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Investigation of a grid-connected solar PV system for the electric-vehicle charging station of an office building using PVSOL software

Abstract: Electric vehicles are predicted to blossom in Egypt in future years as an emerging technology in both the transportation and power sectors, contributing significantly to the decrease of fossil-fuel usage and CO_2 emissions. As a result, to mitigate overloads of the vehicle energy demand on the nation's electric grid, a solar PV system can be used to provide the electricity needs of an EV charging station. This objective of this paper is to present the design, simulation and economic analysis of a grid-connected solar-power system for an electric-charging station at a workplace in 6th October city, Egypt using PVSOL simulation tool to supply energy to the charging station and office-building appliances. The ideal orientation of the PV panels for maximum energy was determined using data from the photovoltaic geographical information system and predicted load-profile patterns. The amount of electricity generated the efficiency of the PV power system, financial analysis in terms of investment costs and the return on assets, and the ability to reduce CO_2 emissions are all estimated in this study. This system also evaluates annual energy predictions and is used for electric-vehicle charging, grid feeding, and appliance consumption. Due to the relatively high solar insolation in Egypt; PV production energy was 10,463 kWh per year and the annual yield is 1,786.69 kWh/kWp. Of the power from PV generation, 66% is utilized for charging the electric

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vehicle and 34% for electrical appliances. After applying the financial analysis for 20 years; the electricity production cost is 0.0032 $/kWh and the payback period for this proposed system is about five years. The annual energy costs after the installation of PV systems proposed system created a financial saving of 21%. The performance ratio of this system inverter is 84% and the monthly average of the electric vehicle SOC over a year doesn't decrease out of 27% plus 5 tons of CO_2 emissions per year were avoided. This research can be used as a recommendation for stakeholders who want to use this energy source for vehicle charging.

KEYWORDS: clean solar energy, electrical vehicles, charging station, CO_2 emissions, economic appraisal

Introduction

The global expansion in the electrical power demand, the impact of environmental pollution, and the depletion of fossil fuel supplies have all prompted the development of alternative power sources. Concerns about energy supply, climate change, and economic competitiveness are causing a paradigm shift in global energy systems (Alsharif et al. 2021). Climate change has been identified as the most serious concern facing the world in the coming decades by the majority of governments. The shift to renewable energy sources (RESs) on distribution systems is becoming increasingly pronounced, and this trend is expected to continue. Hybrid systems have been extensively reported to include renewable energy technologies. Solar energy is the most abundant source of renewable energy. The biggest problem in establishing a solar PV source in real-time is the source's cost and availability. PV generating is promising and is widely used around the world, but the main problem is ensuring a steady supply of energy. Solar energy is weather-dependent and it has an impact on technical issues like power fluctuation and instability. Solar photovoltaic resources are expected to generate 5% of the global energy demand in 2030, escalating to 11% in 2050 (Nhede 2020). Furthermore, the EU has set sustainability goals for the transportation sector, requiring reductions in GHG emissions by 2050.

In the hope of contributing to reducing green house gas (GHG) emissions, renewable energy sources, energy efficiency, and new transportation technologies will all require broad exploitation, incentives, and improved integration as a result of decarburization programs. As a consequence, huge avenues and initiatives for the integration of eco-friendly electric cars (EVs) or the reduction of investments or development incentives for traditional internal combustion engine vehicles (ICEVs) are already provided or are in progress (Das et al. 2019). Compared to ICEVs, EVs not only have the potential for low GHG emissions over their lifetime, but they also have the potential to minimize air and noise pollution. Electric vehicle technology is quickly advancing; with the potential to one day replace traditional automobiles. Electric vehicles use a rechargeable lithium-ion battery to power an electric motor instead of an internal combustion engine. Electric vehicles require charging stations similar to those used by gasoline engines for mobility. The cost of solar power is falling as photovoltaic technology advances, boosting the practicality of solar projects (Sylvia 2020). Electric vehicles (EVs) are vehicles that are powered in part by stored energy and may travel on roads, highways, trains, planes, and ships. There are two major types of EVs (Hasan et al. 2021): fully battery electric vehicle (FBEV), hybrid electric vehicle (HEV). HEVs are usually used in rural and urban areas, and when they operate in the city center, they can provide significant battery assistance and turn on the motor. PEVs (plug-in electric hybrids) and FCEVs (fuel cell electric cars) are the two accessible varieties of HEVs. The growing demand for EVs (Fig. 1) (Electric Car Batteries 2022) is driven by cost, long-term battery value and availability, tax revenue, e-commerce accessibility, power system involvement, and the interface between conventional and electrical automation mobility options. Electric vehicles are fast becoming more popular around the world, with a global market share of 2.6 percent in 2019 (Ahmad et al. 2021). Over five million electric vehicles have been listed from all over the world. Electric vehicle revenues increased by 2% in the United States, 3% in Portugal, 5% in China, 7% in Ireland, 8% in the Netherlands, and 50% of new EVs were sold in Norway (Hasan et al. 2021). Consumer and government spending on Evs is increasing, and their market share is growing, indicating a trend towards the electrification of the mobility industry (Kandasamy et al. 2021). Electricity generation for mobility is particularly beneficial from a climate aspect in countries like Europe, where the electricity mix has low carbon intensity. Electric vehicles are becoming increasingly popular in Europe and China (Ghotge et al 2021). Global warming and greenhouse gas emissions, on the other hand, constitute a hazard to the environment, which can be mitigated

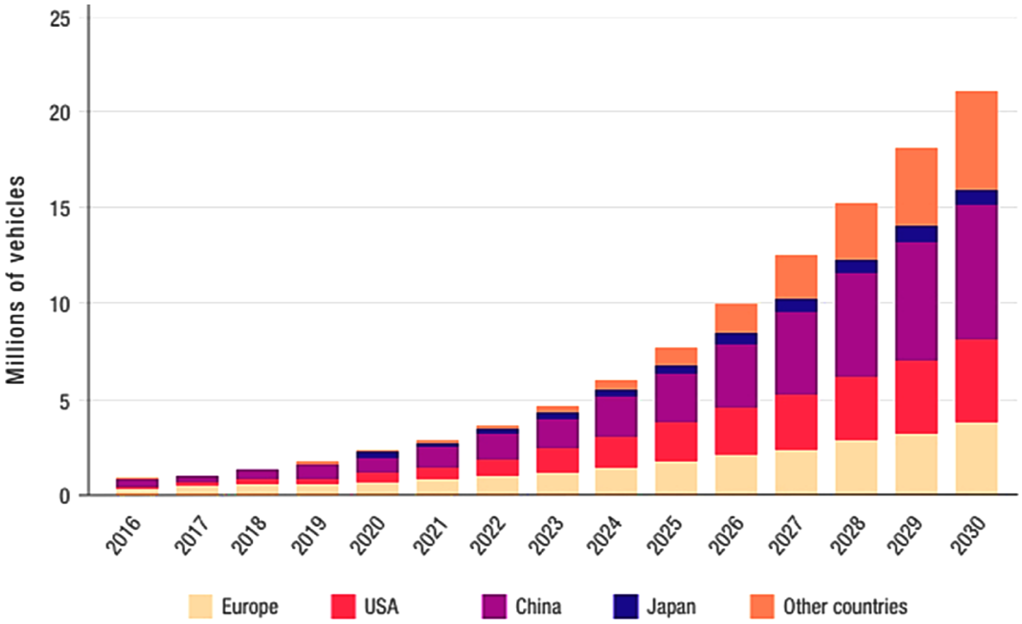


Fig. 1. Electric car deployment in selected countries, 2016–2030 (Electric Car Batteries 2022)

Rys. 1. Liczba samochodów elektrycznych w wybranych krajach w latach 2016–2030 by increasing the use of electric cars to replace ICEVs. Many countries and businesses have begun to implement policies and encourage their citizens to adopt electric vehicles.

Electric vehicles will help Egypt cut its consumption of petroleum products – a process that will coincide with the government's goal of reducing petroleum imports by 10% by 2019 (Farrag 2018). In February 2018 (Is Egypt ready for electric vehicles? 2020), on the Cairo-Suez highway, the country's first electric vehicle charging station opened at a state-owned Wataniya gas station. Bavarian Auto, a BMW distributor, introduced the BMWi, Egypt's first electric automobile, two months later. The Wataniya charging station is owned by Revolta Egypt, an electric vehicle technology business. The company now has seventeen charging stations (Electric vehicles in Egypt 2019) in the country, according to Badawi. Revolta Egypt has ambitious plans to cover nearly the entire country over the next two years.

Many domestic and international studies have been conducted to investigate the power supply for EV charging stations. An in-depth look at a current photovoltaic system, electric vehicle, and battery ideas, as well as how they might be applied to the concept of solar parking lots are described in the literature (Osório et al. 2021b). Nguyễn (Nguyễn 2017) built a solar-energy system for an EV charging station and utilized PVSOL premium software to test the ability to charge an electric vehicle's battery. Chandra Mouli et al. (Chandra Mouli et al. 2016) constructed a 10 kW solar-power system for an electric-car charging station and explored the possibility of using solar energy to charge battery electric automobiles at work in the Netherlands. Domínguez-Navarro et al. (Domínguez-Navarro et al. 2018) described a quick charging station for electric vehicles that incorporates renewable energy and storage devices. Several previous studies (BirnieIII 2009; Nunesa et al. 2015; Tulpule et al. 2013) looked at the design of an EV charging station based on solar PV, presenting the mutual benefit of charging EVs with solar energy, the negative effects of excess solar generation from PV on a national scale, and the economic incentive and CO_2 offsets for PV charging being greater than charging the EV from the grid. Solar- and biogas-energy charging stations were investigated and economically analyzed using HOMER software by Karmaker et al. (Karmaker et al. 2018); cost of energy (COE) of \$0.1302/kWh, total net present cost (NPC) of \$56,202, and operating cost of \$2,540 are estimated plus the CO_2 emissions reduced by 34.68% compared to a conventional grid charging station. Ekren et al. (Ekren et al. 2021) built a wind-solar hybrid charging-station system using HOMER software and discovered that the best solution for the hybrid system contains 44.4 percent wind resources. To evaluate the performance of an off-grid solar photovoltaic system for the charging of electric vehicles, a feasibility study (Alsharif et al. 2021) for establishing an EV charging station for the residential area based on a renewable hybrid system connected with a utility grid was explored. CO_2 emissions are expected to rise in Vietnam in the coming years/near future (Thanh 2021), with electric vehicles (EVs) playing a significant role in reducing fossil fuel consumption, So Thanh examined the design, simulation, and economic evaluation of a grid-connected solar-power system for an electric charging station at Thu Dau Mot University. Three different module areas were considered for PV panels that are connected to the grid, electric appliances, electric vehicles, and battery systems, which were then analyzed using PV sol simulation by Pushpavalli et al. (Pushpavalli et al. 2021) to examine the overall set-up of the system, i.e. module areas of the PV panel with different tracking methods and climate data for the specific location. Srujana et al. (Srujana et al. 2021) reviewed the components of the battery-electric vehicle framework, simulated the model using MATLAB-Simulink, and established the linked electrical system components and their accompanying verification equations. A study by Fotouhi et al. (2019) comprises the development of an energy-consumption-estimation model for use in an EV fleet management system (FMS); a commercially available passenger car is modeled using MATLAB/Simulink, and the impact of energy consumption estimation accuracy on a larger scale for a fleet of EVs is investigated.

Mehrjerdi (Mehrjerdi 2019) built stochastic optimization programming to design an off-grid charging station for electric and hydrogen vehicles powered by solar panels, and the results show that the cost of switching stations is covered by the investment cost of the solar system (95%), the operational cost of the diesel generator (4.5%), and the investment cost of the diesel generator (0.5%). Another study (Fathabadi 2017); designed and built a novel grid-connected solar/wind-powered electric-vehicle charging station with the vehicle to grid technology, demonstrating that the charging station not only provides electric energy to charge electric vehicles but also helps to balance the load demand in the grid-connected to it. The efficiency of an off-grid solar photovoltaic system for charging electric vehicles (EVs) in a long-term parking lot is investigated (Ghotge et al. 2021) with three strategies for prioritizing vehicles with a low state of charge to best utilize the system's available energy. An off-grid charging station (OGCS) is required to meet the energy demand and Improve the charging station's sustainability, whereas a system has been proposed (Kumar et al. 2019) that consists of an energy-storage system (ESS) along with a PV source and an EV charger to increase the use of electric vehicles (EV) in remote locations while reducing the burden on the grid in urban areas. Colak et al. (Colak et al. 2016) present the development of a model for a PV-based electrical car that anticipates the total power production in specific Ankara city conditions; PV cell parameters are determined, and then a PV array with cells built is formed to compute the cumulative effect. Using improved chicken-swarm optimization to optimally place solar-powered charging stations in an IEEE 33 bus system, a comprehensive framework for optimally placing solar-powered charging stations in a distribution network with an improved voltage profile, minimum power loss, and reduced cost is proposed (Ahmad et al. 2021). A grid-connected load-following hybrid solar PV and small-hydro micro-grid with a grid isolated electric-vehicle charging system have been presented (Olatunde et al. 2020). Osório et al. (Osório et al. 2021a) propose an EV fast charger with an integrated PV system as a news aggregator operator in the energy system, as well as the effectiveness of a solar-powered EV parking lot. The use of available photovoltaic (PV) electricity to charge EV batteries while keeping the low-voltage network within its operational constraints is a linear programming (LP)-based optimization approach for charging electric cars (EVs) in a decentralized manner as described in the literature (Cortés Borray et al. 2021). Even though two charging strategies are analyzed and compared using the TRNSYS simulation tool, the investigated smart grid is designed (Calise et al. 2021) to meet the energy demands of a district, including the energy demand for space heating and cooling, as well as the electric energy of a large number of buildings occupied by people who only use electric vehicles. The Stochastic Firefly Algorithm (SFA) model for Maximum Power Point Tracking (MPPT) control to obtain maximum power from the solar power plant is used (Goswami and Sadhu 2021) to predict the arrival time, the State of Charge (SOC), and the charging demand, and the findings show that using SFA enables fast charging of the batteries while also increasing the charging station's profit. A Comprehensive optimization approach for constructing an off-grid solar-powered charging station to offer electricity to electric cars (EVs) and hydrogen to hydrogen vehicles was provided by Wang et al. (Wang et al. 2020); the results show that the overall annual cost increases by 13.75 percent. Mclaren et al. (Mclaren et al. 2016) present a summary of expected emission levels from battery-electric and plug-in hybrid electric vehicles for four charging scenarios and five power grid profiles, and the results show that charging during the off hours leads to higher carbon output for all vehicle types when compared to other charging situations.

An on-grid solar photovoltaic (PV) system for charging electric cars (EVs) parked in parking lots is investigated in this study. In 6th October, Giza, Egypt, these parking spots, where autos are parked for eight hours, are frequently positioned adjacent to the designated site's office building. The proposed system's advantages include the elimination of grid capacity, which would result in a significant reduction in the capital costs of the installation of EV-charging infrastructure. This study uses a collection of monthly solar radiation and ambient temperature data for a specific site produced with high precision and resolution from the Photovoltaic Geographical Information System (PVGIS). In addition, the actual load demand profile is estimated. The study's key goals are as follows:

- Estimating percentage of required electricity production which is covered by PV power or the national grid,
- Designing a rooftop building solar-power system for an EV charging station,
- The state of electric car charging is also calculated for a year,
- Assessing the study's economic feasibility in terms of total investment costs, electricity generation costs, and cash flow in and out.
- Using the PVSOL software package, evaluating the solar-power system's system performance ratio and the amount of CO_2-emission reduction.

This paper is organized as follows: in Section 2, mathematical modeling for each component is described, along with the simulation methodology, which is implemented using the PVSOL software package. In Section 3, we show the structure of the charging of electric vehicles (EVs) using solar PV, as well as site geography, resource data, load-profile data, as well as specifications of the system components. Section 4 discusses technical, economical, and environmental issues. Finally, Section 5, presents the findings of our study as well as some suggestions for future research.

1. Methodology

The proposed technique in this work is separated into two parts: mathematical modeling and simulation. This investigation is carried out sequentially. The site's location is picked first. The solar power system is then installed and equipment is chosen to meet the actual load requirement. The study of mathematical modeling of system components is also considered. The PVSOL software tool is then used to model and analyze the solar-power system's energy efficiency. Finally, the project's economic feasibility and the extent of the avoided emissions are assessed.

1.1. Mathematical modeling

A model is a method of establishing the goals, variables, and constraints of a scenario. PV, solar panels, and other components can be modeled using a mathematical equation to calculate the output power under various climatic circumstances and energy policies in Egypt. To improve the charging station's reliability, the renewable energy source is run at full capacity.

1.1.1. PV generator capacity

In the grid-connected mode, the solar cells' output should be able to meet network load requirements with the addition of a small amount of electricity to compensate for system losses. The number of PV modules per parallel thread in a series connection, as well as the number of parallel strings linked in parallel. The modeled equation that is used to calculate the PV system's output power is presented in Equation 1 (Alsharif et al. 2021).

$$P_{pvout}(t) = P_{pv\,rated} \cdot \frac{G(t)}{1000} \cdot [1 + \alpha_t (T_{amb} + (0.03125 \cdot G_t)) - T_{Cstc} \tag{1}$$

where:

$P_{pvout}(t)$ – the output power generated from PV [watts],

$G(t)$ – refers to solar irradiance [W/m^2], and 1000 W/m^2 refers to the reference irradiance,

$P_{PVrated}$ – denotes as rated power for PV [watts] at standard test condition (STC),

α_t – the temperature coefficient ($3.7 \cdot 10^{-3}$) 1/C,

T_{CSTC} – the cell temperature [°C],

T_{amb} – the ambient temperature [°C], respectively. The T_{CSTC} can be obtained by Equation 2 (Bhandari et al. 2014).

$$T_{CSTC} = T_{amb} + G(t) \cdot \left(\frac{NOCT - 20}{800} \right) \tag{2}$$

where:

$NOCT$ – the manufacturer's model-able nominal operating cell temperature in degrees Celsius.

1.1.2. Electric vehicle charge station

To improve security and economic sustainability, the battery in electric vehicles is employed to address several supply restrictions. The rated capacity of an electric-car charging station is one of the most important factors to consider when modeling it. The rated capacity is calculated using Equation 3 (Arancibia and Strunz 2012; Cortés Borray et al. 2021).

$$S_{rated} = \left(\frac{k_{load} \cdot N_{slot} \cdot P_{EV}}{\mathrm{Cos}\,\varnothing} \right) \tag{3}$$

where:

S_{rated} – the rated capacity of the vehicle station,
$\mathrm{Cos}\,\varnothing$ – the power factor,
N_{slot} – the amount of charging slots for each EV,
k_{load} – the overload factor for covering overloading in transients,
P_{EV} – the maximum power rate of each EV.

1.1.3. Inverter

An inverter, with 95% efficiency, is essential for transporting power between renewable sources and loads (Singh et al. 2016). The rating of the inverter was identified to determine the system's overall annual cost. The inverter rating $P_{inv}(t)$ can be calculated using Equation 4 (Dufo-López and Bernal-Agustín 2008).

$$P_{inv}(t) = P_L^m(t) \cdot \eta_{inv} \tag{4}$$

where:

$P^m{}_L(t)$ – denotes the peak load demand which is the key in choosing the right inverter,
η_{inv} – refers to the inverter efficiency.

1.1.4. National Grid

If renewable energy sources are insufficient to meet load requirements, the grid can assist in filling the gap. As indicated in Equation 5 (Barakata et al. 2020), R_{grid} is utilized to calculate the money earned from energy sales to the utility grid.

$$R_{grid} = \sum_{t=1}^{8760} ratefeed - in \; x_{Egrid(selling)} \tag{5}$$

where:

$rate_{feed - in}$ – refers to the feed-in tariff rate,

$Egrid(selling)$ – the selling price of energy. Furthermore, the cost power from grid C_{grid} is calculated using Equation 6 (Barakata et al. 2020).

$$C_{grid} = C_p \cdot \sum_{t=1}^{8760} Egrid(purchased) \tag{6}$$

where:

C_p – the cost of buying electricity from the grid, refers to the total cost of buying power from the grid for a year in per-hour terms.

1.2. Simulation using PVSOL

Valentin tools create cutting-edge software for design, dynamic simulation, and yield estimation (Software 2021). This company offers design tools for photovoltaic (PVSOL), solar thermal (TSOL), and heat pump (Geo TSOL) systems. PVSOL 2021 R8 was used for this study as it is a simple, quick, and reliable software tool for the simulation of the solar PV system (Mehadi et al. 2021). PVSOL is a dynamic simulation tool for designing and optimizing solar systems in conjunction with appliances, battery systems, and electric vehicles. PVSOL can design and simulate all types of modern PV systems, from modest rooftop systems with a few modules to large solar parks with up to 100,000 modules (Software 2021). PVSOL searches for the best connection between your PV modules and the inverter based on all of the important parameters, such as location, component specifications, site radiation statistics, and load profile. The software calculates the solar yield based on the required annual PV energy, solar fraction, and solar yield data.

2. Design of the proposed on-grid photovoltaic system

This study presents a smart technique for a grid-connected photovoltaic system for office -building appliances with electric-vehicle charging stations, but it does so by describing the flow power with the PVSOL software package. The consumption of office-building appliances and electric-vehicle charging stations is regarded as a daily load, and forecasting the charging station's periodic power requirement is highly recommended. Additionally, the electrical grid's contribution is merged in this design as a backup option for common advantage when photovoltaic power is unable to protect the station's needs, on the one hand, and then when the charge station's battery that is required to be charged is fully charged and the photovoltaic system can incorporate excess energy into the grid.

2.1. Architecture of the charging station

This work is based on the case study of a project with thorough specifications, such as meteorological data for PV-panel design and the daily energy demand for office building appliances and electric vehicle batteries to modify the rated capacity of the solar station. While the grid's contribution to the structure remains vital, the controller unit's power flow algorithms and how they affect the grid, both positively and negatively present some complex challenges. In this study, a 5.9 kWp solar-power system with a charging station is installed on the roof of an office building. This solar-power system powers both the charging station and the office building. Electricity generated by photovoltaic power plants can be directly charged to an electric vehicle during the day. If the amount of electricity generated exceeds the vehicle's need, a two-way meter can be used to sell the excess energy to the grid. During the night, the office space and charging station receive electricity from the national grid via the two-way meter. Two bidirectional grids and EV ports, as well as a single unidirectional PV port, are included in the EV–PV charger. A central DC-link connects the PV converter, grid inverter, and separated EV charging. Because of the lower conversion steps and higher efficiency, the direct DC link of EV and PV would be chosen over the AC interface. EV charging is evaluated by standards In the United States (Arar 2020). A layout of the proposed system is shown in Figure 2. This technique provides power to electric vehicles and appliances and returns excess power to the grid.

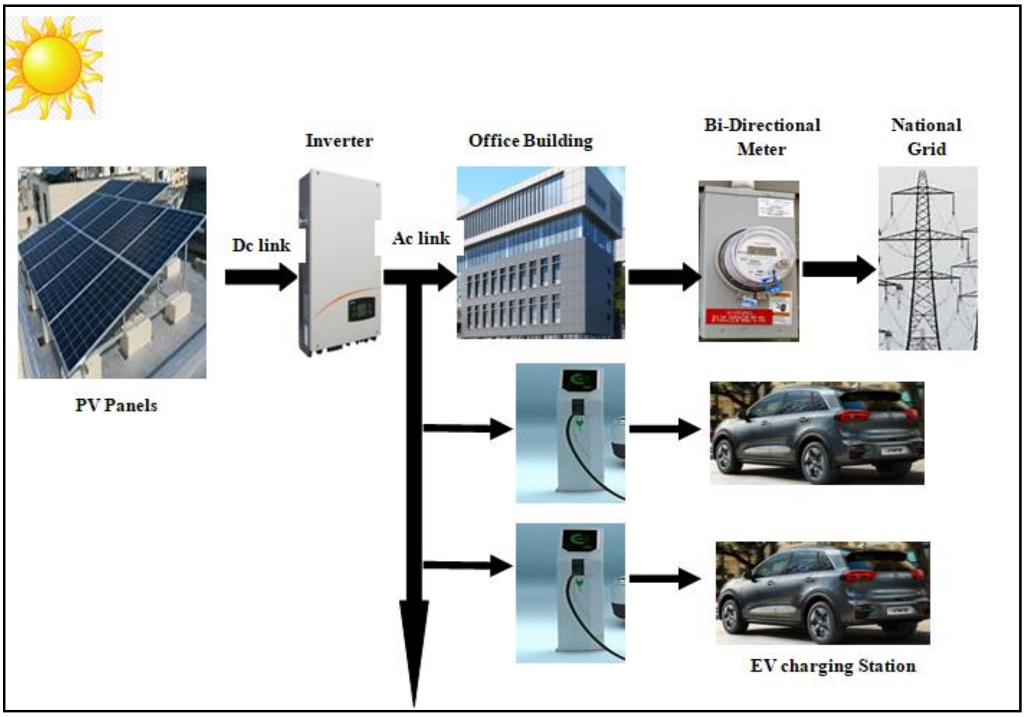


Fig. 2. Schematic of on-grid PV solar system proposed for appliances with-electric vehicle charging

Rys. 2. Schemat przyłączenia systemu fotowoltaicznego proponowanego dla urządzeń z ładowaniem pojazdów elektrycznych

2.2. Collection Data

2.2.1. Site geography

The location is an office building next to a Family commercial plaza in 6th October City, Giza, Egypt. Next to this office building is an electric-vehicle charging station. Family Mull has a unique site in the city, as it is located on the 6th of October city's central axis and amid the city's greatest educational edifices. The project is located in one of the city's most exclusive areas, just steps from the Al Hosary Mosque, the city's most famous mosque, and the 6th of October Club, the city's largest gathering of people. The Family Mall is located at 29.9 N latitude and 30.9 E longitude, with an elevation of 226 meters above sea level.

2.2.2. Site resources data

For the heating runtime environment, meteorological data on solar radiation is critical. Solar radiation and temperature data for the chosen site are used to calculate the design of the system. Typical meteorological year (TMY) files are used to retrieve satellite-derived irradiance and meteorological data for the site chosen using the photovoltaic geographical information system (PVGIS) web-server (PVGIS data 2021). Figure 3 depicts the monthly average of solar radiation and temperature at the site (PVGIS Data 2021). These meteorological statistics were compiled using observations of the hourly averages of solar radiation and temperature in the chosen location between 2014 and 2020. In this particular location, the monthly averages of global radiation and temperature are 1544 kWh/m^2 and 22°C, respectively. The maximum solar radiation was 2,200 kWh/m^2 in June, whereas the maximum temperature was 29.5°C in July.

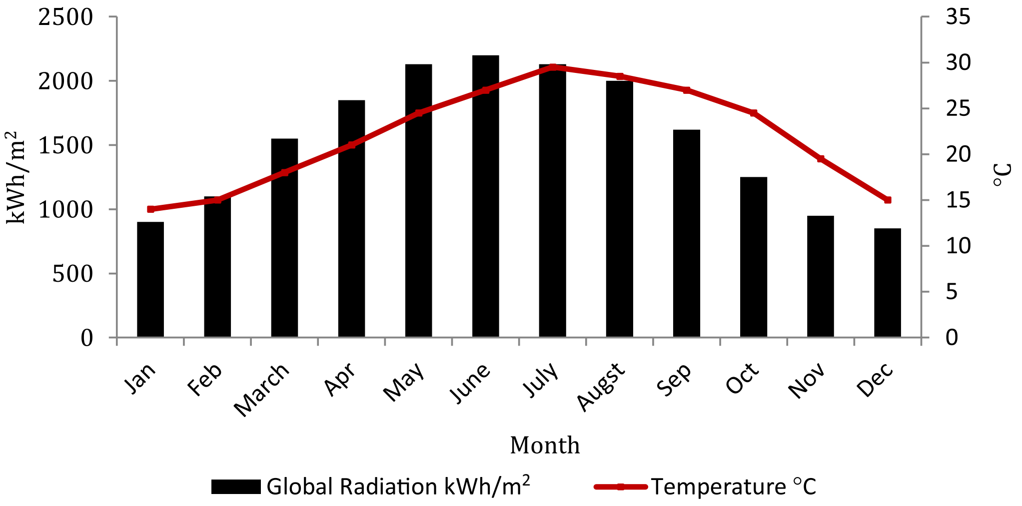
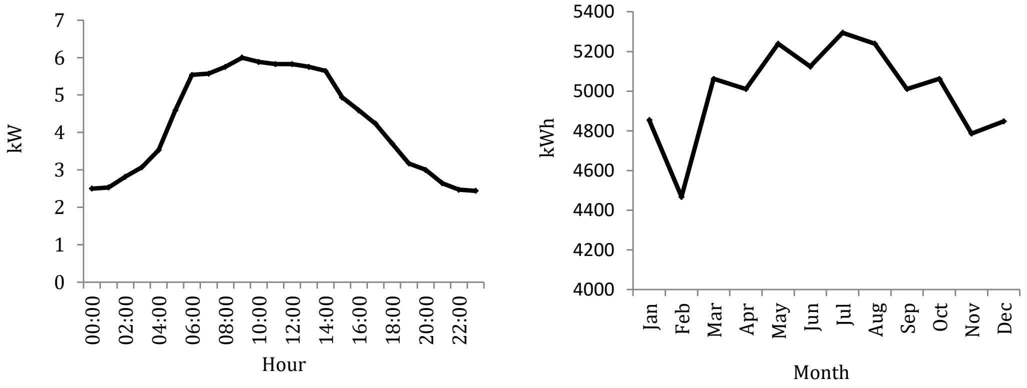


Fig. 3. Site resources data (irradiation and temperature), 2014: 2020 (PVGIS Data 2021)

Rys. 3. Dane o zasobach terenu (napromieniowanie i temperatura), 2014: 2020

2.2.3. Load profile

The chosen site office building is estimated to accommodate 1,000 employees in a size that meets this building requirement, with usage occurring five days per week (Sunday to Thursday) between the hours of 8 am and 5 pm for a total of nine working hours. Light bulbs, fans, and PCs are among the wide range of electrical appliances used here. Figure 4a depicts the office building's daily electrical use, whereas Figure 4b depicts the monthly electric energy demand. At 10 am, the peak load is 6.3 kW, and the annual energy usage is approximately 60,000 kWh. The consumption of electric vehicles is also discussed in the following sections.



a - Daily load profile

b - Monthly electric consumption

Fig. 4. Electric consumption profile of the selected office building in this study

Rys. 4. Profil zużycia energii elektrycznej w wybranym dla przeprawdzenia badań budynku biurowym

2.3. System description and data used

2.3.1. Selection of PV panels

The total capacity of the system to be installed is projected to be 5.88 kWp. A PV panel's rated power is 325 W, and the number of panels to be installed is estimated based on:

$$N_{PV} = P_{PVrequired}/P_{Array} = 5880/325 = 18 \text{ panels} \tag{7}$$

where:

N_{PV} – the number of solar panels needed to be installed,
$P_{PVrequired}$ – the power of the PV system needed to be installed,
P_{Array} – the rated power of solar panel.

Since the PV generating surface is 34.9 m^2, the selected number of modules is 18, and the specifications of the solar panels are detailed in Table 1 (Solar panels specifications 2021), and a graphic coverage design of the concrete roof building is displayed in Figure 5. The selected roof is concrete and the installation of solar panels on the roof parameters is: PV direction which facing south and angle of inclination equals 30°.

Table 1. Specifications of PV panels

Tabela 1. Specyfikacje paneli fotowoltaicznych

Characteristic	Value
Model	STP325S-24/Vem
Dimensions	1.9×0.9×0.04 m
Cell type	Si Monocrystalline
Cell count	72 cell
Nominal output	325 W
Total solar capacity	5.88 kWp
Maximum power voltage	36.72 V
Maximum power current	1.73 A
Open circuit voltage	43.9 V
Short circuit current	1.84 A
Efficiency	16.77 %

Source: Solar-panel specifications 2021.

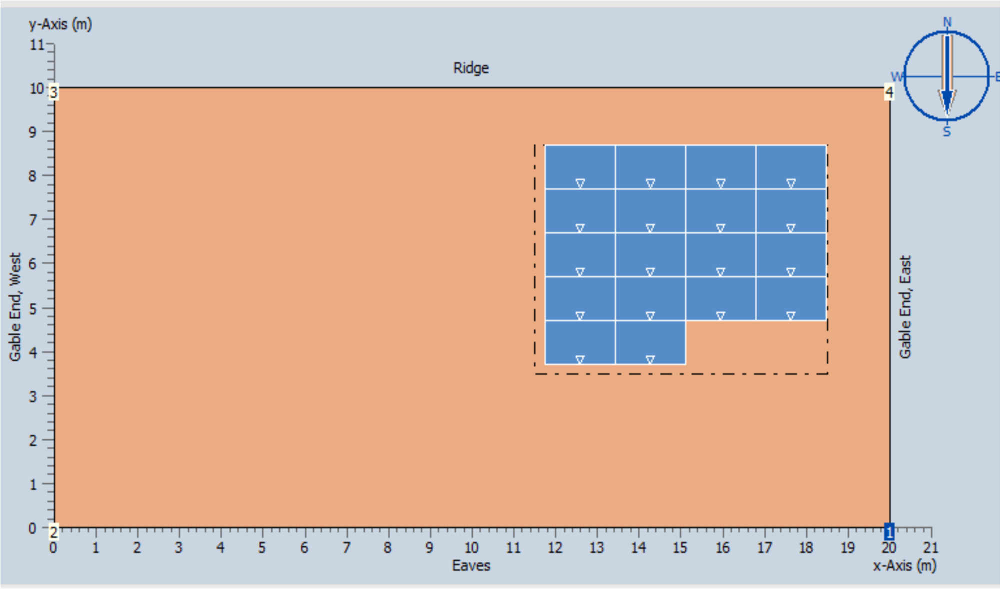


Fig. 5. Building concrete roof graphic coverage scheme

Rys. 5. Schemat graficzny pokrycia dachu budynku betonem

2.3.2. Selection of inverter

The power of the inverter is selected according to the rule by (Mondol et al. 2006; Nguyen and Hoang) is shown in Equation 2 (Advanced... 2022).

$$P_{inv} = P_{PVrequired}/1.17 = 5880/1.17 = 5000\ (\mathrm{W}) \tag{8}$$

where:

P_{inv} – the rated power of the inverter and 1.17 is a compatibility coefficient selected according to experience. The power of the chosen inverter is 5 kW, and the inverter's full characteristics are listed in Table 2 (Operation Manual 2013).

Table 2. Specifications of the inverter

Tabela 2. Dane techniczne falownika

Characteristic	Value
Model	Conext RL 5000 E
Company	Schneider Electric
Maximum DC power	5 kW
Maximum DC input voltage	550 V
Maximum DC input current	36 A
AC power rating	5 kW
No of phases	1
Maximum AC power rating	5 kVA
No. of MPP Trackers	2
Efficiency	97%

Source: Operation Manual 2013.

The number of panels to be put in this study is 18, and the inverter has two MPPTs. As a result, when using the power optimizer mode, the system is separated into two parallel strings, each with nine solar panels connected in series.

2.3.3. Specifications of electric-vehicle charging station

The electrical charging station can simultaneously charge ten vehicles; Table 3 includes the specifications of electric automobiles and charging stations (Kia Niro EV Specifications 2021).

TABLE 3. Electric-vehicle parameters and charging-station specifications

TABELA 3. Parametry pojazdów elektrycznych i specyfikacje stacji ładowania

Electric vehicle	
Model	e-niro 136 (AC charging 10.5 kW)
Manufacturer	Kia
Range in accordance with WLTP	289 km
Consumption	15.3 kWh/100km
Battery capacity	39.2 kWh
No of seats	5
Empty weight	1667 kg
Top speed	155 km/h
Engine power	100 kW/136PS
Discharge power	10.5 kW
Charging station	
Charging-station technology	AC type 2
Charging power	10×10.5 kW
Charging mode	PV optimized
Desired range per week	350 km
Time at charging station	8h (from 9 am to 5 pm)
No of trips per week and per vehicle	12 (29.2 km per journey)
Mileage per year	10×18,250 km (27,923 kWh/a)

Source: Kia Niro EV Specifications 2021.

2.3.4. Ac Grid Mains

The grid voltage is 230 V with three phases and the displacement power factor (cos ϕ) is 1.

2.3.5. Cables

The total loss in cables is taken as 2%.

2.4. Simulation

The PVSOL 2021 R8 software package is used to simulate a grid-connected PV system with electrical appliances and electric cars. Figure 4 shows the block diagram of this suggested system, together with the required circuits and cables, and Table 6 shows the simulated technical and financial parameters used.

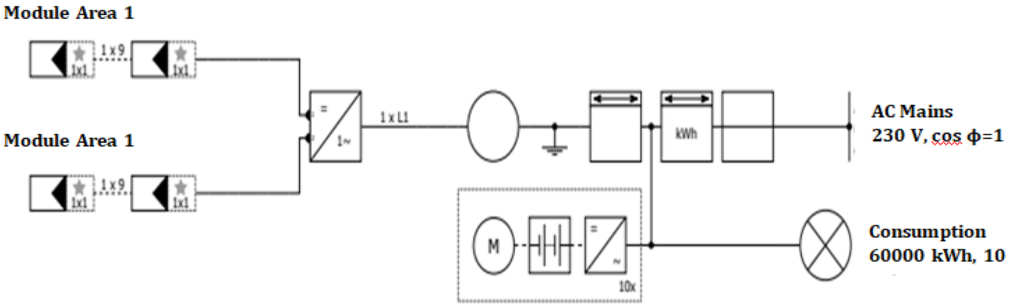


Fig. 6. Block diagram of proposed PV system connected to grid and electric vehicle

Rys. 6. Schemat blokowy proponowanego systemu PV podłączonego do sieci i pojazdu elektrycznego

Table 4. Simulation parameters for this study

Tabela 4. Parametry symulacji dla tej analizy

Technical Parameters	
Simulation period	Whole year
Time-step	One hour
Financial Analysis Parameters	
Assessment period	20 yr
Annual average return on capital employed	1.5%
Energy balance/feed in concept	Net-metering
Inflation rate for energy price	3%
Electricity purchasing price	0.103 \$/kWh (Egypt electricity prices 2021)
Value-added sales Tax	All entries are gross

3. Results

3.1. Overview Results

The planned study, which will take place in 6th October City, Egypt, would use simulation to estimate the energy, environmental impact, and economic aspects of a PV system for EV charging. Rooftop PV systems are frequently being erected on office buildings adjacent to commercial enterprises. Table 5 shows the bill of quantity (BOQ) sheet for this proposed system. Table 6 shows the overall outcomes of the simulation.

Table 5. Bill of quantity of this proposed system

Tabela 5. Przedmiar robót proponowanego systemu

Item	Type	Manufacturer	Name	Quantity	Unit
1	PV Module	Suntech Power	STP325S-24/Vem	18	piece
2	Inverter	Schneider Electric	Conext RL 5000 E	1	piece
3	Power optimizer	Solar Edge	P3000EU-APAC	18	piece
4	Electric vehicle	Kia	e-niro 136 (AC charging 10.5 kW)	10	piece
5	Component		Energy-flow Sensor	1	piece
6	Component		Bidirectional meter	1	piece
7	Component		Office connection	1	piece

Table 6. Overall results of grid-connected PV system with electric vehicle

Tabela 6. Wyniki dla systemu fotowoltaicznego podłączonego do sieci z pojazdem elektrycznym

PV generator energy (AC grid)	10,463 kWh/year
Energy from grid	80,798 kWh/year
Annual yield	1,786.69 kWh/kWp
Performance ratio	84.8 %
Solar fraction	11.5 %
Accrued cash flow (cash balance)	2,087 $
Total investment costs	566 $
Annual revenue or saving	110 $/year
Electricity production cost	0.0032 $/kWh
Payback period	5.1 year
CO2 emissions avoided	4,912 kg/year

3.2. Technical Results

Figure 7 shows the energy flow graph of the system over a year. The total consumption of this system study is 91,261 kWh/year; 60,000 kWh/year consumption of eclectic appliances for the office buildings and 31,261 kWh/year consumption of electric vehicle stations. This total

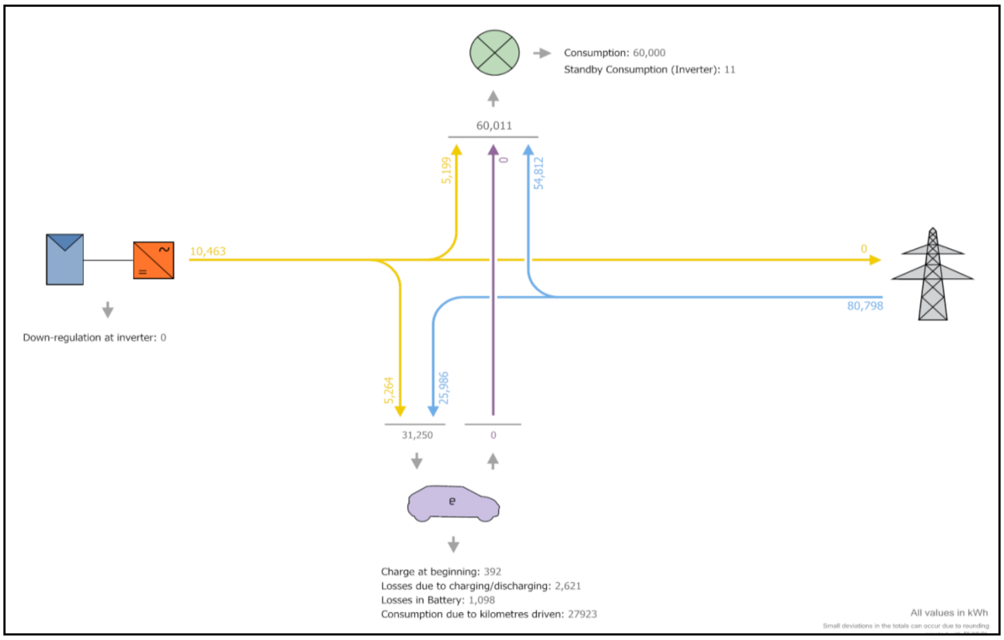


Fig. 7. Energy flow graph of proposed grid-connected PV system with electric vehicle

Rys. 7. Wykres przepływu energii proponowanego podłączenia do sieci

consumption is covered by PV power of 10,463 kWh/year and 80,798 kWh/year is covered by the national grid since there is no electricity sold to the national grid which means the level of self-sufficiency is 11% as shown in Figure 8. The PV generator output is 5.9 kWp, the amount of electricity produced from the solar-power system is 10,463 kWh/year, the direct use for the office building is 5,199 kWh/year and the amount of electricity supplied to the charging vehicle station is 5,264 kWh/year. Also, losses due to charging/discharging of electric vehicle are estimated with 2,621 kWh/year, losses in the battery are 1,098 kWh/year and the consumption due to kilometers driven is 27,923 kWh. The energy balance for the irradiance of this system is illustrated in Table 7.

PV module irradiance versus temperature distributions for the whole year is described in Figure 9 while Figure 10 shows electric-vehicle lower limit state of charge percentage for the whole year and monthly averages performance ratio of the inverter is illustrated in Figure 11.

As seen in Figure 9; the average monthly irradiance of PV modules over the course of a year is 880 W/m^2 since the highest value in both January and February is around 1,000 W/m^2. Simultaneously, the highest value module temperature is about 55°C in both September and October. From Figure 10, it is found that the monthly average of electric vehicle SOC is about 23.8% since the highest value is 28% in January while in Figure 11, the average performance ratio of an inverter is 84.4% for the whole year since it also the biggest performance is in both of January and December.

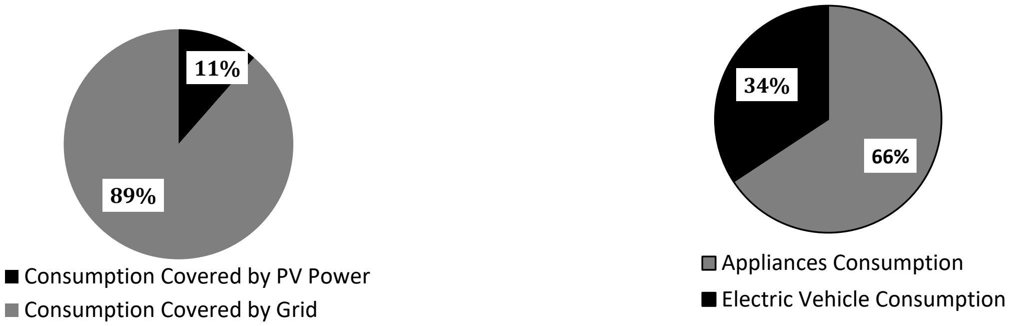


Fig. 8. Consumption percentages covered by national grid and PV power (Appliances and Vehicles)

Rys. 8. Procenty zużycia pokrywane przez sieć krajową i energię fotowoltaiczną (urządzenia i pojazdy)

Table 7. PV System energy balance for irradiance

Tabela 7. Bilans energii systemu fotowoltaicznego dla natężenia napromieniowania

Global radiation – horizontal	2,003.57	kWh/m^2	
Deviation from standard spectrum	–20.04	kWh/m^2	–1.00%
Ground reflection (Albedo)	26.57	kWh/m^2	1.34%
Orientation and inclination of the module surface	108.71	kWh/m^2	5.41%
Shading	0.00	kWh/m^2	0.00%
Reflection on the module interface	–33.89	kWh/m^2	–1.60%
Global radiation at the module	2,084.93	kWh/m^2	
	2,084.93 x 34.926	kWh/m^2 x m^2	
	= 72,818.85	kWh	
Global PV radiation	72,818.85	kWh	
Soiling	0.00	kWh	0.00%
STC conversion (rated efficiency of module 16.77%)	–60,608.25	kWh	–83.23%
Rated PV Energy	12,210.59	kWh	
Low-light performance	3.61	kWh	0.03%
Deviation from the nominal module temperature	–1,018.17	kWh	–8.34%
Diodes	–55.98	kWh	–0.50%
Mismatch (manufacturer information)	0.00	kWh	0.00%
Mismatch (configuration/shading)	0.00	kWh	0.00%
Power optimizer (DC conversion/down-regulation)	–134.27	kWh	–1.21%

PV energy (DC) without inverter down-regulation	11,005.79	kWh	
Failing to reach the DC start output	–1.16	kWh	–0.01%
Down-regulation on account of the MPP voltage range	0.00	kWh	0.00%
Down-regulation on account of the max. DC current	0.00	kWh	0.00%
Down-regulation on account of the max. DC power	0.00	kWh	0.00%
Down-regulation on account of the max. AC power/cos ϕ	0.00	kWh	0.00%
MPP matching	0.00	kWh	0.00%
PV energy (DC)	11,004.63	kWh	
Energy at the inverter input	11,004.63	kWh	
Input voltage deviates from rated voltage	0.00	kWh	0.00%
DC/AC conversion	–328.03	kWh	–2.98%
Standby consumption (Inverter)	–10.95	kWh	–0.10%
Total cable losses	–213.53	kWh	–2.00%
PV energy (AC) minus standby use	10,452.12	kWh	
PV generator energy (AC grid)	10,463.07	kWh	

3.3. Energy Forecasting Results

Table 8 shows the energy supply account of the planned system for the entire year. Figure 12 depicts the monthly average production energy forecast with consumption, whereas Figure 13 depicts the production forecast per inverter.

Table 8 and Figure 9 show that the maximum value consumption of 7976 kWh occurred in July, and the largest energy production from PV modules also occurred in July. As a result of the projected PV on-grid system, the overall costs are estimated to be $853 against $963 without solar PV, saving $110 per year. According to the largest output of PV modules, as listed in Table 8, the average monthly production prediction of an inverter is 871 kWh, with the greatest value in July is as shown in Figure 13.

3.4. Financial Results

This proposed system is subjected to a twenty-year economic examination. Each year’s accrued cash flow is computed using the investment amount, the export tariff for grid feed-in, the electricity savings, and the annual cash flow. Figure 14 shows the cash amount at the end of twenty years, which is predicted to be $2,875. Figure 15 shows the monthly electricity cost savings before and after PV installation, and Figure 16 shows the evolution of energy costs over the project’s lifetime.

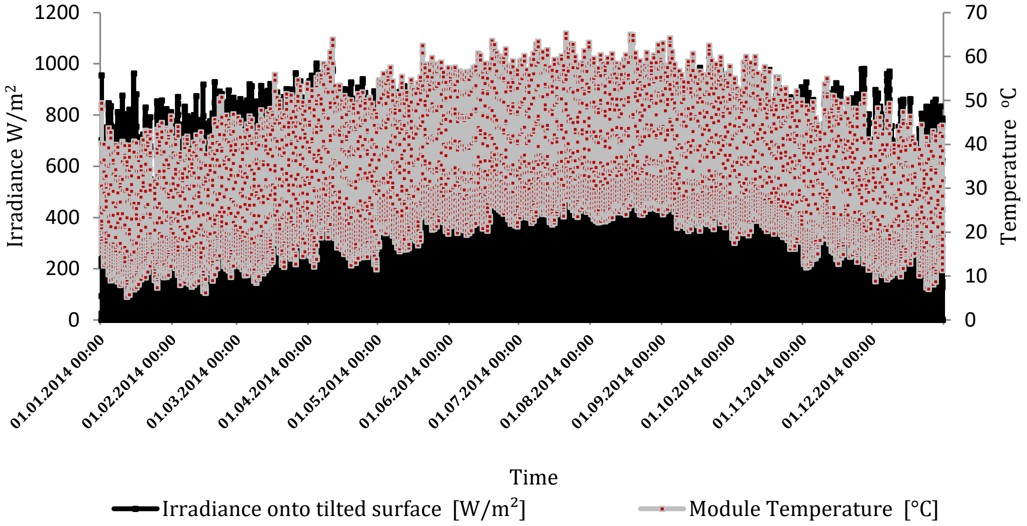


Fig. 9. PV module irradiance vs. temperature distribution for the whole year

Rys. 9. Naświetlenie modułu fotowoltaicznego a rozkład temperatury przez cały rok

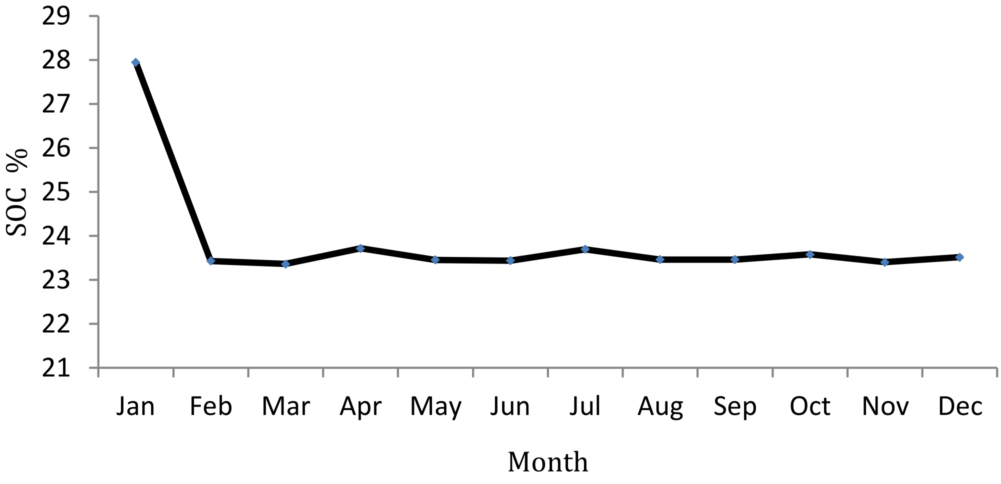


Fig. 10. Lower limit SOC of electric-vehicle station over a year

Rys. 10. Dolna granica SOC stacji pojazdów elektrycznych w ciągu roku

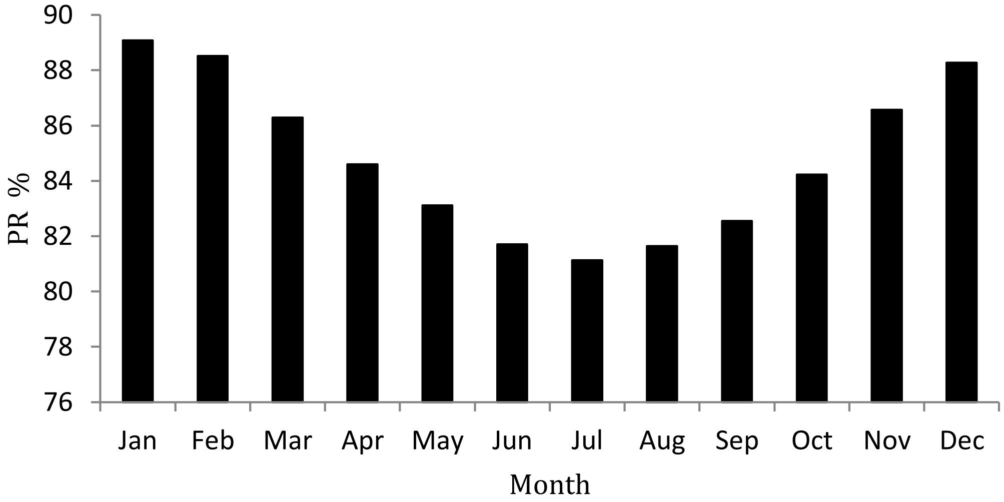


Fig. 11. Performance ratio of inverters over a year

Rys. 11. Współczynnik wydajności falowników w ciągu roku

From Figure 16, it can be seen that the cost trend before the installation of a solar PV system is higher than the cost trend after PV system installation. After the project's twenty-year life cycle, annual energy expenses after installation of PV systems are anticipated to be about \$1,400, while costs before installation are estimated to be around \$1,700, indicating that the solar PV proposed system resulted in a financial saving of 21%.

3.5. Environmental Results

The world today is on the search for pollution-free technology that is environmentally favorable. The rooftop solar installation not only saves money on energy bills, but also helps the environment by lowering CO_2 emissions. Egypt's grid electricity emission factor is 0.6 $kgCO_2/kWh$ (Carbon Pricing Dashboard 2020) and the price for a ton of CO_2 is 50–100 USD (Carbon Pricing 2020). As a result, the quantity of CO_2 emissions reduced by solar PV in a year predicted using PVSOL software is 4,912 kg per year, resulting in savings of roughly \$500 per year. When it comes to solar energy, there are almost no pollutants. As a result, the proposed PV system is beneficial for the environment.

In the end, when the proposed system is compared to other studies (Kumar et al. 2016; Velaga and Kumar 2012; Deshmukh and Singh 2019), it is demonstrated that it is efficient due to the lowest capital cost, payback period, and environmental consequences. The novelty of this paper includes the elimination of grid capacity, which would result in a significant reduction in the

Table 8. Energy supply account of the proposed system for the whole year

Tabela 8. Rachunek dostaw energii dla proponowanego systemu za cały rok

Reference	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Consumption [kWh)]	7,211.95	6,883.97	7,740.69	7,593.92	7,968.40	7,708.80	7,976.84	7,968.87	7,590.77	7,737.78	7,403.19	7,464.61	91,249.780
Energy production [kWh]	724.68	723.55	922.63	964.95	966.42	963.01	984.82	979.59	931.07	871.86	733.15	686.38	10,452.120
Energy balance [kWh]	6,487.27	6,160.42	6,818.06	6,628.97	7,001.97	6,745.79	6,992.02	6,989.28	6,659.70	6,865.91	6,670.04	6,778.23	80,797.660
Costs without solar energy system [$]	76.16774	72.70387	81.75161	80.20129	84.15677	81.41484	84.24581	84.16129	80.16839	81.72065	78.1871	78.83613	963.7155
Costs with solar energy system [$]	68.51419	65.06194	72.00774	70.01032	73.94968	71.24452	73.84452	73.81613	70.33484	72.5129	70.44452	71.5871	853.3277
Cost savings value [$]	7.653	7.641	9.743	10.190	10.206	10.170	10.401	10.345	9.833	9.207	7.743	7.249	110.387

Over the whole observation period, degradation and inflation rates are applied monthly. In the first year, this is completed.

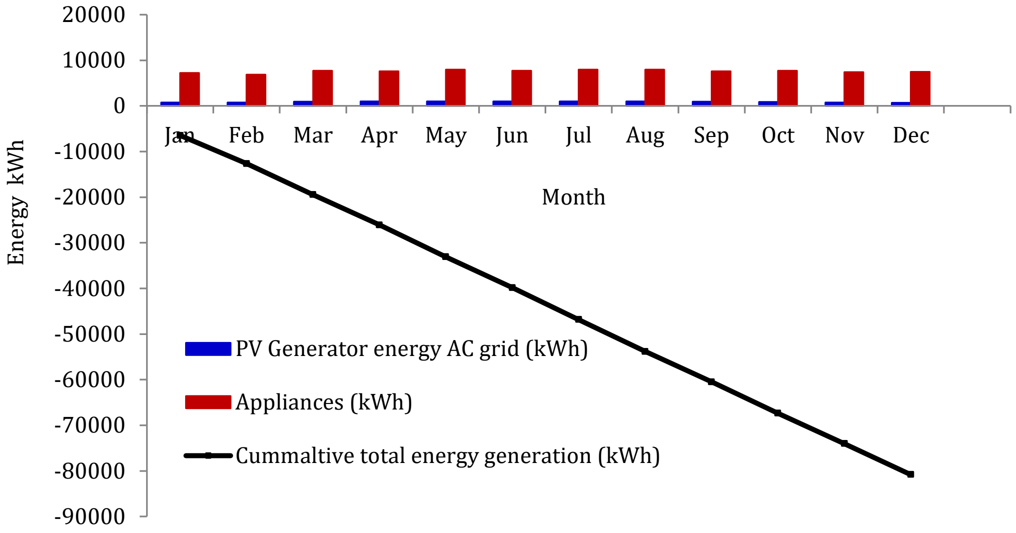


Fig. 12. Production forecast with consumption for the whole year

Rys. 12. Prognoza produkcji ze zużyciem na cały rok na cały rok

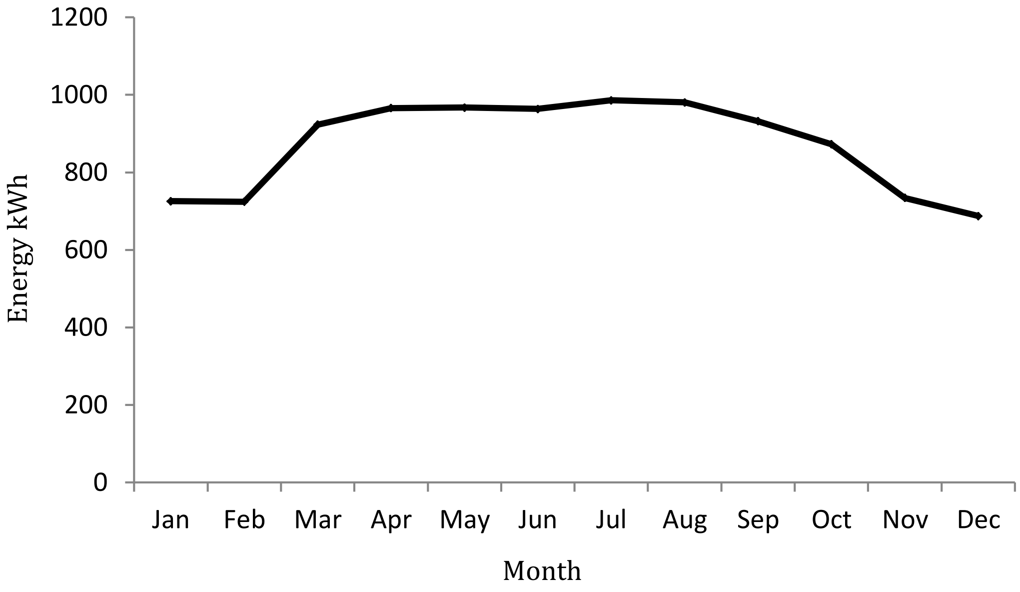


Fig. 13. Production forecast per inverter for the whole year

Rys. 13. Prognoza produkcji falownika na cały rok

Table 9. Economic analysis parameters of this proposed system for 20 years

Tabela 9. Parametry analizy ekonomicznej proponowanego systemu przez 20 lat

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20	Year 21
Investments [$]	–566	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Electricity Savings [$]	106	110	111	113	115	52	54	56	57	59	61	0.65	2	4	6	8	10	12	14	16
Annual Cash Flow [$]	–459	110	111	113	115	52	54	56	57	59	61	0.65	2	4	6	8	10	12	14	16
Accrued Cash Flow [$]	–459	–348	–236	–123	–7	44	34	25	19	14	11	10	13	17	24	32	43	53	5	22

Throughout the observation period, degradation and inflation rates are applied monthly. During the first year, this is accomplished.

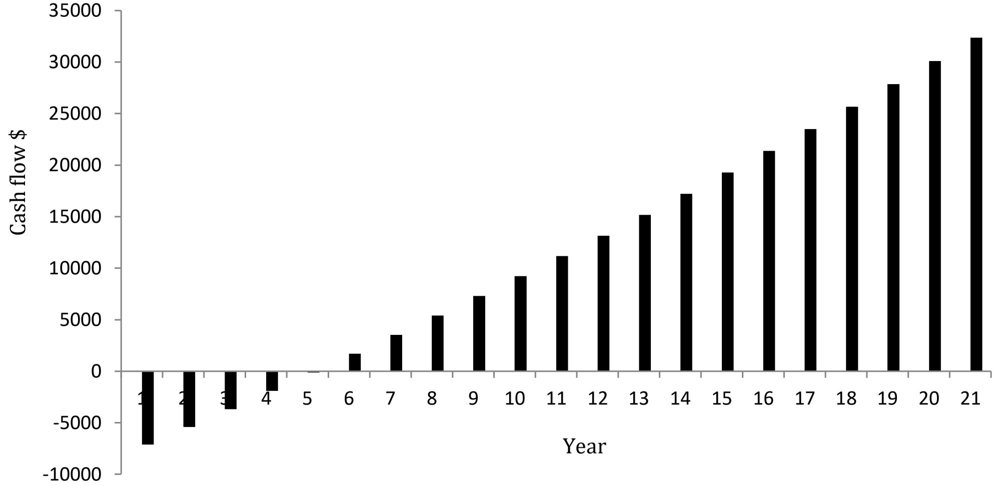


Fig. 14: Cash flow balance of the proposed system for 20 years

Rys. 14: Bilans przepływów pieniężnych proponowanego systemu za 20 lat

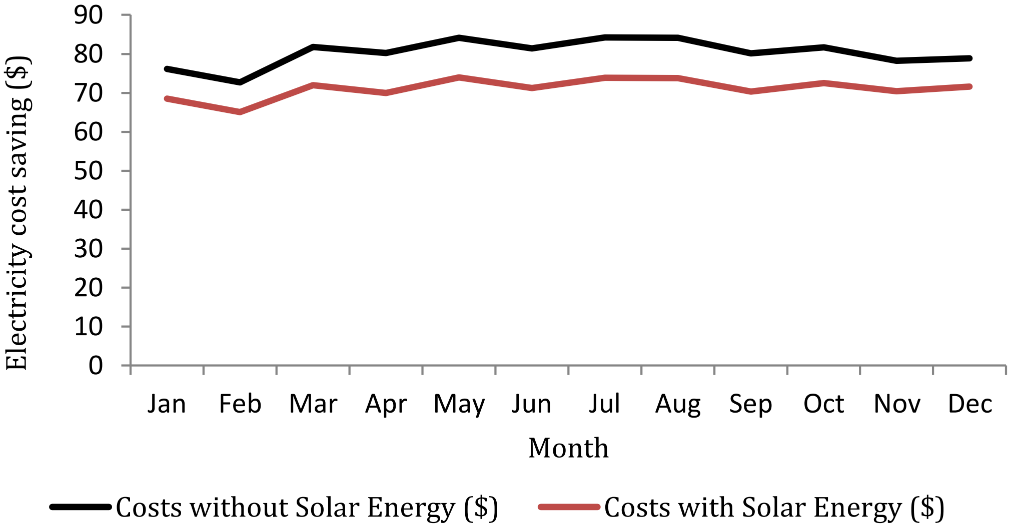


Fig. 15. Electricity cost saving of this proposed system for a whole year

Rys. 15. Oszczędność kosztów energii elektrycznej proponowanego systemu przez cały rok

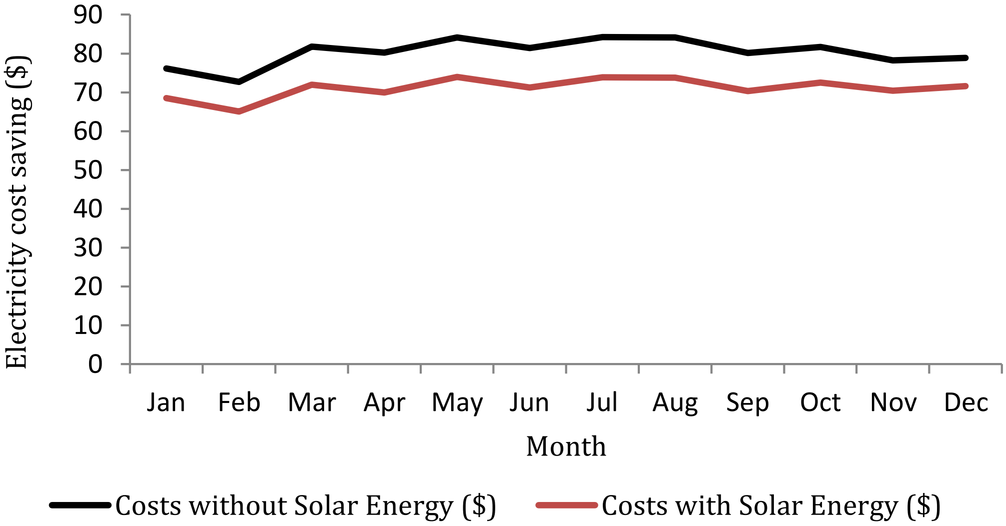


Fig. 16. Annual developments of energy costs every year

Rys. 16. Roczne zmiany kosztów energii w każdym roku capital costs of EV charging infrastructure installation which can be used as a recommendation for stakeholders that want to use this energy source for vehicle charging. Higher profits will motivate utilities to invest in charging stations, resulting in the greater market penetration of electric vehicles since the Egyptian government is now offering a reasonable price for purchasing electricity generated by rooftop solar-power projects.

Conclusions

Electric-vehicle technology is now advancing at a rapid pace, with the potential to replace regular automobiles in the future. Based on simulation using PVSOL software, this study is being carried out to assess the energy, environmental impact, and economic aspects of an on-grid PV system for electrical appliances of a workplace office building with EV charging. The suggested system's sizing is perfect and matches the load demand for the on-grid system. Through simulations, The generated energy is 10,463 kWh/year, the yearly specific yield in kWp is 1,786.69 kWh, and the saved CO_2 emissions are 4.9 kg/year. PV power is used to charge electric vehicles to the tune of 66% and to power electrical appliances to the tune of 34%. The production cost of energy is 0.0032 $/kWh after applying the financial analysis for twenty years, and the payback period for this suggested system is roughly five years. The annual energy costs after installing the PV systems proposed system were reduced by 21%. The Egyptian government is now offering a reasonable price for purchasing electricity generated by rooftop solar power projects; However, the price is expected to fall in the following years, lengthening the payback period and lowering the system's economic value. To summarize, this system is technically and financially feasible in terms of energy output. Higher profits will motivate utilities to invest in charging stations, resulting in the greater market penetration of electric vehicles.

Nomenclature

Abbreviations	
CO_2	Carbon dioxide
COE	Cost of energy
ESS	Energy storage system
EVs	Electric vehicles
FBEV	Fully battery electric vehicle
GHGs	Green house gases
HEV	Hybrid electric vehicle
ICEVs	Internal combustion engine vehicles
MPPT	Maximum power point tracking
NPC	Net present cost
OGCS	Off-grid charging station
PV	Photovoltaic
PVGIS	Photovoltaic geographical information system
RESs	Renewable energy sources
SFA	Stochastic firefly algorithm
SOC	State of charge
TMY	Typical meteorological year
Letters	
$\sum_{t=1}^{8760} Egrid(purchased)$	Per hour summation of annually buying electricity from the grid for one year
$Cgrid$	Cost power from the grid
Cp	Cost of buying electricity from the grid
$Egrid(selling)$	Selling energy price
$G(t)$	Solar irradiance
k_{load}	Overload factor for cover overloading in transients
$NOCT$	Nominal operating cell temperature
N_{PV}	Number of solar panels needs to be installed
N_{slot}	Amount of charging slots for each EV
P_{Array}	Rated power of solar panel
P_{EV}	Maximum power rate of each EV
P_{inv}	Rated power of the inverter
$P_{inv}(t)$	Inverter rating
$P^{m}{}_{L}(t)$	Peak load demand
$P_{pv\ rated}$	Rated power for PV at standard test condition
$P_{pvout}\ (t)$	Output power generated from PV
$P_{PVrequired}$	Power of PV system needs to be installed

$rate_{feed\text{-}in}$	Feed-in tariff rate
R_{grid}	Money earned from energy sales to the utility grid
S_{rated}	Vehicle station rated capacity
T_{amb}	Ambient temperature
T_{CSTC}	Cell temperature
Greek symbols	
Cos ∅	Power factor
α_t	Temperature coefficient
η_{inv}	Inverter efficiency.

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Marwa M. Ibrahim

Badanie systemu fotowoltaicznego podłączonego do sieci dla stacji ładowania pojazdów elektrycznych w budynku biurowym przy użyciu oprogramowania PVSOL

Streszczenie

Przewiduje się, że w najbliższych latach pojazdy elektryczne rozwiną się w Egipcie jako technologia wschodząca zarówno w sektorze transportu, jak i energetyki, przyczyniając się znacząco do zmniejszenia zużycia paliw kopalnych i emisji CO_2. Dlatego proponuje się, że aby złagodzić przeciążenia krajowej sieci elektrycznej wynikające z zapotrzebowania pojazdów na energię, można wykorzystać system fotowoltaiczny do zaspokojenia zapotrzebowania na energię elektryczną w stacjach ładowania pojazdów elektrycznych. Celem niniejszego artykułu jest przedstawienie projektu, symulacji i analizy ekonomicznej, z wykorzystaniem narzędzia symulacyjnego PVSOL, dla podłączonego do sieci systemu zasilania energią słoneczną biura w mieście Madinat as-Sadis min Uktubar w Egipcie celem dostarczania energii do stacji ładującej i urządzeń biurowych. Idealną orientację paneli fotowoltaicznych dla uzyskania maksymalnej energii określono na podstawie danych z fotowoltaicznego systemu informacji geograficznej i przewidywanych wzorców profilu obciążenia. W niniejszym opracowaniu szacowana jest ilość wytworzonej energii elektrycznej, sprawność systemu fotowoltaicznego, analiza finansowa pod kątem kosztów inwestycji i zwrotu z aktywów oraz zdolność do redukcji emisji CO_2. System ten ocenia również roczne prognozy zużycia energii i jest używany do ładowania pojazdów elektrycznych, zasilania sieci i zaspokojenia zużycia urządzeń. Ze względu na stosunkowo wysokie nasłonecznienie w Egipcie produkcja energii fotowoltaicznej wyniosła 10 463 kWh rocznie, a roczna wydajność to 1786,69 kWh/kWp. 66% energii z produkcji fotowoltaicznej jest wykorzystywane do ładowania pojazdów elektrycznych, a 34% do urządzeń elektrycznych. Po przeprowadzeniu analizy finansowej w okresie 20 lat: koszt produkcji energii elektrycznej wynosi 0,0032 $/kWh, a okres zwrotu nakładów dla proponowanego systemu to około pięć lat. Obliczono, że roczne oszczędności zużycia energii po instalacji takich systemów PV przyniosły w wymiarze finansowym 21%. Współczynnik wydajności tego falownika systemowego wynosi 84%, a średnia miesięczna SoC pojazdu elektrycznego w ciągu roku nie zmniejsza się o 27%, a dodatkowo mamy oszczędność 5 ton emisji CO_2 rocznie. Badania te można wykorzystać jako rekomendację dla interesariuszy, którzy chcą wykorzystać to źródło energii do ładowania pojazdów.

Słowa kluczowe: czysta energia słoneczna, pojazdy elektryczne, stacja ładowania, emisja CO_2, ocena ekonomiczna