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Investigation of Grid-connected PV System with Electrical Appliances, Electric Vehicles

by ***Nguyen Ba Thanh*** *(Thu Dau Mot University)*

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Corresponding author: thanhnb@tdmu.edu.vn
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ABSTRACT

Electric vehicles (EVs) making a significant contribution to the reduction of fossil fuel consumption and CO2 emissions are expected to thrive in Vietnam in the upcoming years/in the near future. However, such vehicles' energy demand could become a burden on the transmission networks, causing overloads to the electric grid of the nation. Hence, to solve this problem, a solar PV system can be utilized to fulfill the electricity needs in an EV charging station. This article presents the design, simulation and economic analysis of a grid-connected solar power system for an electric charging station at Thu Dau Mot University (TDMU). The photovoltaic (PV) power system is designed to supply energy to the charging station and office building. The study estimates the generated electricity, the efficiency of the PV power system and the ability to reduce CO2 emissions. This paper can be a recommended input for stakeholders to consider using this energy source for charging vehicles.

Keywords: *on-grid rooftop PV, solar PV system, PV*SOL, photovoltaic system, electrical vehicles, charging station*

1. Introduction

Vietnam is a country with high economic growth, with an annual gross domestic product (GDP) of about 7% over the past decade (IMF., 2019; Kimura et al., 2019). With a dynamic economy and high energy demand, however, in the field of energy, Vietnam still has to depend mainly on hydropower and thermal power from fossil fuels

(Nong et al., 2020). Vietnam has great potential for solar radiation, with an average radiation intensity of 5kWh/m2 (Polo *et al.*, 2015). However, the use of solar power in Vietnam has progressed slowly in recent years. Solar power had not been considered a viable power generation option until 2015 when Vietnam's Renewable Energy Development Strategy was enacted (Government of Vietnam, 2015). Besides, the Prime Minister issued Decision on the mechanism for the development of solar power in Vietnam (The Prime Minister, 2017). In addition, Vietnam is currently facing many serious environmental problems such as air pollution, water pollution, land degradation, etc. mainly due to industrial production and transportation. As a result, electric cars will be one of the most promising means of transport that helps reduce environmental pollution and energy pressure in Vietnam (Bellekom et al., 2012).

Currently, electric vehicle technology is developing rapidly and will completely replace traditional vehicles in the future. Electric vehicles use an electric motor instead of an internal combustion engine, powered by a rechargeable lithium-ion battery. For convenience of mobility, electric vehicles need charging stations such as gas stations of gasoline engines (Salah *et al.*, 2019; Larcher &. Tarascon, 2015). With the development of photovoltaic technology, the price of solar power is decreasing, thereby increasing the feasibility of solar projects (Green, 2019). There are many domestic and foreign authors who have studied the power supply for EV charging stations:

Nguyễn (2017) researched an EV charging station in Da Nang city. The thesis calculated and designed a solar energy system used for an EV charging station and evaluated the ability to charge electric vehicle's battery. PV*SOL Premium 2017 software was adopted to design, calculate and simulate the operation of electric vehicle charging stations.

Chandra Mouli et al. (2016) designed a 10kW solar power system for an electric vehicle charging station.

Domínguez-Navarro et al. (2018) designed an electric vehicle fast charging station that integrates renewable energy and storage systems.

Karmaker et al. (2018) designed and economically evaluated a solar and biogas renewable energy charging station project by using HOMER software. The proposed electric vehicle charging station is an integration system of a solar PV module (10kW), three biogas generators (10kW), 25 lead acid batteries (each 100Ah), a converter (10kW) and charging assemblies. This configuration estimated a Cost of Energy (COE) of $0.1302/kWh, total net present cost (NPC) of $56,202 and operating cost of $2,540. In addition, the proposed model reduced the CO2 emissions by 34.68% compared to a conventional grid-based charging station.

Ekren et al. (2021) designed a wind-solar hybrid charging station system by using HOMER software. The optimal solution for the hybrid system consists of 44.4% wind energy and 55.6% solar energy and the annual electricity production is 843,150 kWh with the $0.064/kWh production cost.

Pushpavalli et al. (2021) have evaluated the economic and technical aspects of the solar power system for electrical appliances, EVs and battery systems by using PVSOL software.

Rooftop solar power has been strongly developed in recent years (Le Nguyen *et al.*, 2019), but there are no adequate studies for the setting up of electric vehicle charging stations in weather conditions in Vietnam (Nguyen et al., 2020). In this study, the proposed grid-connected rooftop solar power system for electric vehicle charging station at Thu Dau Mot University is presented. The main purposes of the research are:

– Designing a rooftop solar power system for an EV charging station;

– Evaluating efficiency and the amount of CO_2 saved emissions of the solar power system by using the PVSOL software;

– Evaluating economic feasibility of the project.

2. Materials and Methods

This study is conducted with the steps shown in Figure 1. First, the solar power system is designed and equipment is selected to meet the actual load demand. Next, the solar power system is simulated by the PVSOL software (Software , 2021) to evaluate energy efficiency. Finally, economic feasibility of the project is calculated.

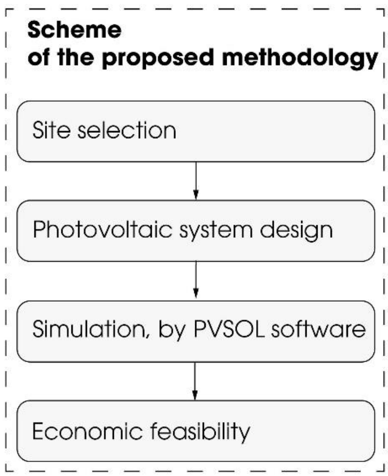

Figure 1. *General scheme of the proposed methodology used in the study*

2.1. Brief summary of electric vehicles and charging stations

2.1.1. Types of electric vehicles

EVs can be divided into two main categories (Das et al., 2020) hybrid electric vehicles (HEVs) and all-electric vehicles (AEVs). While each has advantages and disadvantages, they all save on fuel and emit fewer greenhouse gas than vehicles that burn fossil fuels only. They also recharge their batteries through regenerative braking. In this process, the vehicle's electric motor assists in slowing the vehicle and recovers some of the energy normally converted to heat by the brakes.

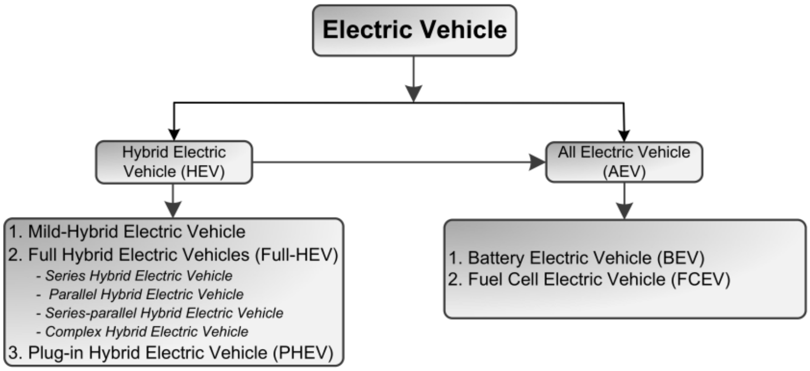

Figure 2. *Basic types of electric vehicles (Tie & Tan, 2013)*

Figure 2 describes the classification of different types of EVs. In Table 1 below, the technical specifications of commercially available EVs released by different manufacturers are presented. The approximate charging time required to charge the vehicle from 0% to at least 80% in different charging standards are also shown in the table. Here, Level 1 corresponds to the charging voltage of 110–120 V, Level 2 is of 220–240 V and Level 3 or DC fast charging (DCFC) is of 200–800 V. It should be noticed that the range of an EV based on battery drive is about 100 km for most of the vehicles, however, several models have the battery-drive ranges around 200 km–400 km (Das et al., 2020).

AEVs are equipped with only electric motors powered by electrical sources. AEVs can be further classified into Battery EVs (BEVs) and Fuel Cell EVs (FCEVs). A FCEV does not require an external charging system. However, a BEV relies only on external power from the grid for charging the storage unit. A plug-in hybrid EV (PHEV) is one type of HEVs with an option to recharge its battery from the grid (Tie & Tan, 2013).

TABLE 1. Popular commercially available EV and its specifications (Das et al., 2020).

Vehicle model	Manufacturer	Model Year	Type	Battery Capacity (kWh)	Range (km)	Charging Time (0%–80%) (h)		
						Level 1	Level 2	DCFC
Prius Prime	Toyota	2018	PHEV	8.8	40 (battery)	5.5	2.1	-
Fit	Honda	2014	BEV	20	132	15	3	-
Model S	Tesla	2018	BEV	100	506	96.7	10.7	1.33
Focus	Ford	2016	BEV	23	161	20	3.5	0.5
i3	BMW	2018	BEV and PHEV	33	183 (battery)	13–16	5	0.5

2.1.2 Architecture of the charging station

EV charging is defined by the standards in (IEC., 2014). The charging plug type widely used in Europe for AC charging is the Type 2 Mennekes plug. It supports both single and three-phase AC charging at Level 2 charging power level (Chandra et al., 2016).

In this paper, a 12 kWp on-grid PV system providing energy for cars will be considered and shown in Figure 3 below. Since the cars are parked for long durations of 6–10 hours at the workplace, fast charging would be unnecessary.

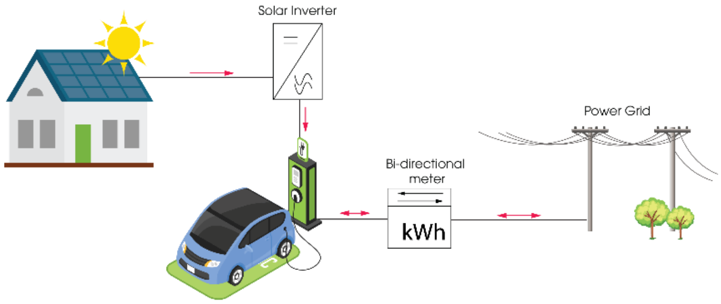

Figure 3. *Diagram of on-grid photovoltaic system for the EV charging station*

2.2 Design of the proposed on-grid photovoltaic system

In this study, the 12kWp solar power system is located on the roof of the E1 building (TDMU) and the charging station (as shown in Figure 4). This solar power system supplies the power to the charging station and the office building.

The electricity generated from PV power plants during the day can be charged directly to the electric vehicle. If the amount of electricity generated exceeds the demand of the vehicle, the excess energy can be sold to the grid via a two-way meter. In contrast, at night, the office area and the charging station get electricity from the national system through the two-way meter.

Figure 4. *The proposed solar power system for the EV charging station at TDMU*

The process of designing a rooftop solar power system includes the following steps:

Step 1: Surveying the construction;

Step 2: Calculating the demand;

Step 3: Calculating the capacity of the solar PV arrays;

Step 4: Selecting inverter and related devices;

Step 5: Pre-feasibility assessment.

The building has the geographical location and weather parameters shown in Table 2 and Figure 5.

TABLE 2. Geographical location and weather parameters

Parameter	**Value**
Longitude	10°58'48.6"N
Latitude	106°40'31.4"E
Height	29 m
Hours of sunshine	4.58 h
Radiation intensity	3.915 (kWh/day/m2)
Wind speed	2.3 m/s

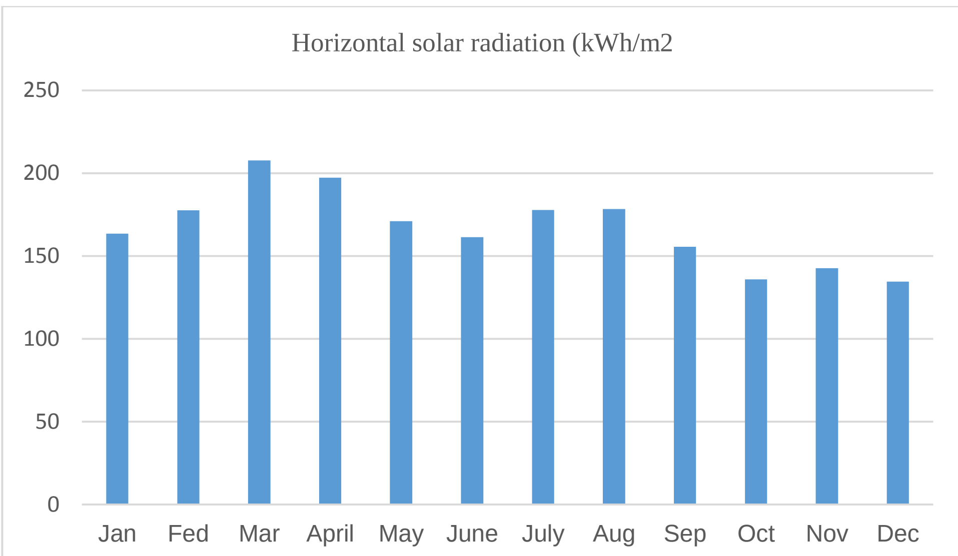

Figure 5. *Monthly solar radiation intensity*

The electrical demand of the office building is depicted in Figure 6. The electric vehicle charging station can charge five vehicles at the same time, the typical parameters of the vehicle are described in Table 3.

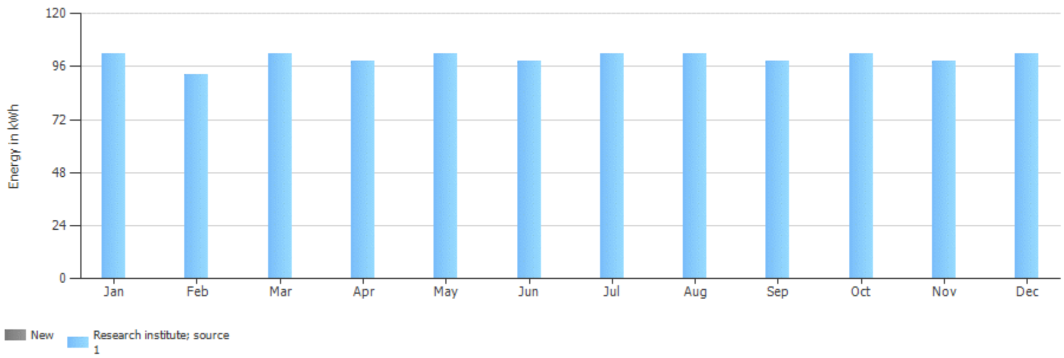

Figure 6. *Monthly electrical demand of the office building*

TABLE 3. Specifications of a typical EV

Electric vehicle	BMW i3 (AC charging 11 kW) (AC Typ 2 @ 11 kW)
Manufacturer	BMW
Range in accordance with WLTP	359 km
Battery Capacity	42.2 kWh
Consumption (input/ calculated))	13.1/11.8kWh/100km
Number of seats	4
Engine power in	125 kW/170 PS
Desired range per week	250km
Time at charging station	8h

The following section describes the selection of panel and inverter which are the most important components of the solar PV system.

Selection of PV panels

The total system capacity to be installed is estimated at 12kWp. The rated power of a PV panel is 400W, then the number of panels to be installed is:

$N_{PV} = P_{PV,required} / P_{Array} = 1200/400 = 30$ (panels). (1)

Where, N_{PV}: number of solar panels needs to be installed; $P_{PV,\ required}$: power of PV system needs to be installed (Wp); P_{Array}: rated power of solar panel (Wp).

In this project, the selected number of modules is 30 and its model is AE 400HM6-72. The detailed specifications of solar panels are described in Table 4.

TABLE 4. Specifications of PV panel

Specifications	**Values**
Model	AE 400HM6-72
Manufacturer	AE Solar
Nominal max power (Pmax)	400Vp
Maximum power voltage (Vmp)	41.45V

Maximum power current (Imp)	9.65A
Open circuit voltage (Voc)	49.72V
Short circuit current (Isc)	10.44A
Module efficiency	20.18%
Maximum system voltage DC	1000V

Selection of inverter

The power of the inverter is selected according to the rule (Mondol et al., 2006; Nguyen & Hoang, 2021).

$P_{Inv} = P_{PV,\ required}/1.2 = 12000/1.2 = 10000$ (W) (2)

Where, P_{inv}: the rated power of the inverter; 1.2 is a compatibility coefficient which selected according to experience; $P_{PV,\ required}$: power of PV system needs to be installed (Wp).

In this project, the power of the inverters selected is 10kWp, its model is ABB PVI–10.0-TL OUTD. The detailed specifications of the inverter are described in Table 5.

TABLE 5. Inverter specifications

Inverter	**Specifications**
Model	ABB PVI–10.0-TL OUTD
Manufacturer	ABB
Max. DC Power Pmax-DC(W)	13 kW
MPP(T) Voltage Range Uin (V)	300~750 V
Max. DC Voltage Vmax (V)	900 V
Min. DC Voltage to Start Feed In (V)	360 V
Max. DC Current Isc (A)	34 A
Max. AC Power Pmax-AC (W)	11 kW
Output AC Voltage Range Uout (V)	320~480 V
Rated AC Voltage	400 V
Max. AC Current (Iout-sc)	16.6 A
Frequency (Hz)	50, 60 Hz
Max. Efficiency (%)	97.1 %

In this study, the number of panels to be installed is 30, the inverter has two MPPTs. Therefore, the system is divided into two strings and each string has 15 solar panels attached.

2.3. Simulation

In this research, PVSOL software is chosen because it is an easy, fast and reliable software tool for the simulation of solar PV system (Dondariya *et al.*, 2018). The PV*SOL software supports system designers in deciding the PV system. The software evaluates the necessary data and calculates the solar yield. The main steps involved in the simulation are given below:

Step 1: Fill in the information of the design;

Step 2. Choose PV system type and weather;

Step 3: Determine the civil load;

Step 4: Select the electric vehicle type and the parameters of the charging station;

Step 5: Choose the power cord to connect;

Step 7: Run the simulation;

Step 8: Following the simulation, a summary of the project report is given. This report is ready to be printed out.

The single-line diagram of the solar PV system and 3D configuration of PV panels on the PVSOL software are described in Figure 7 and Figure 8.

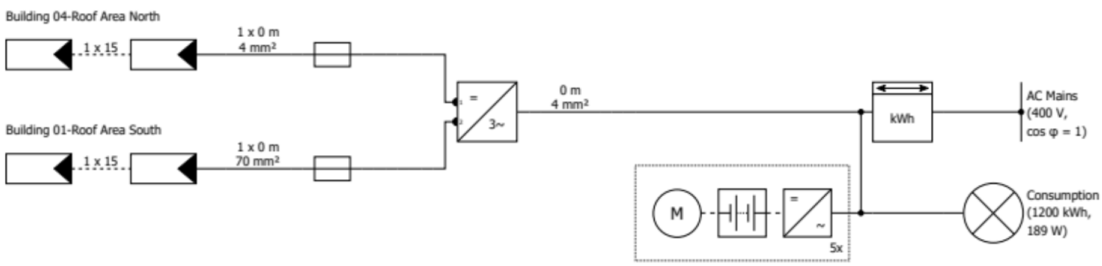

Figure 7. Proposed diagram of PV system connected to grid and EV

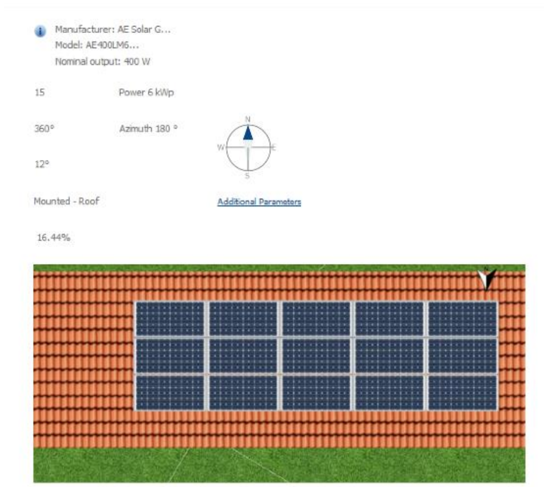

Figure 8. *3D configuration of solar panels on PVSOL software*

3. Results of Simulation

Figure 9 and Table 6 show the energy flow of the system over a year. The amount of electricity produced from the solar power system is 16,864 kWh; the amount of electricity sold to the national grid is 4,087kWh, the amount purchased from the national grid is 597kWh, the amount of electricity supplied to the charging station is

12,160kWh and the efficiency of the system is 78.7%.

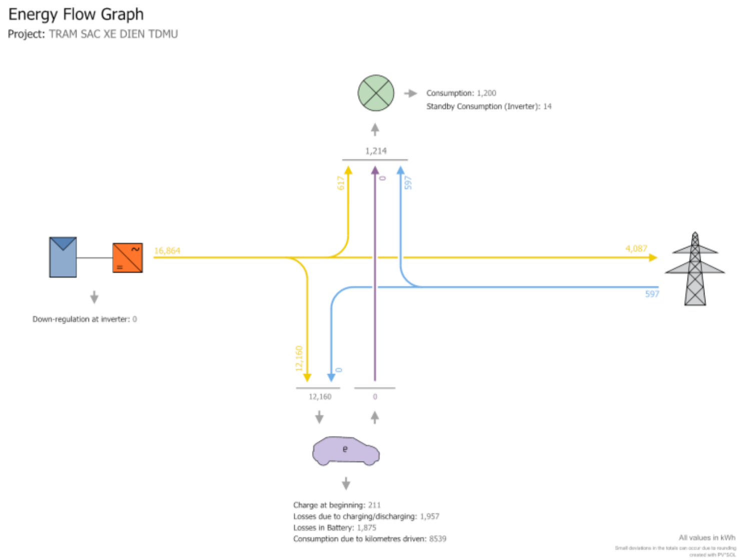

Figure 9. *Energy flow graph*

TABLE 6. The simulated yield of the PV system

Parameters	**Values**
PV generator energy (AC Grid)	16,864 kWh/year
Spec. annual yield	1,404.11 kWh/kWp
Performance ratio (PR)	78.7 %
Grid feed - in	4,087 kWh/year

Figure 10 shows production forecast with monthly consumption. Figure 11 represents the uses of PV energy for grid feeding, electric vehicle charging and own usage. It can be seen from Figure 10 that the PV generation in March is highest. In March, PV generation is 1526.2 kWh, electric vehicle charging is 1035.3 kWh, grid feeding is 438.2 kWh, and the remaining power is for internal use.

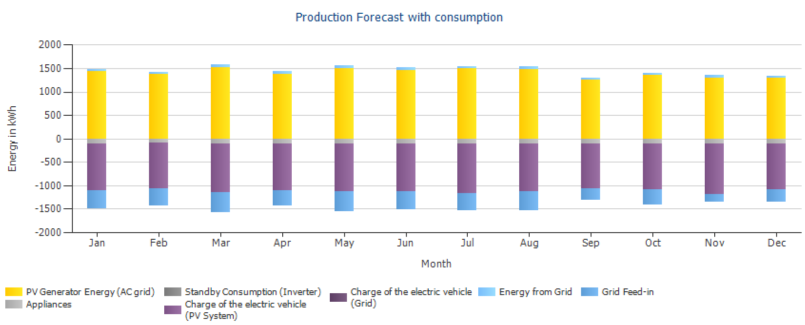

Figure 10. *Production forecast with consumption*

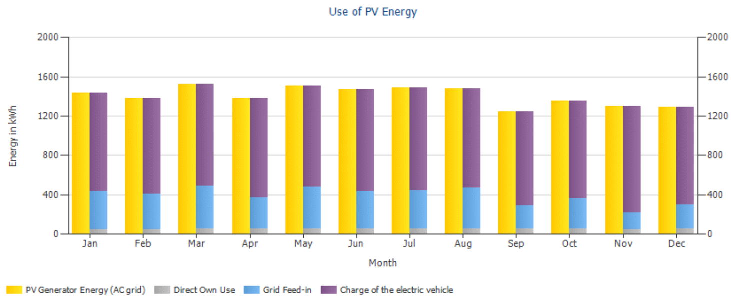

Figure 11. *Use of energy*

4. Environmental Impact and Economic Analysis

4.1. Environmental impact

The rooftop solar project not only brings energy benefits but also contributes to reducing CO2 emissions to the environment. The amount of CO2 emission reduction of the solar PV within a year simulated by PVSOL software is 7,919 kg. Figure 12 shows the environmental and output parameters of the solar PV system.

The yield

The yield	
PV Generator Energy (AC grid)	16,864 kWh
Direct Own Use	617 kWh
Charge of the electric vehicle	12,160 kWh
Grid Feed-in	4,087 kWh
Down-regulation at Feed-in Point	0 kWh
Own Power Consumption	75.7 %
Solar Fraction	95.5 %
Spec. Annual Yield	1,404.11 kWh/kWp
Performance Ratio (PR)	78.7 %
Yield Reduction due to Shading	1.3 %/Year
CO_2 Emissions avoided	7,919 kg / year

Figure 12*. The amount of CO2 emission reduction of the solar PV in a year*

4.2. Economic analysis

This section describes the calculation of the initial investment cost of the solar PV system, profitability and simple payback period. The initial investment cost which is calculated based on the market price and the structure of the designed solar PV system is described in Table 7. The lifetime of the PV system is estimated to be 20 years. The electricity bought from Vietnam Electricity Group (EVN) is calculated at the price for administrative units which is 1,659 VND/ kWh (EVN., 2021). The residual electricity is sold back to EVN at the price of 1,943 VND/ kWh (Table 8) (The Prime Minister, 2020).

TABLE 7. Initial investment for the proposed solar PV system

Items	**Price (VND)**

Solar Panel 400Wp	109,500,000
Inverter ABB PVI-10.0-TL-OUTD	57,602,000
Other equipment	120,915,500
Installation cost	10,000,000
Total initial cost	298,017,500

TABLE 8. Feed-in tariff for solar power

No.	Rooftop solar power project	Feed-in Tariff	
		VND/kWh	**Equivalent to UScent/kWh**
1	Floating solar power project	1,783	7,69
2	Ground mounted solar power project	1,644	7,09
3	Rooftop solar power project	1,943	8,38

(Note: The applicable exchange rate between VND and USD is the central exchange rate published by the State Bank of Viet Nam on 10th March 2020)

TABLE 9. Economic benefits of the PV system.

Without PV system		With PV system						Simple payback period (years)
Energy from grid (kWh)	Payment to EVN (1000 VND)	PV generator energy (kWh)	Energy from grid (kWh)	Payment to EVN (1000 VND	Grid feed-in (kWh)	Money from selling (VND)	Profit/year (1000 VND)	
13,374	22,187.47	16863.8	597	990.42	4087.2	7,941.4	29,138.45	10.23

Table 9 describes benefits of the PV system. If there is no solar power system, the annual load is 13,374 kWh, the corresponding amount to be paid is 22,187,466.00 VND. When the solar power system is installed, the amount of electricity purchased from EVN is 597kWh, thus reducing the annual amount to be paid to EVN by 21,197,050.0 VND. In addition, the system can also sell the unused amount of solar energy to the grid according to Circular 13 which is equivalent to 7,941,429.60 VND. Thus, the total profit earned in the first year is 29,138,450 VND.

5. Conclusıon

The study is carried out to determine the energy, environmental impact and economic parameters of the PV system for EV charging based on simulation. The rooftop PV systems are now increasingly installed. Through simulations, the obtained energy is 16,864 kWh/year, the annual specific yield in kWp is 1,404.11 kWh and the avoided CO2 emission is 7,919 kg/year. However, economic problems still exist, making investment efficiency low because of the payback period is so long. Currently, the Vietnamese government is offering a relatively high price for purchasing electricity generated from rooftop solar power projects, nevertheless it is forecasted that the price will be lower in the coming years, making the payback period longer and reduces the economic values of the project.

To conclude, from financial aspect, this project is not very efficient, however, the project is feasible in terms of energy production.

Acknowledgement

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