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Analysing Energy and Environmental Performance of a Residential Grid-Connected Photovoltaic System in Thu Dau Mot City, Vietnam

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ABSTRACT

*The electricity obtained from the photovoltaic (PV) system highly depends on various factors such as geographical location, solar radiation, weather conditions and orientation of solar panels. The electricity produced by the solar PV system can be assessed by using simulations. This paper presents a technical feasibility assessment of a 10 kWp rooftop solar PV system for a household in Thu Dau Mot City, Vietnam. The study presents the amount of electricity produced, the performance of the PV system and the system potential to reduce CO_2 emissions into the environment. The designing and evaluating of the system performance is done by PV*SOL, PVsyst and PVGIS software. The research provides useful information for the pre-feasibility assessment phase of a residential solar PV project in Vietnam.*

***Keywords**: rooftop solar, on-grid rooftop PV, solar PV system, PV*SOL, PVsyst, PVGIS, performance analysis, CO_2 emission*

1. Introduction

In the context of more and more exhausted fossil energy sources and severe environmental pollution and climate change, governments around the world have issued policies towards using energy efficiency and developing clean energy sources in the overall strategy to reduce the greenhouse effect (de la Cruz-Lovera et al., 2017; Bataineh & Alrabee, 2018). Solar power is a sustainable energy source that can be selected to reduce energy shortages and reduce the pollution from buildings, factories and cities (Dimond & Webb, 2017). Vietnam has issued a development strategy for renewable energy up to 2050, including rooftop solar power (PM Decision 2068/QD-TTg, 2015). In particular, Decision No. 13/2020/QD-TTg of the Prime Minister of the Government has created a strong motivation for people and businesses to invest in rooftop solar power projects (PM Decision 13/2020/QĐ, 2020).

Rooftop solar power systems in urban areas contribute to reducing CO_2 emissions and meeting load demand of households and organizations (Hernandez et al., 2018). There are diverse studies around the world on the design and performance evaluation of rooftop solar PV systems. Yadav et al., (2015) simulated and analyzed the solar PV system in the Hamirpur area, Himachal Pradesh, India. The results pointed out that the system performance ratio over the whole year was estimated as 0.724 and total amount of energy generated by the system and various losses occurring in the system were also analyzed and presented. Kumar et al., (2017) studied a 100 kWp grid-connected solar PV system with PVsyst V6.52 software, the results of the study showed that the PV system generated 165.38 MWh/year, and the annual performance ratio was around 80%. Dondariya et al., (2018) analyzed the energy efficiency of residential solar PV systems in Ujjain, India by using the PV*SOL, PVGIS, SolarGIS and SISIFO software, the results pointed out that PV*SOL software demonstrated to be an easy, fast and reliable software tool for the simulation of a solar PV system. Bouzguenda et al., (2019) developed and evaluated a single-phase 10 kW solar system at King Faisal University, Al Hofuf, United Arab Emirates. The study indicates that daily energy production by the real system was slightly below the rated values and in some months of the year, the station’s performance was better than the simulated one using PVsyst software. Rawat et al., (2020) evaluated the performance of a 30.5 kWp on-grid solar system in Gwalior city, India by using PVsyst software. The total installed capacity was 30.5 kWp which means approximately 55.670 MWh/year DC energy was generated from the array. (Tarigan, 2020) studied a 3 kWp solar power system in Surabaya, Indonesia; the research results showed that the annual energy obtained energy 4,200 kWh, and the daily energy obtained energy 11.67 kWh. Chauhan et al., (2020) designed and evaluated a 15kWp grid-connected power system. The simulation showed the system performance ratio of 79.48% and the yearly produced power of 32.272 MWh. Satish et al., (2020) simulated a 200kWp power system in Dubai. The annual energy output was 352.6 MWh and 1757 kWh/kWp/year, the system's annual performance ratio was 81.67%. Saxena & Gidwani, (2018) studied the energy estimate of a 100kWh rooftop PV power plant at Nagar Nigam Kota Rajasthan by using PVsyst software, the PV system’s energy calculated by PVsyst software was 167822 kW/h/year.

Vietnam has a great potential to develop solar power. On average, the total solar radiation in Vietnam is about 5kW/h/m^2/day in the Central and Southern provinces, and about 4kW/h/m^2/day in the Northern provinces. The number of sunny hours per year in the North is about 1,500-1,700 hours while in Central and South Vietnam it is about 2,000-2,600 hours per year (The World Bank, 2019; Polo et al., 2015). Thu Dau Mot is a city in the south of Vietnam, so it has a very good potential for exploiting solar energy. On the other hand, with the aim of becoming a green city, the city government and people have been taking many actions to contribute to climate change mitigation and sustainable development, including the development of rooftop solar power. To contribute to the development of the household solar power projects in Thu Dau Mot city, this article conducts a technical pre-feasibility assessment for the household rooftop solar power project.

The purposes of this article are:

• Assessing the solar resource potential at a specific household of Vietnam;

• Predicting the performance of a 10 kWp grid-connected rooftop solar system using PVsyst, PV*SOL and PVGIS software;

• Comparing the annual energy yield, performance ratio and energy yield of the PV system from various software;

• Calculating the amount of CO_2 emissions saved.

2. Materials and Methods

2.1 The proposed on grıd-connected PV system

In this project, a rooftop solar PV system in Thu Dau Mot City, Vietnam with the latitude and longitude of 11°00'07" and 106°39'46" respectively is studied (Figure 1). The solar radiation coefficient on the horizontal plane in one year is 1804 kWh/m^2/year (The World Bank, 2019). Figure 2 describes the solar radiation level at the surveyed site. A lifelike house is described in Figure 3 and the load as shown in Table 1. The direction of the house is north-south and the roof tilt angle is 38^o.

The household grid-connected solar PV system in Vietnam consists of the following components: solar panels, inverters, electrical wires, mechanical structures, electrical cabinets and a two-way meter (Figure 4). This system is widely applied to households and small commercial buildings and directly connected to the local grid via a two-way electric meter. If more solar energy is generated than a household needs, the excess energy is discharged into the grid. In contrast, if the generated solar energy is not enough to meet household needs, the remaining demand is met by importing electricity from the grid. The energy flows in a grıd-connected PV system is illustrated in Figure 4.

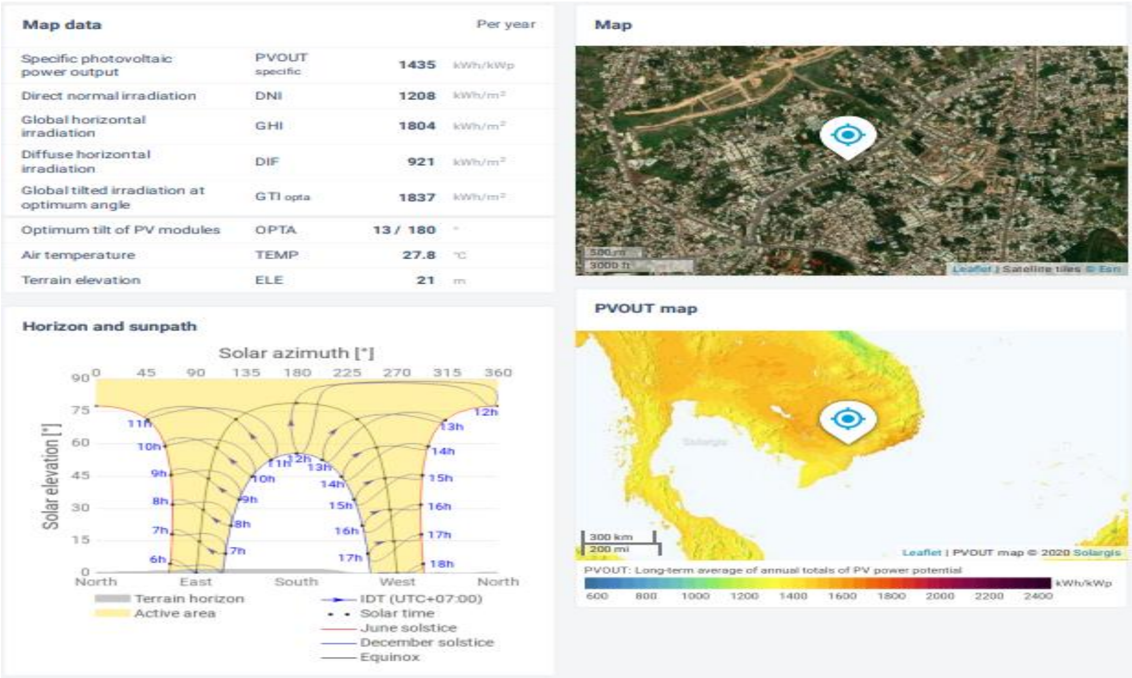

Figure 1. *Site information and solar radiation (The World Bank, 2019).*

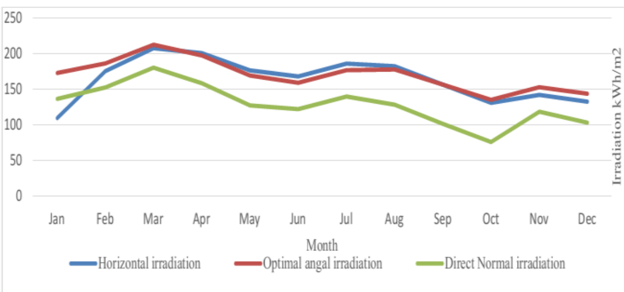

Figure 2. *Monthly solar irradiation estimates (PVGIS data, 2021)*

Figure 3. *Model 3D house in Sketchup software*

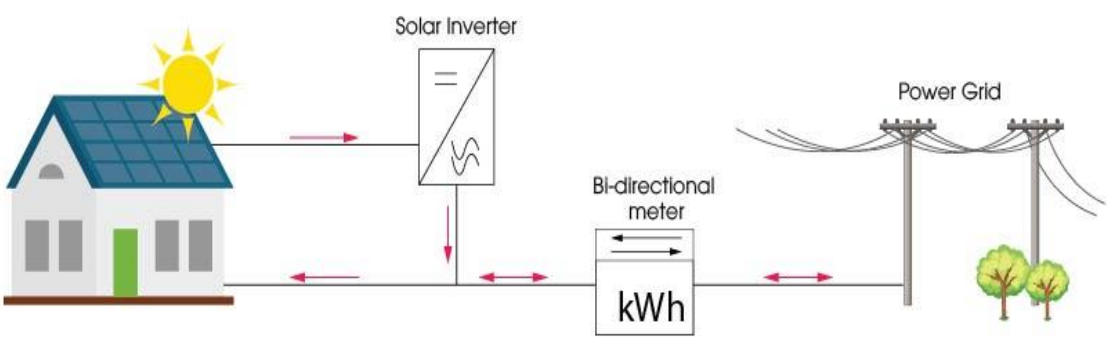

Figure 4. A typical household grid-connected solar PV system in Vietnam

TABLE 1. Estimation of household's demand

Appliances	Power (W)	Quantity	Uses (h/day)	Energy (Wh/day)
LED Light Tube	18	5	10	900
Induction Cooking	2,000	1	1	2000
Fan	40	2	10	800
Electrical Cooker	800	1	1	800
Refrigerator	500	1	24	12000
Air-conditioner	1125	1	5	5625
Total energy consumption per day 22125 (Wh)				

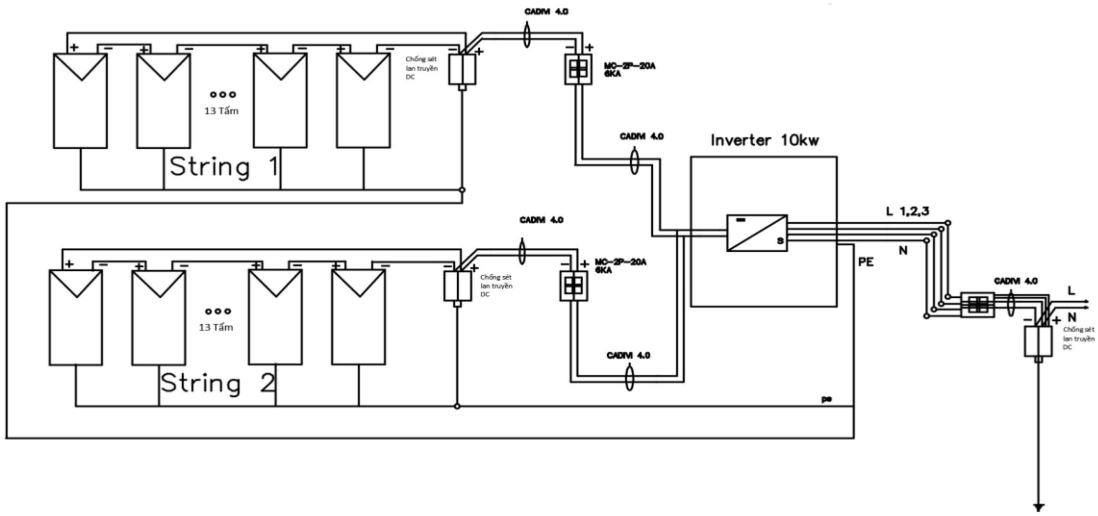

Figure 5. Single Line Diagram of Proposed PV System

Figure 5 is a single-line diagram of the solar PV system plotted by the AutoCAD software. The system consists of 26 monocrystalline 390Wp panels, divided into 2 strings connected to a 10 kWp inverter. The main parameters of a household solar system are described in Table 2-4. The specifications in this section are input parameters to simulate in the software presented in Part 2.2 of the paper.

TABLE 2. PV module specifications

PV module	Specification
Model	AE390LM6-72
Manufacturer	AE Solar
Type and no. of cell	Mono-crystalline
Rated Power (P_{max})	390Wp
Maximum power voltage (Vmp)	40.79V
Maximum power current (Imp)	9.56A
Short-circuit current (I_{sc})	10.10A
Maximum system voltage DC	1500V
Open-circuit voltage (U_{oc})	49.06V
Efficiency at STC/ module area	19.29%
Operating temperature	-40°C ~ +85°C
Dimensions	2018*1002*40mm

TABLE 3. Inverter specifications

Inverter	Specification
Model	ABB PVI-10.0-TL-OUTD
Manufacturer	ABB
Number of maximum power point (MPP) trackers	2
Rated output power	10 kW
Maximum power point (MPP) voltage	300V to 750 V
Input current maximum (I_{in})	34A
Maximum input short circuit current for each MPPT	22A
Maximum DC input power for each MPPT	6500 W
Absolute maximum DC input voltage	900 V
Maximum efficiency	97.8 %

TABLE 4. Parameters of the rooftop solar power system

Parameters	Specification
PV Generator Output	10.14 kWp
Module area	52.2 m^2
Cell area	47.2 m2
Space requirement for system installation	65 m^2
Roof area	130 m^2
Number of PV modules	26
Number of inverter	1
Number of string	2
PV field orientation	2 orientations
Tilts/azimuths	$38^o/90^o$ and $38^o/-90^o$

2.2. Methodology

The design of a solar power system needs to take into account many factors, including the level of the sun's radiation, the orientation, inclination and capacity of the panels and the quality of the inverter. This section presents the design and simulation of a household solar PV system with capacity of 10 kWp implemented by PVSOL, PV system and PVGIS software. The simulation process performed by the tools is shown in Figure 6. There are the two following parameters that must be in place before the simulation is carried out on the software:

• Geographical location parameters: location, weather, solar radiation, roof direction and inclination, expected energy, configurations of solar panels and inverters, etc.

• Specifications: provided by the user or by the default of the software.

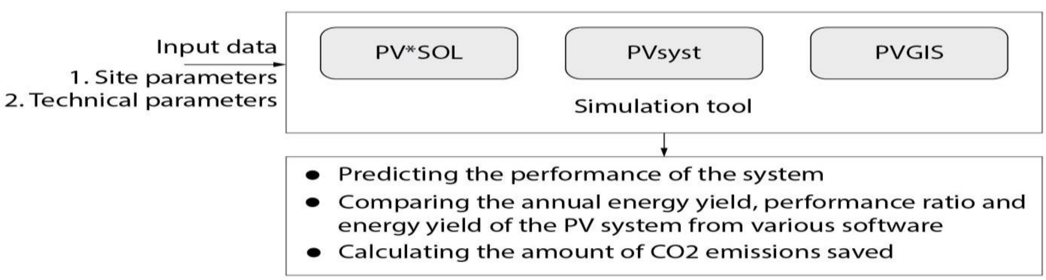

Figure 6. Research process

2.2.1. Performance parameters

Solar PV system performance evaluation is defined in IEC 61724 standard (International Electrotechnical Commission, 1998). It is described as follows:

• Array Yield (YA)

$$YA = \frac{E_{DCout}}{P_{PV,rate}} \quad (1)$$

Where:

YA (array yield): the ratio of PV array power output to its rated power [kWh/kWp/day],

E_{DCout}: daily DC energy output from solar arrays (kWh/day),

$P_{PV, rate}$: the rated output power of the PV array (kWp).

• System Yield (Y_{SY})

$$Y_{SY} = \frac{E_{ACout}}{P_{PV,rate}} \quad (2)$$

Where:

Y_{SY} (system yield): the ratio between the total AC energy obtained from the inverter's output and the rated power of the solar PV arrays [kWh/kWp/day],

E_{ACout}: the total AC energy of the inverter generated by the PV power system for a specific time (kWh).

• Reference System Yield (Y_{RSY})

$$Y_{RSY} = \frac{S_{ra}}{G_{or}} \quad (3)$$

Where:

Y_{RSY} (reference system yield): the ideal array yield according to array nominal installed power at standard condition as defined by manufacturer, without any loss. Y_{RSY} is numerically equal to the incident energy in the array plane, expressed in [kWh/m²/day].

S_{ra}: the total horizontal radiation on the panel (kW/m2);

G_{or}: the global radiation at standard test conditions (1kW/m2).

• Performance Ratio (PR)

$$PR = \frac{Y_{SY}}{Y_{RSY}} \quad (4)$$

In which, performance ratio (PR) of the whole system is related to the finally output power of the PV system and the nominal installed PV power.

*2.2.2. Simulation by PV*SOL Software*

PV*SOL software was developed by Valentine Software, Germany in 2004. PV*SOL software assists designers in evaluating solar system performance. The software automatically determines the required position on the map, and the built-in weather data is meteonorm 7.3 (https://meteonorm.com).

The process of designing and simulating a solar power system is quite complicated, including the main steps as described in Figure 7 below.

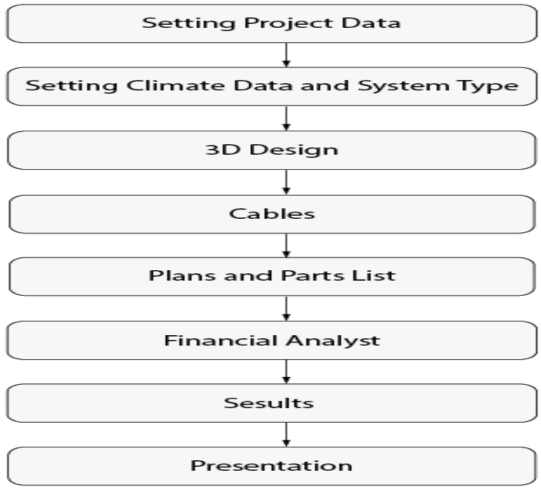

Figure 7. Process of solar PV simulation using PV*SOL software

Parameters are entered into the software according to the calculated and selected results which described in Part 2. Each roof consists of 13 panels that connected to the 10 kWp inverter, the system surface is 52.2 m2. Figure 9 shows the 3D design of the system while Figure 8 describes a single-line diagram of the system.

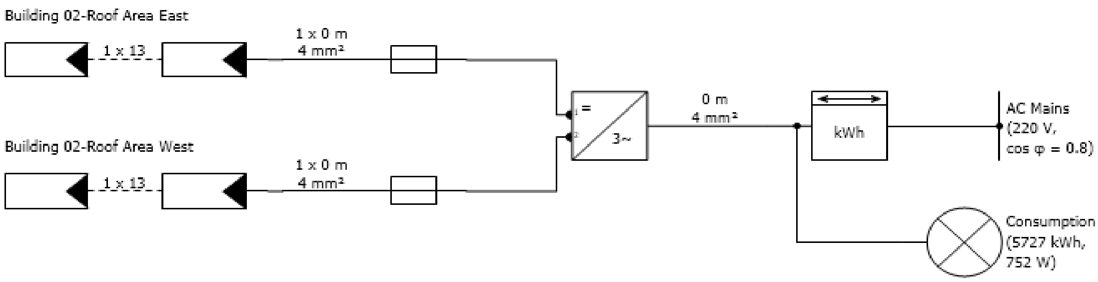

Figure 8. Circuit Diagram of Proposed Solar System in PV*SOL software

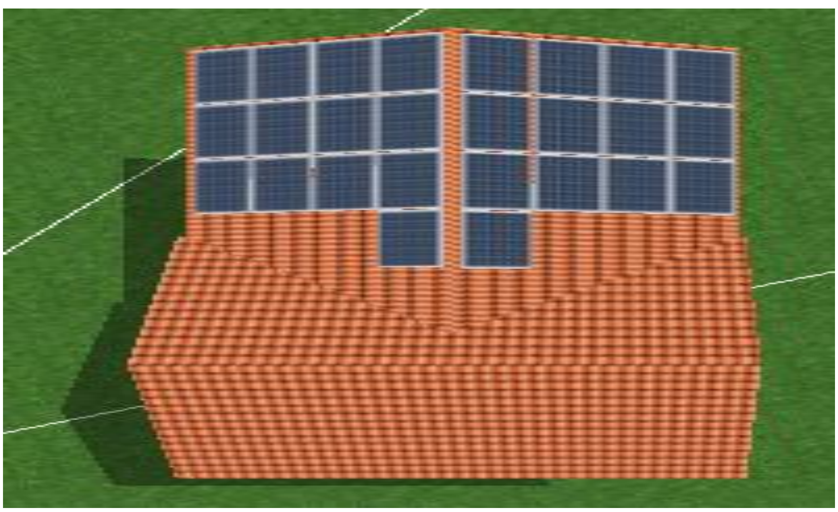

Figure 9. 3D visualization in PV*SOL software

2.2.3. Simulation by PVyst Software

PVsyst software was developed by a Swiss physicist, Andre Mermoud and a Swiss electrical engineer, Michel Villoz. The functions of the software consist of calculating and designing solar energy systems, including on-grid connected solar PV systems, off-grid connected solar PV systems, solar pump systems and solar PV DC grid systems.

In this study, PVsyst software version 7.1 is exploited to evaluate the performance of the proposed solar PV system. The weather data integrated in the software is meteonorm 7.3.

The design and simulation process is described in Figure 10. In the first step, the project parameters such as geographic location and weather are set up. Secondly, the tilt and direction of the solar panels are decided. Thirdly, the capacity of solar panels and the type of solar modules to be installed are chosen. Next, the inverter is selected. Then, the appropriate strings are arranged. After that, the simulation is run. Finally, the report is checked.

Figure 10. Process of simulation and design in PVsyst software

2.2.4. Simulation by PVGIS software

PVGIS software is an open source research tool for performance assessment of PV technology in geographical regions and as a support system for policymaking in the world. The software based on the data inputs evaluates the daily irradiation, energy production, annual yield and total system losses. The simulation is performed in the following manner (Dondariya et al., 2018):

• Step 1: Start ‘‘PVGIS’’ online simulation software.

• Step 2: Enter radiation databases as ‘‘Climate SAF-PVGIS’’.

• Step 3: Choose the PV technology to be used in the system.

• Step 4: Enter system capacity requirement for installation.

• Step 5: Enter the permissible total system losses.

• Step 6: Choose the mounting scheme, the angle of azimuth and inclination and tracking options.

• Step 7: Click on calculate to run the simulation.

• Step 8: A report is generated; giving data of average daily/ monthly electricity production, average daily/monthly sum of global irradiation per square meter received by the modules and combined PV system losses.

3. Results and Discussion

The simulation results of the 10 kWp solar power system by using PVsyst, PV*SOL and PVGIS software are described in Table 5. Annual electricity output is 12.973 MWh which is calculated by PV*SOL software, 11.81 MWh by PVsyst software and 10.67 MWh by PVGIS. Production capacity in kWp is 1,287.05 kW, 1164.00 kWh and 1040.00 kWh simulated by PV*SOL, PVsyst and PVGIS, respectively.

The performance of the system simulated by PV*SOL software is 79.2%, simulated by PVsyst software is 81.18%, simulated by PVsyst software is 86.00% by PVGIS software.

The rooftop solar project not only brings energy benefits and contributes to solving the problem of electricity shortages, but also contributes to reducing CO_2 emissions to the environment. The amount of CO_2 emission reduction of the project is calculated by the following formula (5). Table 5 shows the amount of CO_2 saving emitted into the environment of the solar power system corresponding to each software.

$$t_{CO_2} = \sum_{n=1}^{N} E_{Grid_n} x EF_{Grid} \quad (5)$$

Where, E_{Gridn}: the energy produced by the system in year; EF_{Grid} (the CO_2 emission factor of the Vietnamese grid) = 0.8649 t_{CO2}/MWh (Phap & Nga, 2020).

Table 6 and Figure 11 show that the electricity outputs simulated by PVGIS, PVSOL and PVsyst software are similar and this amount of electricity does not change much in the different months of the year. Electrical energy outputs obtained from April to July are higher than the remaining months of the year because these are in the high irradiation period. The energy obtained from PVSOL software is the highest.

TABLE 5. The CO_2 emissions and energy of the proposed PV system by simulation

Characteristics	PV*SOL Software	PVSYST Software	PVGIS Software
PV Generator Energy (AC grid) (MWh/year)	12.973	11.810	10.670
Specific energy production in kWh/kWp	1,287.05	1164.00	1040.00
Performance Ratio (%)	79.20	81.18	86.00
Avoided CO2 emissions	11.22 ton/year	10.21 ton/year	9.23 ton/year

TABLE 6. Monthly energy production by simulation

Month	Energy production in kWh		
	PV*SOL software	PVsyst software	PVGIS software
Jan	1074.5	634	1573.9
Feb	1029.6	743	1546.1
Mar	1176.7	1044	1565.6
Apr	1074.5	1098	1295.5
May	1178.4	1351	1093.6

Jun	1147.9	1390	975.8
Jul	1166.1	1474	1037.9
Aug	1160.5	1245	1171.5
Sep	962.5	908	1137.9
Oct	1035.2	807	1321.2
Nov	991.1	638	1434.8
Dec	991.1	574	1545.0

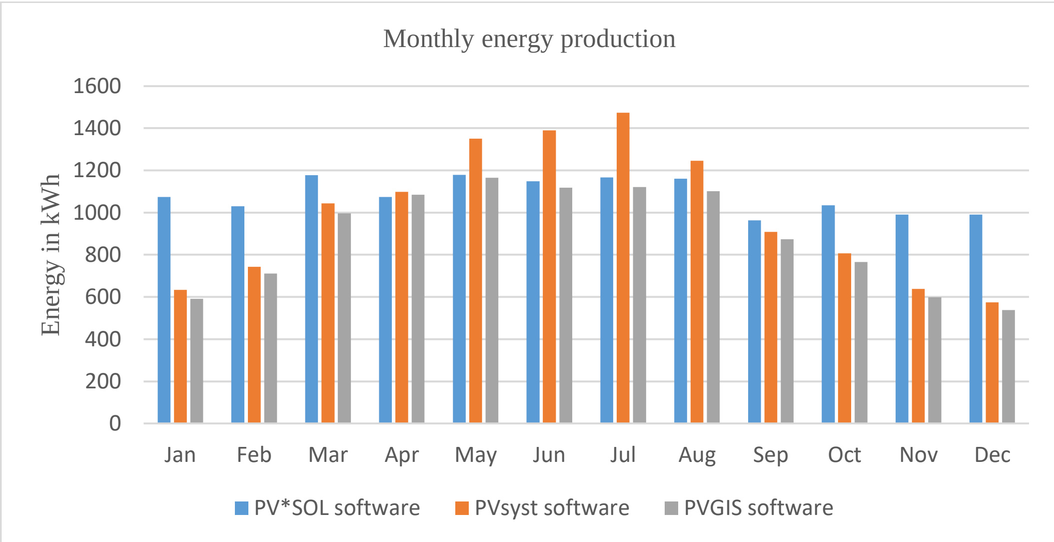

Figure 11. The monthly energy production by PV*SOL, PVsyst and PVGIS software

4. Conclusıon

The study is carried out to determine the energy and environmental performance of an 8.36-kWp on-grid connected rooftop solar PV system based on simulation. The study presented simulation results through PV*SOL, PVsyst and PVGIS software. The major findings of the present study are as follows:

The system's simulated annual energy yield of 12.973 MWh is a good indicator for installing the residential grid-connected systems in Thu Dau Mot City.

From this study, the following results obtained from the adopted software prove the feasibility of the system with a specific design position: the average annual energy generated is from 10.67 MWh to 12.973 MWh; the power in kWp is from 1040.00 kWh to 1,287.05 kWh; the average system performance ratio simulated by PV*SOL, PVsyst and PVGIS software is from 79.2% to 86%; and the avoided CO2 emission simulated by these three types of software is 11.22 ton/year, 10.21 ton/year and 9.23 ton/year, respectively.

The study results also show that PVSOL software gives higher results than PVsyst and PVGIS software. Among the simulation software studied, PV*SOL demonstrates to be an easy, fast, and reliable software tool for the simulation of solar PV system. This research provides some valuable insight into the rooftop solar energy exploitation to meet the typical household's energy requirements. Also, it can be used as a reference to simulate grid connected PV system using various types of simulation software.

This research can be used for a pre-feasibility assessment for a similar project in the area of Thu Dau Mot City, Vietnam because the weather conditions are nearly the same in all the areas of the city.

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