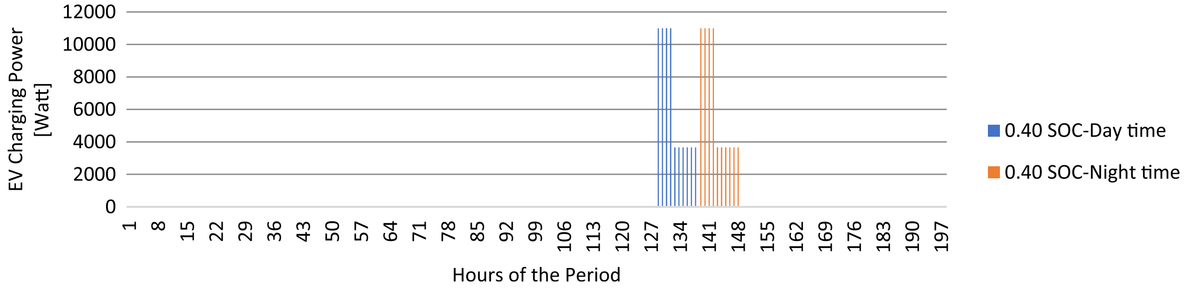


Figure 11
20% SOC of EV charging intervals

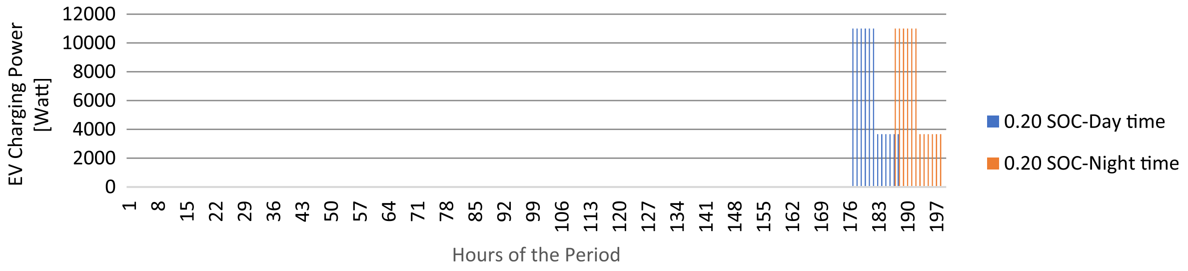


Table 3
PV module catalog information

Power	Arçelik 550 Watt	Units	11
Vmpp	42.20 V	Voc	49.80 V
Impp	13.04 A	Isc	13.94 A
Series	11	Parallel	1
Length	2,279 mm	Width	1,134 mm

3.3. Sizing and logic of the simulation

The PVSyst program models a grid-connected hybrid system with five distinct battery modes. The first of these modes is the battery charging mode. In this mode, if the load consumption is much lower than the currently available solar energy, the produced energy is distributed to the batteries, grid, and loads. The second mode is the battery discharge. In this mode, if the consumer demand is much higher than the currently produced solar energy, the loads receive this energy need from solar energy, the grid, and batteries. The third mode is the direct mode. In the direct mode, when the batteries are full, and the load consumption is below the produced energy, the produced energy is distributed directly to the grid and loads. The fourth mode is the direct mode, which is used when the batteries are empty. In this case, if the consumption is higher than the production, the energy requirement is met by solar energy and the grid. The fifth and last mode is the night mode when solar energy is unavailable. In this case, the grid and batteries meet the energy requirement.

The photovoltaic system is sized as follows: The selected location is Ankara, Turkey. Before the electric vehicles are integrated into the grid, the annual energy consumption of the sample house is 7,288 kWh. The orientation of the panels is placed at an angle of 7 degrees to the east. In this case, the specific production amount in the Ankara region is 1,410 kWh/kWp/year. When the annual consumption amount is divided by the particular production amount, the minimum PV capacity to meet this energy need is 5 kWp. In the study, a PV system with a capacity of 6.05 kWp is simulated. The Catalog information of the photovoltaic module is shown in Table 3.

In the study, a Li-ion battery group was used to provide energy supply in case of possible power outages and no solar energy production. Catalog information for the batteries is shown in Table 4.

Catalog information on the hybrid inverter used is shown in Table 5.

Table 4
Li-ion battery catalog information

Brand	LG Chem RESU 10	Units	1
Energy	8.8 kWh	Cap.@C10	193.2 Ah
Voltage	51.8 V	Isc	13.94 A
Int. res.	11.67 milliohm	Col. Eff.	96 %
Max. ch.	96 A	Max. dc.	96 A
Ser. cell	14 units	Par. cell	3 units

Int. res.: internal resistance, Max. ch.: maximum charging current, Max. dc.: maximum discharging current, Col. Eff.: coulombic efficiency, Cap.: capacity, Par. cell: parallel cells, Ser. cell: serial cells

Table 5
Hybrid inverter catalog information

Brand	Fronius GEN 24+	Units	1
Type	3 phased	Min. V.	80 V
AC P.	5,000 W	Max. V.	800 V
Max. PV	7,500 W	Grid V.	400 V

Min. V.: minimum mppt voltage, Max. V.: maximum mppt voltage, Grid V.: Grid voltage, Max. PV.: maximum PV power, AC P.: AC power.

When the simulation is performed for the situation before the electric vehicles are integrated, 71% of the 8,866 kWh/year of energy produced from solar energy and made available at the inverter output is used directly. In other words, this amount of energy is directly transmitted to the grid and loads. 29% of the produced energy is used through batteries. 2,132 kWh/year of energy is drawn from the grid. Accordingly, there is a difference of 1,243 kWh/year between the amount of energy injected into the grid and drawn from it, which shows that the designed system is positive.

4. Results

Usage ranges, charging times, and cases of electrical vehicles are shown in Table 6.

In this study, variable consumption needs of electric vehicles charged at different times and intervals and the load changes caused by these consumption needs, charge-discharge times, energies, SOC values, efficiency performance of the hybrid system, renewable contribution, and economic indicators of Li-ion batteries in the hybrid system were investigated.

The PVSyst program determines SOC values based on factors such as charging or discharging rate, battery temperature, and aging, which are among the most crucial indicators for batteries, as shown in (11)[2].

$$\mathrm{C_{DR}} = \mathrm{Cap_{C10}}\left(\frac{\mathrm{DR_{Aref}}}{\mathrm{DR_A}}\right)^{\frac{1-k}{k}} \tag{11}$$

---

[2] PVSyst SA, "Capacity as function of the discharge rate," https://www.pvsyst.com/help/physical-models-used/batteries/battery-model/capacity-vs-discharge-rate.html#peukert-model.

Table 6
Cases of electrical vehicle charging

Cases	Used range (km)	SOC (%)	Charge time
Case-1	105	80	Day
Case-2	105	80	Night
Case-3	209	60	Day
Case-4	209	60	Night
Case-5	314	40	Day
Case-6	314	40	Night
Case-7	418	20	Day
Case-8	418	20	Night

where C_{DR} is the capacity of discharge rate in Amp, Cap_{C10}: is nominal capacity, defined for the discharge time of 10 hours, DR_{Aref}: is the reference discharge rate in Amp, DR_A: is the discharge rate in Amp, k is Peukert coefficient (1.02 for Li-ion batteries)

The efficiency performance of hybrid systems and renewable energy contribution can be calculated in (12) and (13) [39].

$$HSEP = \frac{\mathrm{LC}}{(\mathrm{RG} + \mathrm{FG})} \tag{12}$$

where HSEP: hybrid system efficiency performance [%], LC: load consumption [kWh], FG: fossil generation [kWh], RG: renewable generation [kWh].

$$REC = \frac{\mathrm{RG}}{(\mathrm{RG} + \mathrm{FG})} \tag{13}$$

where REC: renewable energy contribution [%], RG: renewable generation [kWh], FG: fossil generation [kWh].

In case 1, the simulation shows that 1,691 kWh of solar energy directly reaches the grid, 4,790 kWh reaches the consumer, and 2,103 kWh reaches the consumer via batteries. In addition, since the total consumption is 11,291 kWh, 4,395 kWh of the energy is withdrawn from the grid. The minimum SOC value seen in the year is 19.5%, and the maximum SOC is 77.5%. While the payback period is 12 years, the IRR, ROI, NPV, and LCOE values are 41.05%, 592.4%, and 3,287,567 TRY and 17.045 TRY/kWh, respectively. Figures 12 and 13 show the SOC and discharge energy of Li-ion batteries used by the consumer after electric vehicles are integrated.

When case 2, where the EV is charged at night, is examined, the energy injected into the grid has increased to 3,335 kWh, and the amount of energy drawn from the grid has increased to 6,071 kWh. The usage rate of the batteries has increased by 5% compared to case-1, reaching 29.5%.

While the payback period increases to 12.3 years, the IRR, ROI, NPV, and LCOE values are 39.83%, 488.3%, 2,710,022 TRY, and 17.109 TRY/kWh, respectively. Since the batteries are used more in case-2 than in case-1, daytime charging status, the annual amount of unused energy in the batteries decreases from 6,896 kWh to 5,220 kWh. When case 3, where electric vehicles are charged during the

Figure 12
Case-1 SOC of the Li-ion battery

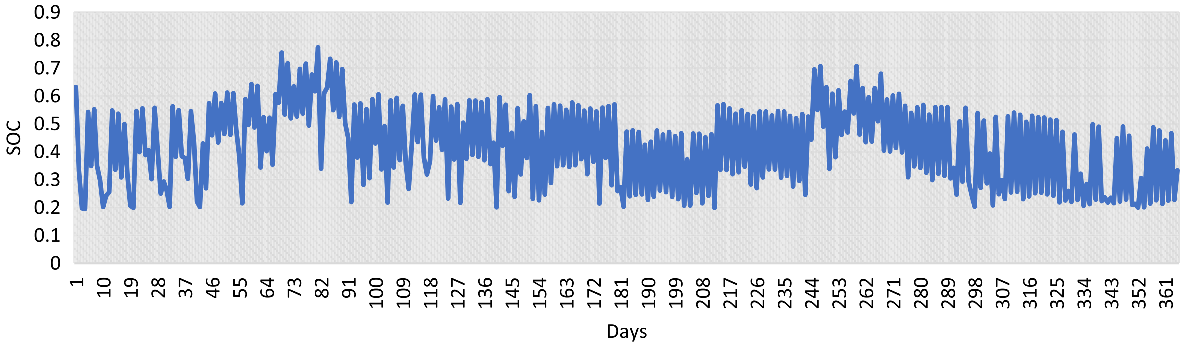
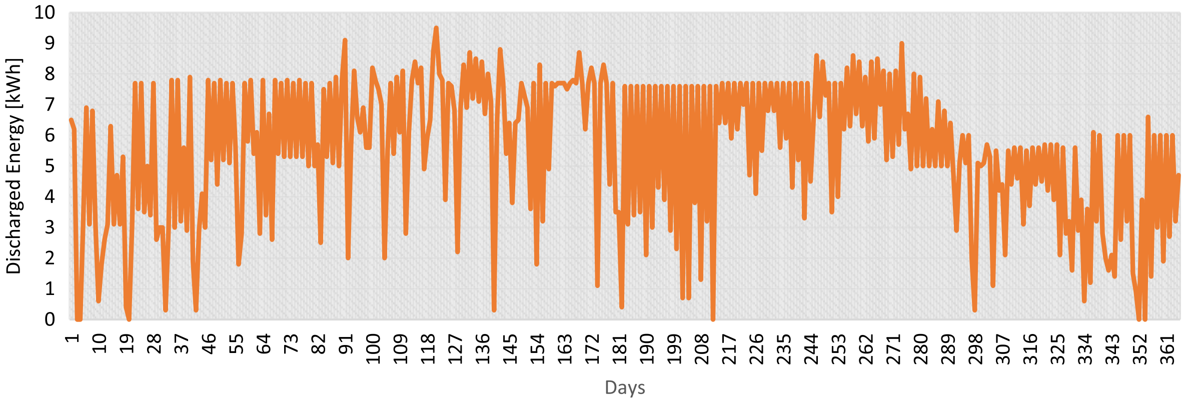


Figure 13
Case-1 discharged the energy of the Li-ion battery



day after traveling 209 km, is examined, the annual amount of solar energy injected into the grid is 2,516 kWh, the energy drawn from the grid is 5,224 kWh annually, and the amount of unused energy in the batteries is 6,068 kWh. While IRR, ROI, NPV, and LCOE values are 40.16%, 520.2%, 2,887,250 TRY, and 17.053 TRY/kWh, respectively, the payback period is 12.3 years.

When case 4 is examined, the amount of energy injected into the grid is 3,349 kWh per year, the amount of energy drawn from the grid is 6,103 kWh, and the amount of energy reaching the consumer through batteries is 2,500 kWh. The amount of unused energy in batteries is 5,189 kWh per year; the IRR, ROI, NPV, LCOE, and payback periods are 39.52%, 468.9%, 2,602,480 TRY, 17.146 TRY/kWh, and 12.5 years, respectively. Figures 14, 15, 16, and 17 show the SOC and discharged energy graphs of cases 3 and 4.

When case-5 is examined, the amount of energy injected into the grid is 2,914 kWh, and the energy drawn from the grid is 5,061 kWh. In this case, the payback period is 12.4 years, and the IRR, ROI, NPV, and LCOE values are 39.75, 488.6%, 2,711,543 TRY, and 17.074 TRY/kWh, respectively. The annual amount of unused energy in batteries is 5,659 kWh.

When case 6 is simulated, 3,358 kWh of energy is injected into the grid annually, while 5,545 kWh of energy is withdrawn from the grid. While the ratio of the produced solar energy to the consumer via batteries is 29.2%, the ratio of the directly used solar energy is 70.8%. While the payback period increases to 12.6 years, IRR, ROI, NPV, and LCOE values are 39.40%, 461.2%, 2,559,667 TRY, and 17.156 TRY/kWh, respectively. The amount of unused energy in batteries is 5,175 kWh per year.

When case-7, where the range of the electric vehicle is used the most, and the charging interval is during the daytime and has the longest period, is examined, 2,940 kWh of energy is injected into the grid annually. In comparison, 5,622 kWh of energy is withdrawn from the grid. While the rate of solar energy transferred directly to the consumer is 74%, the IRR, ROI, NPV, and LCOE values are 39.71%, 486%, 2,697,329 TRY, and 17.088 TRY/kWh, respectively. The payback period is 12.5 years.

Figure 14
Case-3 SOC of the Li-ion battery

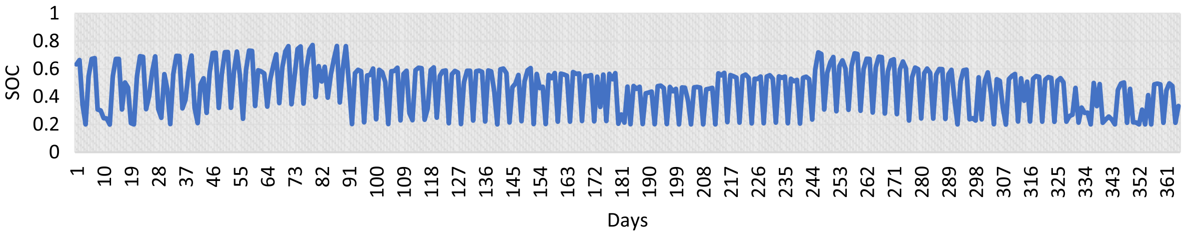


Figure 15
Case-3 discharged the energy of the Li-ion battery

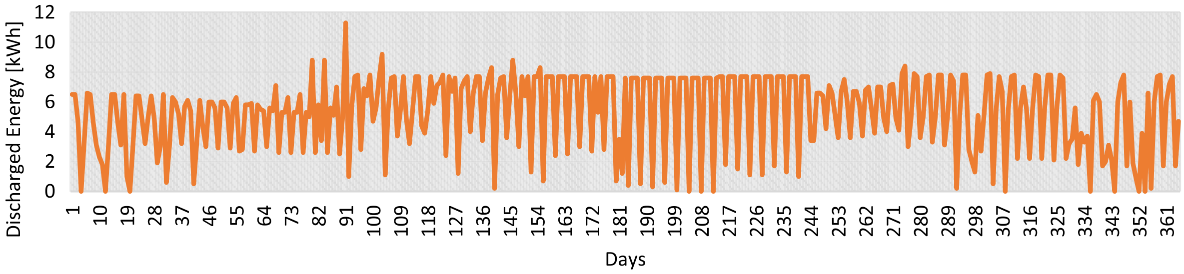


Figure 16
Case-4 SOC of the Li-ion battery

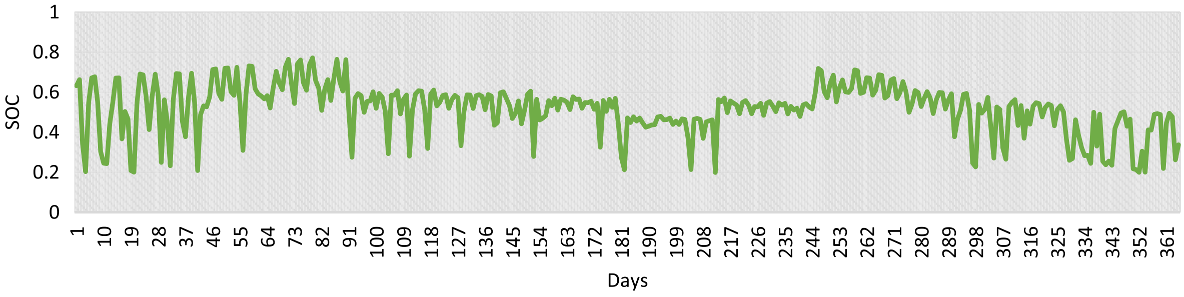


Figure 17
Case-4 discharged the energy of the Li-ion battery

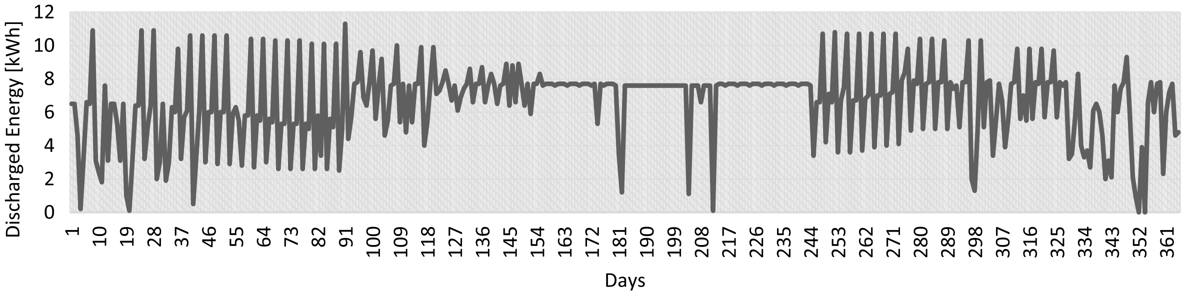


Table 7
Results of Li-ion batteries for daytime and nighttime charging of EV

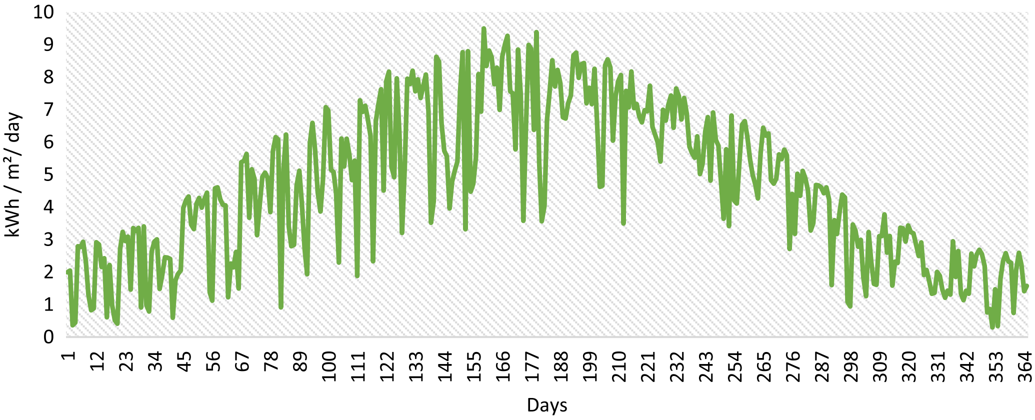
Cases	Min_SOC	Max_SOC	Av_SOC	En_Ch (kWh)	En_Dc (kWh)	H_Ch (hours)	H_Dc(hours)
case-1	0.195	0.775	0.422	2,055.82	2,012.28	1,549.18	2,786.56
case-2	0.197	0.662	0.490	2,484.79	2,434.66	1,719.79	2,303.60
case-3	0.199	0.771	0.461	1,998.88	1,945.55	1,468.73	2,777.75
case-4	0.199	0.771	0.517	2,471.96	2,411.96	1,713.66	2,925.83
case-5	0.199	0.775	0.495	2,143.69	2,091.30	1,493.11	3,020.29
case-6	0.199	0.775	0.528	2,463.14	2,401.10	1,711.09	3,169.77
case-7	0.199	0.780	0.501	2,194.48	2,139.80	1,521.18	3,095.38
case-8	0.199	0.780	0.530	2,460.28	2,397.56	1,709.90	3,220.58

Min_SOC: minimum SOC, Max_SOC: maximum SOC, Av_SOC: average SOC, En_Ch: charging energy into the battery, En_Dc: discharging energy from the battery, H_Ch: charging hours, H_Dc: discharging hours, PV_PR: PV performance ratio.

Looking at the last state of the simulation, case-8, the payback period is 12.6 years; IRR, ROI, NPV, and LCOE values are 39.37%, 459.4%, 2,549,651 TRY, and 17.158 TRY/kWh, respectively. While the amount of unused energy in batteries is 5,171 kWh annually, the energy injected into the grid is 3,361 kWh, and the amount drawn from the grid is 6,077 kWh.

Table 7 shows the batteries' minimum, maximum, and average SOC values, total charge and discharge hours, and total charge and discharge energy for all cases every year. Table 2 shows the performance results of the hybrid system. All results and graphs are prepared based on PVSyst's advanced simulation results. When looking at the results in general, the efficiencies of the lithium-ion batteries used in the hybrid system vary between 97.3% and 97.9%. It is seen that the most efficient hybrid system performance is obtained by charging the EVs at 80% SOC during the day. This situation is followed by case-1 with a rate of 80.14% in case-3. The hybrid system with the lowest efficiency is when the EV starts charging at 40% SOC at night. When the situation shown in Figure 13, where EVs are charged frequently, is examined, the discharge energy level contains too many spikes, and the batteries are charged and discharged too often. Another reason for such a significant change is that the PVSyst program includes the cloudiness index in the weather indicator. The solar radiation that occurs due to the cloudiness rate is shown in Figure 18. According to the discharge energy graph shown in Figure 17, when the hours of solar energy are very high in the

Figure 18
Global horizontal irradiation for Ankara



summer, the discharge energy levels have remained almost constant. Another reason, besides the increase in sunny hours, is that the charging interval for EVs has also increased, and they are charged at night. In this way, the hybrid system's batteries that charge the EVs will be charged from solar energy during the day and will not be subject to extra discharge due to EVs for 4 days. When looking at the average battery SOC values yearly, half of the batteries are used for household and EV consumption, and this used energy is recharged to the batteries via solar energy panels. When the hybrid system performance results are examined, the amount of energy drawn from the grid, which is assumed to be met by fossil resources, increases during night consumption and when the SOC values of the EV batteries start to be charged below 60%.

5. Conclusion and Discussion

This study is similar to the economic and technological analysis sections of hybrid systems in the literature. However, it reveals the difference in the impact of the increasing use of electric vehicles on the installed hybrid systems and in which situations energy consumers charge EVs. In the hybrid photovoltaic system study conducted in Kandi, Benin [26], the consumption model was created by operating household appliances in different combinations. The consumption in all combinations was only between 07:00 am and 07:00 pm. This study conducted in Benin differs from ours because it does not include consumption during night hours, and the integration of electric vehicles is not included in the consumption models. According to the results of the economic analysis conducted for Benin, the NPV values were negative in three different combinations, indicating that the simulated investment is not feasible according to the entered economic indicators. Our study's NPV values are positive, and hybrid systems are suitable for charging electric vehicles. In another hybrid system [27], it was planned to reduce voltage changes and costs by using algorithms. In this study, no algorithm was used. In the study, the charging periods of electric vehicles were changed, and the economic and technological results were investigated. A study conducted in Diyala, Iraq [29], is similar to this study in terms of performing a techno-economic analysis. In the study conducted in Diyala, the payback period was calculated as 10 years for a 5 kWp system, while the performance ratio was 66%. When the performance ratio in Diyala is compared with this study, it is 8% lower than case 6, which is the lowest performance ratio. The low performance of hybrid systems can be explained by two factors. The first of these is insufficient radiation, and the second is insufficient use of solar energy when consumption increases—in the simulation study carried out in MATLAB [30]. The method used is to charge the batteries that charge the vehicles when the electricity tariff is low and discharge them when the tariff is high. In this study, the charging of electric cars is billed only according to the three-time tariff. In other words, the night period is when the electricity tariff is cheap in the three-time tariff. There is no solar energy in this period. For this reason, the batteries of the hybrid system are charged when energy is expensive, and electric vehicles are charged when energy is both expensive and cheap. When we look at the study conducted in Greece [31], the LCOE values vary between 0.42 and 0.62 euros. This is between 15.22 TRY and 22.47 TRY with the current exchange rate. In this study, the LCOE values are at the level of 17 TRY. This shows that a hybrid system installed in Greece has energy costs similar to those of a hybrid system installed in Turkey. When we look at other studies in the literature [32, 34, 35], it is seen that in the simulations carried out, there is no integration of electric vehicles, and only economic analyses are performed. The difference between this study and other studies in the literature is that it examines the technological and financial indicators of hybrid photovoltaic systems used with the integration of electric vehicles.

Thanks to net metering and smart meters, energy can be tracked quickly today, and consumers and system operators can observe the income-expenditure balance. For this reason, every extra load to be connected to the electricity grid should not be considered only as meeting and solving the need, but also how much efficiency will be obtained from the energy systems used and how much profit will be obtained should be taken into consideration. In this context, the contribution of this study to the literature is that it is of great importance that EVs should be charged according to the highest profit and efficiency rather than charging them whenever desired. When looking at the simulation results, after EVs are integrated into hybrid systems, there have been changes in their monthly consumption in line with different charging needs. As a result of these changes, the load exchanges of hybrid system batteries have changed, and the performance rates and accumulated profits of the hybrid system have changed. Accordingly, the priority is to charge electric vehicles during the day instead of at night, providing more profit. Regarding total system efficiency, case-1 gives the highest percentage, and case-6 gives the lowest rate. The situation with the highest renewable energy contribution is case 1, and the problem with the lowest contribution is case 4. After charging electric vehicles at night, an increase is observed in the charging and discharging hours and energy of hybrid system batteries. The SOC values of the batteries, which reach up to 78%, are between 42% and 53% on average. Considering the 25-year power plant life between the charging behavior of EVs that provide the most profit and the situation that provides the least profit, there is a difference of 737,916 TRY. This amount is a severe figure for a small-scale home consumer. If these EVs are integrated into large-scale systems and charged at the proper periods and SOC values, millions of Turkish liras, perhaps billions of TRY, will be saved. Another striking situation in the results is that starting to charge EV batteries at 80% SOC values at night brought more profit than charging them at 20% SOC values during the day. The difference between the NPV value of case-2, which is 2,710,022 TRY, and the NPV value of case-7, which is 2,697,329 TRY, is visible. According to this study, two critical criteria emerge in EV charging. The first is that EVs should be charged during the day, and the second is that EV batteries should be plugged in when their SOC values drop to 60%.

This study will shed light on future investments in application areas. The need to charge EV vehicles during the day instead of at night will lead to an increase in the number of EV charging stations in workplaces and public areas, and even small commercial enterprises are adopting remote working if possible and thus being able to charge their vehicles at home, as a concept that also affects the financial resources and lifestyles of societies.

Ethical Statement

This study contains no studies with human or animal subjects performed by the author.

Conflicts of Interest

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

Data Availability Statement

Data is 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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