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A Comprehensive Assessment of a Rooftop Grid-Connected Photovoltaic System: A Case Study for Central Vietnam

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ARTICLE INFO

Article history:
Received 16 August 2021
Received in revised form
28 November 2021
Accepted 10 December 2021

Keywords:
FiT
Grid-connected
Photovoltaic
Rooftop
Vietnam

ABSTRACT

This paper presented an actual comprehensive assessment of a 1.32 kWp rooftop grid-connected photovoltaic system for residential buildings in Central Vietnam under the tropical monsoon climate. Operational parameters of the grid-connected photovoltaic system were monitored from August 2020 to July 2021. It consists of four photovoltaic modules, a microinverter, and a two-way energy meter. The analysis results of energy performance provided a performance ratio of 78.11%, a capacity utilization factor of 15.07%, and an annual overall system efficiency of 12.89%. In addition, the financial and environmental analysis of the system also indicated that the levelized cost of electricity was pretty low (i.e., 0.063 USD/kWh), the discounted payback period was 5 years, and 1.5 tons CO2 was reduced per year. The results of the analysis were compared and evaluated with other grid-connected photovoltaic systems in the same Southeast Asia region, and they revealed that the integration of the grid-connected photovoltaic system into the distribution grid in Central Vietnam is superior. The obtained data can be used as a guide for applying grid-connected photovoltaic systems in other locations with similar climates, as well as to assist the government in developing a more appropriate rate of feed-in-tariff for real-time grid-connected photovoltaic systems.

1. INTRODUCTION

Electricity consumption in the domestic sector is rapidly increasing due to rapid growth in income, population, and demand for electronic and consumer equipment. After falling by around 1% in 2020, global electricity demand is expected to rise by close to 5% in 2021 and 4% in 2022. The majority of these increases will take place in the Asia Pacific region [1]. Building energy consumption increased by 30% in 2020 as a result of the COVID-19 pandemic [2]. It is expected to rise as the pandemic situation worsens.

In Vietnam, hydropower and coal-fired power are still the main sources of electricity generation [3]. However, solar power projects are strongly developing under the support of policies. It started in 2015 with the target of electricity production from solar energy being planned to reach 1.4 billion kWh in 2020, 35.4 billion kWh in 2030, and 210 billion kWh in 2050 [4]. In April 2017, the government announced the first FiT of 9.35 US cent /kWh according to the Decision 11/2017/QD-TTg for solar power, especially for rooftop grid-connected photovoltaic (GCPV) projects, where the net measurement mechanism is applied. In January 2019, the government allowed rooftop GCPV projects to sell electricity according to FiT1 of 9.35 UScent / kWh through a 2-way electricity meter. Accordingly, by the end of 2019, total solar capacity will have increased by about 5 GWp, including about 4.5 GWp of new GCPV solar power plants and approximately 0.4 GWp of rooftop GCPV systems [4]. FiT2 price is 8.38 US cent/kWh according to Decision 13/2020 of government applied from June 30, 2019 to December 31, 2020. During that period, Vietnam connected 101,029 rooftop solar GCPV projects to the power system with a total installed capacity of 9,296 MWp. The total installed capacity of solar power is about 19,400 MWp (accounting for about 25% of the total installed capacity of the national electricity system) [5]. So far, the rooftop solar power system's installed capacity has reached 9580 MWp [6]. Thus, since the end of FiT2, the construction and installation of the GCPV system have been stopped, and they are waiting for a new decision from the government. During this time, researchers need to make a comprehensive assessment and analysis of the performance and impact of rooftop solar PV systems.

Solar power has become the world's fastest-growing energy technology among renewable energy sources because it uses the most abundant renewable energy on the planet (the sun). Besides, it has low maintenance and low prices compared to other renewable energy technologies. It can be mounted on a small or large scale [7].

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Small-scale grid-connected rooftop PV systems offer high efficiency in urban areas because they do not consume land, reduce electricity bills per month, resist building heat, generate income for households, and reduce transmission and distribution costs. In addition, under the influence of government policies, the installed capacity of rooftop GCPV systems is increasing, and related studies are also increasing in the literature [8]-[12].

More than 32,000 rooftop PV systems in Europe were assessed in terms of time from 2012 to 2019. The results showed that the long-term specific yield is between 947 and 1195 kWh/kWp and the performance ratio is 0.73-0.74 [10]. In Palestine, the 41 kWp GCPV system at the medical faculty building at An-Najah National University, Nablus, has also been evaluated. They also indicated that the final yield, reference yield, power utilization factor, and average annual performance ratio were 1684 kWh/kWp, 2046 kWh/kWp, 18.5%, and 0.84, respectively. The simple average payback period was 4.33 years [11].

In Malaysia, many researchers discussed rooftop GCPV systems. A study of the 7.8 kWp GCPV system at a residential house under the feed-in-tariff (FiT) scheme for two years 2018–2019 was also studied. It showed that the performance ratio, power utilization factor, and annual overall system efficiency were 65-71%, 13% –16% and 10% –12%, respectively. In addition, the payback is about 5-7 years [8]. The GCPV system with a power of 232.5 kWp at Monash University, Malaysia, in 2019 was also evaluated with the self-consumption program achieved performance ratio, power utilization factor, annual overall system efficiency, and levelized cost of electricity are of 85.4%, 14.85%, 9.15%, and 0.396 MYR/kWh, respectively. The payback period has been estimated at 8 years [13]. A 6.08 kWp system was also installed at the Malaysian Energy Center under the Malaysian Integrated Building Photovoltaic program. The system's final yield and performance ratios were presented for 2008 and 2009 [14].

In Indonesia, the Kupang solar power plant, with a capacity of 5 MW under the High Tariff Regulation for Solar PV Power Plant, was evaluated from March 2016 to December 2019. The results indicated that the daily performance ratio is between 70% and 90%, estimated payback period of 8 years [15].

Some simulation and energy analysis tools for GCPV systems are useful to support system design and development in recent years. Several tools such as PVsyst [8], [16]-[19], PVGIS [20], SolarGIS [21], [22] have been used by some researchers for energy prediction and modelling. Others perform economic analysis using HOMER [20], [23], [24]. The simulation results show a relatively low error compared to the actual results, which can be used as initial assessments for GCPV projects.

In Thailand, the research results show that the central region of Thailand is a suitable place for rooftop solar installation in terms of solar radiation and temperature and is more capable of solar power generation than other regions [25]. Rooftop GCPV systems with the FiT scheme had a discounted payback period of 6.1 years, an IRR of 15%, and a PI of 2.57, better than the cases without the FiT scheme [25]. In addition, the first eight months of monitoring the 500 kWp GCPV system in the North West of Thailand gave the following results: the final yield ranged from 2.91 to 3.98 h/d, and the performance ratio ranged from 0.7 to 0.9 [26].

In Vietnam, GCPV systems are developing rapidly. However, there are limited publications on system performance analysis. Simulation analysis of a 15 kWp PV system used in a zero-energy building model in Hanoi, Vietnam has been shown with an optimal tilt angle of 15o. The average system produces only 60% of rated power, even in the sunniest month of the year [17]. An experimental study of a single-axis automatic solar tracker in central Vietnam has shown that average system efficiency increased by 15.2%. The total energy consumption of the solar tracker was approximately 2-8% of the energy generated by the GCPV system [9]. The performance ratios were 66.0% and 69.2% for the GCPV system without and with a single-axis solar tracker, respectively [27]. A simulation of the expected energy output for the project's life, cash flow, and energy income from the FiT program has shown that the payback period was 8 years compared to 20 years in Gia Lai, Vietnam [28]. Research on the GCPV system in the Central Highlands of Vietnam shows that the retail price of electricity affects the payback time, the shortest time is 4 years for the system installed in the household using the highest price [29]. A rooftop solar power system with a capacity of 8.36kWp has been simulated and economically analyzed in a family home in Thu Dau Mot City, Vietnam [30]. The simulation was conducted using PVsyst 6.7.0 software; the amount of electricity produced by the system is 3.64 kWh/kWp/day. The total power of the appliances is about 7 kW, and the estimated household energy consumption is 26.6 kWh/day. Assuming daytime power consumption is fully utilized from the PV system, a project life of 20 years and a discount rate of 3%, then the LCOE of this system is 0.048 USD/kWh and the payback period is 6.74 years [30].

The above analysis shows that the assessment of the GCPV system is highly dependent on the climate, the geographical location of the installation, and the government's energy policies in that area. As a result, this study presents some elements that supplement the existing references through a comprehensive assessment of the rooftop GCPV system in Vietnam's typical monsoon climate under the influence of the FiT scheme. First, the energy performance over a year is analyzed, and the rooftop GCPV system is used in Vietnam’s FiT scheme. To represent the annual tropical monsoon climate in central Vietnam, one-year energy data was presented. Second, this study presented an energy efficiency analysis using a combination of measured power data from the system and accurate weather data from the Solcast open-source platform [31]. Third, the study presented a financial analysis for the rooftop GCPV project in Vietnam's FiT scheme, including levelized cost of electricity (LCOE) and discounted payback period (DPBP). This contributes to the inclusion of references to this issue in Vietnam. Finally, the estimated avoided CO2 emissions from the GCPV system over the project's one-year period contribute to environmental protection.

2. CASE STUDY

2.1 GCPV System Description

A case study was a rooftop GCPV system with a power of 1.32kWp, installed in a residential building in Central Vietnam (Hue City) at a latitude of 16.47°N, a longitude of 107.60°E, and a height of 15m above ground level in the mid-2020 year. The studied system consists of four commercial polycrystalline photovoltaic (PV) modules SUN330-72P and HY-1200-Pro grid-connected microinverter with four MPPT (maximum power point tracking) inputs (warranty: 25 years). Each PV module has been connected directly to a microinverter's MPPT input. The microinverter has been connected to a single-phase low-voltage AC voltage of 220V, 50Hz. The specifications of the PV module under standard test conditions (STC) and the microinverter are given in Table 1, Table 2, respectively. The initial investment for this rooftop GCPV system is shown in Table 3.

Table 1. Characteristics of PV modules at STC.

PV module	Specifications
Type of cells	Polycrystalline
Power rating	330 Wp
Module Efficiency	17.09%
Number of cells	72
Voltage at maximum power	37.8 V
Current at maximum power	8.73A
Short circuit current	9.22A
Open circuit voltage	45.5V
Temperature coefficient of Pmax	−0.41%/°C
Module dimension	1950x990mm^2
Lifetime	21–25 years

Table 2. HY-1200-Pro Microinverter specification.

Nominal AC power	1,200 W
Recommended Input Power	4 × 210~400W
Maximum DC Voltage	60V
MPPT Voltage Range	25~55V
Maximum efficiency	96.5%
No. of MPPT input	4
Warranty	25 years

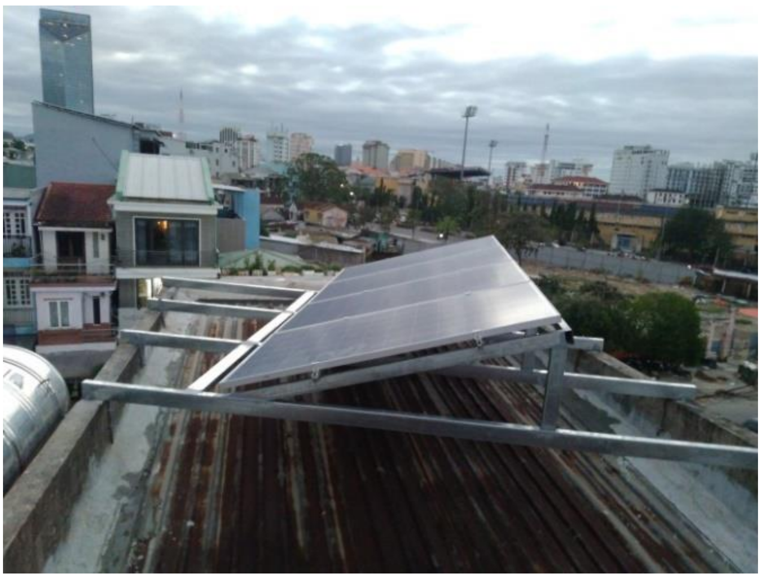

Fig. 1. Installed GCPV system.

Table 3. Initial investment for the rooftop GCPV system.

Component	Costs (million VND)	Costs (USD)
Microinverter	6	264.8
04 PV module 330Wp	7.92	349.5
Cabling cost and other	3.786	167.1
Shipping cost	0.85	37.5
Installation cost	2	88.3
Total initial cost	20.556	907.2

VND/USD exchange rate = 22,660 [Vietcombank exchange rates, 12/8/2021]

Hue city of Vietnam is located in the northern hemisphere. According to the documents [9], [32] the optimal tilt angle is equal to the latitude angle of the installation place, so the PV modules of the system are installed with an optimal tilt angle of about 17° and the surface facing south corresponding to an azimuth of 0°, the system has been shown in Figure 1.

A residential building in this study uses peak electricity load in the periods from 11h00 to 13h00 and 18h00 to 23h00, with low electricity load during working hours of the day. This is a typical household in the central region of Vietnam. During summer days, the peak electricity load of the study residential building from 11h00 to 13h00 was 1.5kW (equivalent to two air conditioners for two bedrooms).

2.2 Data Collection and Monitoring

DC energy output and AC energy output from the GCPV system were collected from the built-in solar data logger in the microinverter with a sampling interval of 5 minutes. It is connected to the local wi-Fi internet, where it transfers all the data obtained to the webserver. In addition, the PV energy injected into the grid and the energy consumption from the grid were recorded by a two-way energy meter, distributed by the Power Company, with sampling time of approximately twice a day. The results presented in this study cover one year of data recorded from August 1, 2020, to July 31, 2021.

Weather data is crucial in evaluating the performance of PV systems. This paper obtained the weather data at the installation site from an open-source platform called Solcast [31]. The data set with a sampling time of 5 minutes uses the latest weather satellite imagery, machine learning, computer vision, and extensive databases, including the following parameters: total in-plane solar irradiance, air temperature, and some other weather parameters.

3. A COMPREHENSIVE ASSESSMENT

A comprehensive assessment for the installed GCPV system consists of 3 parts: Energy analysis; Financial analysis; Environmental analysis.

3.1 Energy Analysis

Based on the analysis of the references, energy analysis includes eight important parameters to check the performance of the installed system: Reference yield; Final yield; Array yield; System loss; Array capture losses; Performance ratio; Capacity utilization factor (CUF); and Annual overall system efficiency.

Reference yield, Y_r is the total in-plane solar irradiation H_t (kWh/m^2) divided by the reference irradiance ($G_{i,ref}$ = 1 kW/m^2). Therefore, the reference yield is the number of peak sun hours and can be expressed as an annual, monthly, or daily value depending on the value of H_t [26], [27]:

$$Y_r = \frac{H_t}{G_{i,ref}} = \sum_k \frac{G_{t,k} * \tau_k}{G_{i,ref}} \quad (1)$$

where, $G_{t,k}$ is total in-plane solar irradiance, kW/m^2; τ_k is sampling time, h.

The final yield is defined as the annual, monthly, or daily net AC energy output of a PV system divided by the peak power of the installed PV system at STC (solar radiation of 1 kW/m^2 and module temperature of 25°C) [26], [27]. The final yield is the yield of the PV system under certain weather conditions:

$$Y_f = \frac{E_{out}}{P_0} = \sum_k \frac{P_{out,k} * \tau_k}{P_0} \quad (2)$$

where, E_{out} is AC energy output, kWh; $P_{out,k}$ is AC power output of the system, kW; P_0 is peak power of the installed PV system, kWp; τ_k is sampling time, h.

The array yield is defined as the ratio of DC energy output from a PV array over a particular period (day, month or year) to its peak power and is given by [11], [13], [26]:

$$Y_a = \frac{E_{DC}}{P_0} = \sum_k \frac{P_{DC,k} * \tau_k}{P_0} \quad (3)$$

where E_{DC} is DC energy output, kWh; $P_{DC,k}$ is DC power output of the system, kW; P_0 is peak power of the installed GCPV system, kWp; τ_k is sampling time, h.

In some ways, energy losses occur in a GCPV system, the most significant of which are system losses and array capture losses. System losses are losses caused by the inverter converting DC to AC and are given as follows [11], [13], [26]:

$$L_S = Y_a - Y_f \quad (4)$$

Array capture losses are any losses due to the PV array, including copper losses on the transmission line to the inverter. They are given as follows [11], [13], [26]:

$$L_C = Y_r - Y_a \quad (5)$$

In addition, reference yield, final yield, array yield, system losses, and array capture losses can be expressed as the average daily value by month, calculated as their monthly value divided by the number of days in the month.

Performance ratio (PR) is a dimensionless index that evaluates the AC power output from a PV system under actual working conditions relative to the theoretical system's energy. PR can be calculated by annual, monthly, or daily. The higher the PR, the greater the amount of solar energy converted into electrical energy. The value of PR shows the overall effect of the loss on the system's productivity [26], [27]:

$$PR = \frac{Y_f}{Y_r} * 100\% \quad (6)$$

where, Y_f is the final yield, kWh/kWp; Y_r is the reference yield, kWh/kW.

The ratio of the actual AC energy output generated by the PV system to the amount of energy that a PV system would generate if it were operated at full rated power over a calculation period called the capacity utilization factor (CUF) [8], [11], [13]. CUF can be expressed as an annual and monthly value depending on the value of net AC energy output and calculation period and is calculated according to the following formula:

$$CUF = \frac{E_{out}}{P_0 * T} * 100\% = \frac{\sum_k P_{out,k} * \tau_k}{P_0 * \sum_k \tau_k} * 100\% \quad (7)$$

where, E_{out} is AC energy output, kWh; $P_{out,k}$ is AC power output of the system, kW; P_0 is peak power of the installed GCPV system, kWp; T is calculation period, h; τ_k is sampling time, h;

The system efficiency describes the ratio of the actual AC energy output of the PV system to the total solar energy obtained from the total area of the PV array [8], [11], [13]. System efficiency can be expressed as annual and monthly values depending on net AC energy output and total in-plane solar irradiation. Monthly or annual overall system efficiency (AOSE) is calculated according to the following formula:

$$\eta = \frac{E_{out}}{A_{pv} * H_t} 100\% = \frac{\sum_k P_{out,k} * \tau_k}{A_{pv} \sum_k G_{t,k} * \tau_k} * 100\% \quad (8)$$

where, E_{out}, is AC energy output, kWh; $P_{out,k}$ is AC power output of the system, kW; τ_k is sampling time, h; A_{pv} is total area of PV modules, m^2; H_t is total in-plane solar irradiation, kWh/m^2.

3.2 *Financial Analysis*

Financial analysis is fundamental to convincing people to invest in the installation of a GCPV system. Indicators such as DPBP and LCOE are considered to assess the financial viability of the GCPV system. In this section, the concepts of inflation rate and retail electricity price increase rate are ignored. The discount rate selected is equal to the current interest rate (5.3% [33]).

LCOE provides the overall competitiveness of different power generation options. LCOE is the present value of the price of electrical energy generated, considering the economic life of the plant and the cost of construction, operation, and maintenance. The LCOE is calculated as follows [34]:

$$LCOE = \frac{C_I + \sum_{n=1}^{N} \frac{AnnualCost_n}{(1+dr)^n}}{\sum_{n=1}^{N} \frac{E_{out,n}}{(1+dr)^n}} \quad (9)$$

where, $LCOE$, USD/kWh; C_I is initial investment cost, USD; $AnnualCost_n$ is the annual cost for nth year, USD; $E_{out,\,n}$ is annual AC energy output from GCPV system of nth year, kWh; dr is discount rate, %; N is payment period, year.

The annual cost for nth year includes the operation, maintenance, future replacement, and insurance costs [34], [35]. However, with the researched GCPV system, the annual cost for the system only includes operation cost, the maintenance cost, other costs are not considered. In addition, the annual power degradation of the GCPV system is also considered, so the LCOE values for the research system are calculated according to the following formula:

$$LCOE = \frac{C_I + \sum_{n=1}^{N} \frac{C_{o\&m}}{(1+dr)^n}}{\sum_{n=1}^{N} \frac{E_{out,1} * (1-D)^n}{(1+dr)^n}} \quad (10)$$

where, D is degradation factor of GCPV system, %; $C_{o\&m}$ is annual operation and maintenance cost; $E_{out,1}$ is annual AC energy output from GCPV system of first year, kWh.

For GCPV systems, annual energy output loss is mainly due to attenuation on PV modules, so the degradation factor has been considered to be 0.6% [35].

DPBP gives the number of years required to recover the initial cost of a project. The longer the DPBP, the higher the risk of the investment not earning the expected return. However, DPBP ignores cash flows that occur after the payback period and gives no information about the total return. DPBP is calculated as follows [23], [25]:

$$\sum_{n=1}^{DPBP} \frac{CES_n}{(1+i)^n} = C_I \quad (11)$$

where C_I is initial investment cost, USD; i is interest rate, %; CES_n is annual energy-saving cost from GCPV system or the net cash flow in period n.

Annual energy-saving cost from GCPV system is calculated as total monthly energy-savings, which counts as benefit from selling PV energy injected into the grid and the differential benefit in the electricity bill with and without GCPV system:

$$\mathrm{CES} = \sum_{j=1}^{12} \mathrm{CES}_j = \sum_{j=1}^{12} [B_{PV\_GCj} + (B_{j\_user} - B_{j\_FrGrid})] \quad (12)$$

where, CES_j is the monthly energy-saving cost from GCPV system, USD; $B_{PV\_GC\,j}$ is the monthly benefit from selling PV energy injected into grid, USD; B_{j_FrGrid} is the monthly electricity bill to pay for Power Company with using GCPV system, USD. B_{j_user} is the monthly electricity bill with a non-using GCPV system is the assumed electricity bill according to the retail electricity selling price of the Power Company with total electrical energy consumption:

$$E\_user = E\_FrGrid + E\_FrPV \quad (13)$$

where, E_user is total energy consumption, kWh; E_PrGrid is energy consumption from the grid, kWh; E_PrPV is energy consumption from GCPV system, kWh.

In Vietnam, electricity prices for domestic, commerce, and industry are different. This study only deals with domestic electricity users. Monthly electricity bills can be calculated according to energy consumption and domestic retail prices in Table 4, suitable for households from 2020 to the present [29].

The studied GCPV system will be applied with a FiT2 scheme for rooftop GCPV systems with rate of 0.0838 USD/kWh by Decision No. 13/2020/QD-TTg of the Prime Minister officially taking effect from May 22, 2020 [29]. The benefit from selling PV energy injected into a grid of GCPV systems is calculated as the product of PV energy injected into the grid (E_GCPV) with a FiT rate.

3.3 Environmental Analysis

The environmental performance of the GCPV system is evaluated using the CO_2 factor - the amount of carbon dioxide that can be reduced by using solar power is calculated as follows [13], [16]:

$$(CO_2)a = \frac{0.8649 * E_{out,year}}{1000} \quad (14)$$

where, $E_{out,\ year}$ is annual AC energy output, kWh; 0.8649 is carbon mitigation factor for Vietnam, tCO_2/MWh [16].

4. RESULTS AND DISCUSSION

4.1 Weather Data

In Hue city, Central Vietnam, during the period from 8/2020 to 7/2021, the total in-plane solar irradiation reached 1690 kWh/m^2, corresponding to 4.63 $kWh/m^2/day$, the highest in May 2021 with 6.33 $kWh/m^2/day$, and the lowest in December 2020 with 1.87 $kWh/m^2/day$, as shown in Table 5 and Figure 2. The average monthly ambient temperature is lowest in January 2021 at 18.35ºC and highest in June at 28.65ºC. The highest temperature was recorded at 38.7ºC at noon in April 2021. The annual average solar irradiation in this study is at the average level of Vietnam, which is higher than the data from northern Vietnam (Hanoi) with 4.03 $kWh/m^2/day$ [16], but lower than the data from the central highlands of Vietnam (Gia Lai) with 5 $kWh/m^2/day$ [28].

Table 4. Retail domestic electricity price (exclusive of 10% value-added tax).

Level i	Retail electricity price (USD/kWh)
Level 1: 0–50 kWh	0.0741
Level 2: 51–100 kWh	0.0765
Level 3: 101–200 kWh	0.0889
Level 4: 201–300 kWh	0.1119
Level 5: 301–400 kWh	0.1251
Level 6: 401 kWh or more	0.1292

VND/USD exchange rate = 22,660 [Vietcombank exchange rates, 12/8/2021]

Table 5. Monthly energy from GCPV system, grid and consumption, and energy-saving cost from GCPV system.

Month	Total energy consumed. *E_user* kWh	Energy consumes from the grid *E_FrGrid* kWh	Product of PV energy injected into the grid *E_GCPV*, kWh	AC energy output from GCPV system E_{out}, kWh	Energy consumes from GCPV system *E_FrPV*, kWh	DC energy output from GCPV system, E_{DC}, kWh	Total in-plane solar irradiation H_t kWh/m^2	Energy-saving cost from GCPV system CES_j, USD
8/2020	781	610	0	171	171	178	172.7	24.303
9/2020	753	576	0	177	177	185	176.1	25.155
10/2020	635	556	1	80	79	84	75.6	11.311
11/2020	388	310	16	94	78	99	85.1	12.075
12/2020	417	362	9	64	55	67	57.8	8.399
1/2021	602	500	7	109	102	114	96.8	15.083
2/2021	458	347	52	163	111	163	155.1	19.894
3/2021	351	266	72	157	85	158	155.2	17.237
4/2021	438	320	60	178	118	179	177.9	21.438
5/2021	684	524	40	200	160	201	196.2	26.091
6/2021	951	794	16	173	157	180	169.9	23.654
7/2021	941	785	20	176	156	178	171.3	23.847
Annual	7399	5950	293	1742	1449	1786	1689.7	228.487

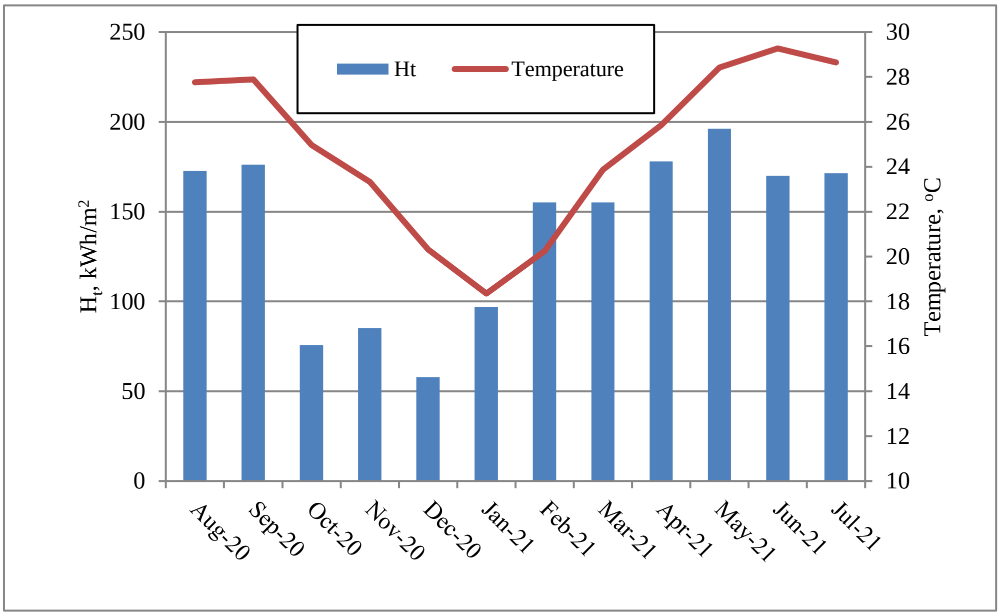

Fig. 2. Total in-plane solar irradiation and the average temperature in Hue city.

4.2 Energy

Monthly energy from GCPV system, grid, and energy consumption of load has been shown in Table 5. Figure 3 shows the average daily value by month of reference yield, final yield, array yield, system losses, array capture losses. In May, the highest final yield was 4.89 kWh/kWp/day (due to the high number of sunny days with clear skies), the lowest final yield in December 2020 is 1.57 kWh/kWp/day (due to cloudy days and frequent rains). In general, the annual average final yield is 3.62 kWh/kWp/day, corresponding to the total AC energy output of the GCPV system in the entire year of 1742 kWh.

The final yield of the system depends on the factors of weather, temperature, shade, dust, and especially solar irradiation, or reference yield, which is clearly shown in Figure 3. Final yields are low in October, November, December, and January. This is due to heavy rainfall from the northeast monsoon and cloudy days from October to January. Array capture losses are low in October, November, December, and January, respectively. This can be explained under the influence of monsoon and rain. Many modules' surface is cleaned, and the temperature is low in those months, leading to better energy conversion. System losses are pretty low. Its average value is high in June, July, August, September and the highest is 0.2 kWh/kWp/day. This is explained by the highest temperature in these months of the year, affecting the working efficiency of the microinverter.

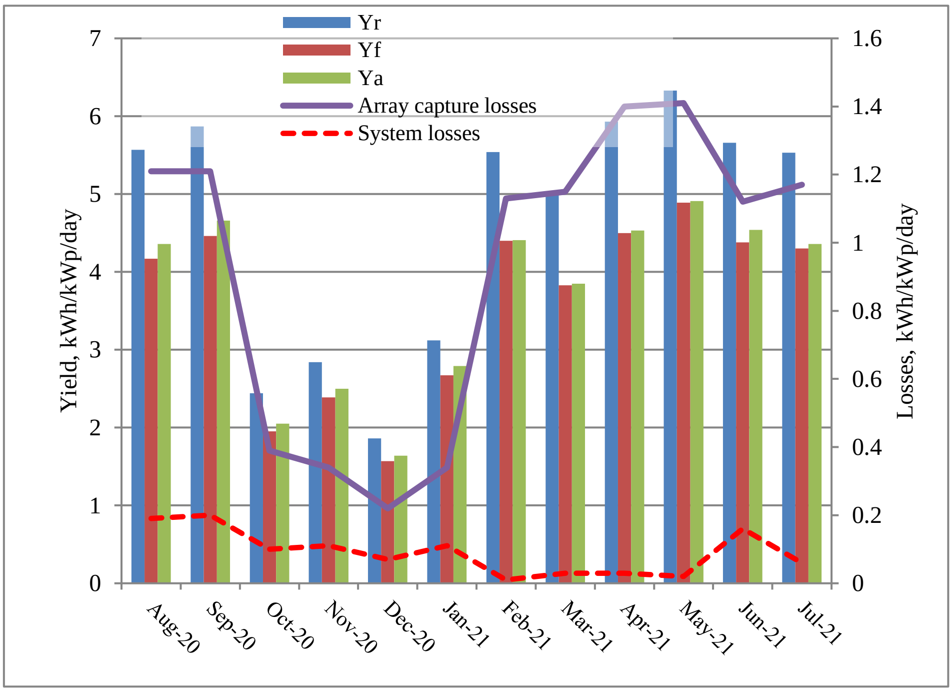

Fig. 3. Monthly yield and losses of the GCPV system.

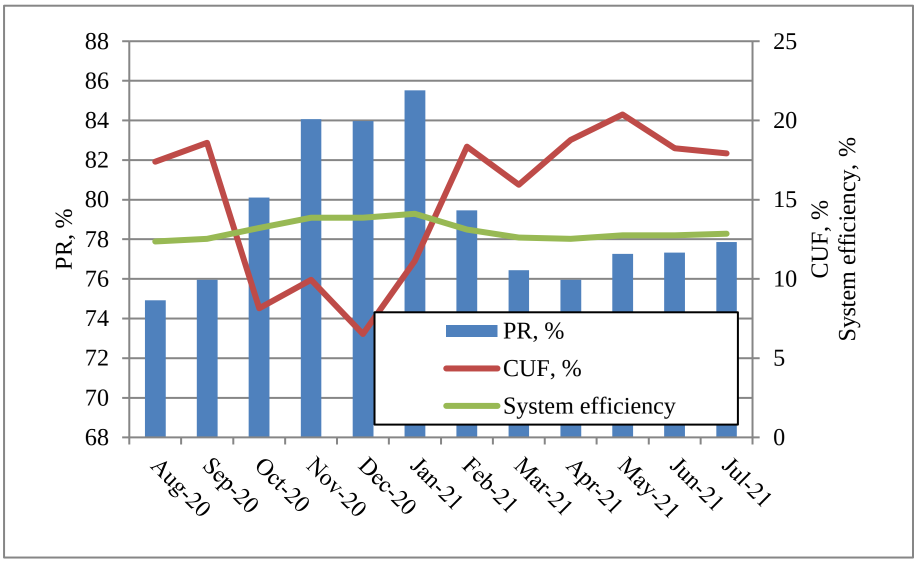

Fig. 4. Monthly PR, CUF, and system efficiency of studied GCPV system.

The performance ratio (PR), annual CUF, and AOSE of the studied GCPV system during the study period were 78.11%, 15.07%, and 12.89%, respectively. Their monthly values are shown in Figure 4. The highest PR of 85.51% was observed in January 2021, and the lowest was 74.93% in August 2020. The PR index is high at 90% for GCPV systems with good quality or good operation and maintenance concepts, is less than 60% for systems with poor quality or poor operation and maintenance concepts, and reaches 70-80% for about 50% of GCPV systems [6]. Table 6 presents a comparison of the performance of GCPV systems in Southeast Asia. The main focus parameters of the comparison are PR, CUF, and AOSE. The PR of the studied GCPV system has reached the average level compared with other systems in Table 4.

The monthly CUF of the studied GCPV system ranges from 6.5% (in December 2020) to 20.3% (in May 2021), with an annual CUF of 15.07%. Furthermore, the value CUF is in proportion to the total solar radiation on the module surface, which means they are subject to location and climatic conditions. The annual CUF of the studied GCPV system is close to the CUF value for tropical climates (14.69% –17.51% with a mean of 15.70%) [13], [36].

As depicted in Figure 4, system efficiency of the studied GCPV system was relatively stable, with minimal fluctuations throughout the year. The average is 12.89%, with the minimum in August 2020 (12.36%) and the maximum in January 2021 (14.11%). These levels are higher than the GCPV systems in Malaysia with 10-11% [8] and 9.15% [13]. This is possible because the studied GCPV system uses a microinverter with 4 independent MPPT inputs for 4 PV modules, ultimately reducing the effect of individual PV module efficiency on the system, different from comparison systems that use only 1 MPPT input for PV arrays or PV strings.

4.3 Finance

The studied GCPV system is connected to the local grid. A load of houses uses the electrical energy generated from this system. The part of excess electrical energy is injected into the grid and sold back to the Power Company. Moreover, when energy consumption is high, part of the electrical energy will be taken from the grid. In Figure 5, presented monthly energy and electricity bills, where E_user is total energy consumption, E_FrGrid is energy consumption from the grid, E_GCPV is PV energy injected into the grid, Bill_user is the monthly electricity bill with a non-using GCPV system, and Bill_FrGrid is the monthly electricity bill to pay for Power Company.

Table 6. Comparison of GCPV systems from different regions of Southeast Asia.

Location	Final yield (kWh/kWp/day)	PR (%)	CUF (%)	AOSE (%)	Ref.
Dong Ha, Vietnam	3.20	66	N/A	N/A	[27]
Gia Lai, Vietnam	3.71	74.11	N/A	N/A	[28]
Hue, Vietnam	3.62	78.11	15.07	12.89	This study
Hanoi, Vietnam	3.26	81.06	N/A	N/A	[16]
Thudaumot Vietnam	3.64	81.7	N/A	N/A	[30]
Terengganu, Malaysia	3.30-3.78	65-71	13.71-15.72	10-11	[8]
Malaysia	N/A	77.28	15.70	N/A	[36]
Bandar Sunway, Malaysia	N/A	85.40	14.85	9.15	[13]
Kupang, Indonesia	3.77-3.41	0.81	14.45-15.97	N/A	[15]
Mae Hong Son, Thailand	2.91 -3.98	0.7 to 0.9	N/A	N/A	[26]

For the calculation of LCOE, DPBP factors such as the life of the solar power system (20 years), discount rate, current interest rate (5.3%), PV energy injected into the grid, electrical energy consumption from the grid, and annual electricity generated by the studied GCPV system are considered.

In Table 7, the values of energy output, saving the cost of the GCPV system, and annual cost over a 20-year life cycle under the FiT contract. The GCPV system has been operated and studied under actual weather conditions, so the performance of this system is greatly affected by dust and dirt on the surface of the PV panels, so the research team cleaned the PV panels twice in a research year of October 2020 and April 2021. The studied GCPV system was installed at a capital investment cost of 907 USD over a 20-year life cycle under the FiT contract and 30 USD for operation and maintenance costs (twice surface cleaning per year). The studied GCPV system has a low investment rate compared to other published studies in Table 8. This is achieved because the system has been invested in the appropriate period and does not consider the value-added tax. Based on Equation (9) and data in Table 7, the LCOE for the studied GCPV system was 0.063 USD/kWh, which is significantly lower than the LCOE of 0.095 USD/kWh [13] and higher than 0.042-0.05 USD/kWh [8].

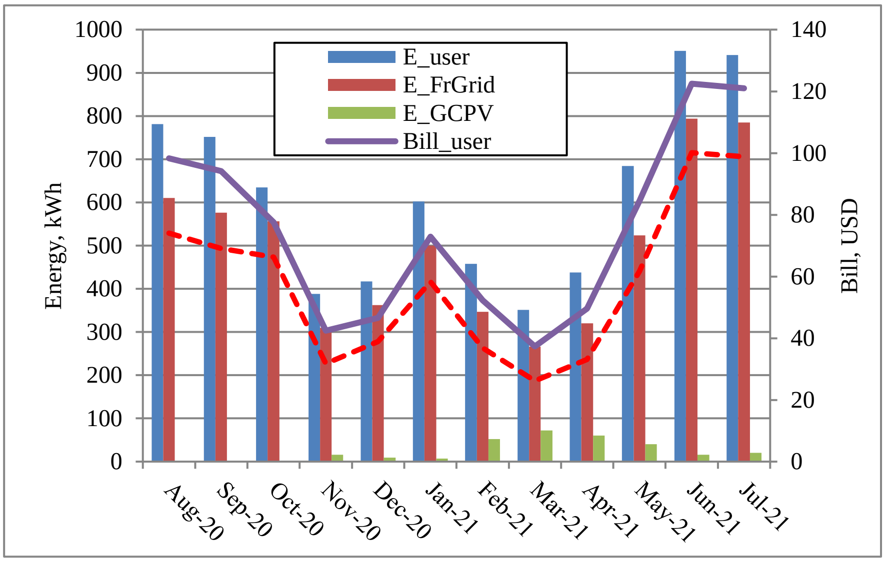

Fig. 5. Monthly energy and electricity bill.

Table 7. Energy output and saving cost of GCPV system over life cycle under FiT contract.

Year, n	E_out, kWh	CES_n, USD	$\sum_n \frac{CES_n}{(1+i)^n}$, USD	Annual cost, USD
0	0	0	0	907.2
1	1742	228.487	216.9867	30
2	1732	227.097	421.7984	30
3	1722	225.855	615.2376	30
4	1711	224.382	797.7425	30
5	1700	222.891	969.9098	30
6	1691	221.81	1132.619	30
7	1681	220.569	1286.273	30
8	1672	219.366	1431.398	30
9	1662	218.027	1568.378	30
10	1651	216.589	1697.604	30
11	1641	215.308	1819.601	30
12	1632	214.155	1934.837	30
13	1621	212.678	2043.518	30
14	1612	211.601	2146.206	30
15	1602	210.252	2243.104	30
16	1592	208.864	2334.518	30
17	1583	207.803	2420.889	30
18	1573	206.522	2502.407	30
19	1562	204.996	2579.251	30
20	1553	203.838	2651.814	30

Table 8. Comparative financial analysis of GCPV systems.

Location	PR, %	LCOE, USD/kWh	Investment rate, USD/kWp	PBP, Year	Ref.
Terengganu, Malaysia	65-71	0.042-0.05	1653.6	6.64- 5.79	[8]
Bandar Sunway, Malaysia	85.40	0.095	772.5	8	[13]
Hue, Vietnam	78.11	0.063	687	5	This study
Gia Lai, Vietnam	74.11	N/a	799.6	5.7-7.9	[28]
Daklak, Vietnam	N/a	N/a	850-1200	4-11	[29]
Thudaumot Vietnam	81.7	0.048	682.3	6.7	[30]
Nablus, Palestine	86.33	N/a	1269.5	4.33	[11]
Thailand	N/a	N/a	2100	6.1	[25]
Kupang, Indonesia	0.81	N/a	1641.3	8	[15]

Based on Equation (11) and annual energy-saving cost data from the GCPV system in Table 7, the estimated DPBP is 5 years for the GCPV system, which is only a quarter of the system's life, the duration of the contract. Table 8 presents a comparative financial analysis of the GCPV systems. The payback period of the studied GCPV system is relatively shorter than other GCPV systems in Vietnam and Malaysia, but higher for the Nablus project in Palestine, with a DPBP of 4.3 years [11]. In a study [11], the GCPV system has a higher investment rate, but the DPBP is low. This can be explained because the PR of the GCPV system in Nablus, Palestine, is 86.33%, and the rate of FiT for the PV system is relatively high at 0.18 USD/kWh. This is more than two times in Vietnam at the time of the research.

4.4 Environmental

The annual AC energy output from the studied GCPV system is assumed to have a degradation factor of 0.6% over the project's life. The output of the years is shown in Table 7. The total avoidable CO_2 emissions of a house with a 1.32 kWp GCPV system annually is 1.5 tons. In project life of 20 years, it is in the range of 28.5 tons, a significant number for a better environment.

5. CONCLUSION

A comprehensive assessment of a 1.32 kWp rooftop GCPV system was conducted by considering energy, financial, and environmental aspects in Central Vietnam, with its tropical monsoon climate under the FiT scheme. In general, the annual average final yield is 3.62 kWh/kWp/day, which corresponds to the total AC energy output of the studied GCPV system in the entire year of 1742 kWh. Low final yields detected in October, November, December, and January were caused by heavy rains from the northeast monsoon and cloudy days from October to January.

The energy performance analysis gives the PR, CUF, and AOSE of the studied GCPV system over the study period as 78.11%, 15.07%, and 12.89%, respectively. Comparing the energy efficiency of the studied GCPV system with other Southeast Asia shows that the Central region of Vietnam is very suitable for developing and installing GCPV systems.

In addition, the financial and environmental analysis of the system has shown a relatively low LCOE of about 0.063 USD/kWh, a DPBP of 5 years, and an annual avoidable carbon dioxide of 1.5 tCO_2. From a financial perspective, the GCPV system under FiT schemes is considered profitable. The obtained data can be used as a guide for the application of GCPV systems in other locations with similar climates, as well as to assist the government in developing a more appropriate FiT rate for the real-time GCPV system.

ACKNOWLEDGEMENT

This work was supported by a grant (No. DHH2021-18-01) from Hue University.

ABBREVIATIONS

AOSE	Annual overall system efficiency
CUF	Capacity utilization factor
DPBP	Discounted payback period
FiT	Feed-in-tariff
GCPV	Grid-connected photovoltaic
LCOE	Levelized cost of electricity
MPPT	Maximum power point tracking
PV	Photovoltaic
PR	Performance ratio
STC	Standard test condition

NOMENCLATURE

A_{pv}	Total area of PV modules, m^2
$AnnualCost_n$	Annual cost for n^{th} year, USD
B_{j_FrGrid}	Monthly electricity bill to pay for Power Company with using GCPVS, USD
B_{j_user}	Monthly electricity bill with non-using GCPV system
$B_{PV\_GC\,j}$	Monthly benefit from selling PV energy injected into grid, USD
C_I	Initial investment cost, USD
$C_{o\&m}$	Annual operation and maintenance cost
CES_n	Annual energy-saving cost from GCPV system or the net cash flow in time period *n*
CES_j	Monthly energy-saving cost from GCPV system, USD

CUF	Capacity utilization factor, %
D	Degradation factor of GCPV system, %;
DPBP	Discounted payback period, year
dr	Discount rate, %
E_{DC}	DC energy output, kWh
E_{out}	AC energy output, kWh
$E_{out,\,n}$	Annual AC energy output from GCPV system of n^{th} year, kWh
$E_{out,1}$	Annual AC energy output from GCPV system of first year, kWh
E_user	Total energy consumption, kWh
E_PrGrid	Energy consumption from the grid, kWh.
E_PrPV	Energy consumption from GCPV system, kWh
E_GCPV	PV energy injected into grid, kWh
$G_{i,ref}$	Reference irradiance (= 1 kW/m^2)
$G_{t,k}$	Total in-plane solar irradiance, kW/m^2
H_t	Total in-plane solar irradiation, kWh/m^2
i	Interest rate, %
L_s	System losses, kWh/kW
L_c	Array capture losses, kWh/kW
LCOE	Levelized cost of electricity, USD/kWh
N	Payment period, year
$P_{out,k}$	AC power output of the system, kW
P_0	Peak power of the installed PV system, kWp
$P_{DC,k}$	DC power output of the system, kW
PR	Performance ratio, %
T	Calculation period, h
Y_a	Array yield
Y_f	Final yield, kWh/kWp
Y_r	Reference yield kWh/kW
τ_k	Sampling time, h
η	Annual overall system efficiency, %
$(CO_2)a$	Amount of carbon dioxide, tons

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