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Research Article

Long-term performance of roof-top GCPV systems in central Viet Nam

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Abstract. In pursuit of the objective of achieving "net zero emissions," many countries worldwide, including Viet Nam, have prioritized the utilization of photovoltaic technology for energy conversion. Specifically, the implementation of roof-top grid-connected photovoltaic systems (GCPV) has emerged as a highly efficient solution in urban areas. These systems offer several advantages, such as minimizing land usage, lowering monthly electricity expenses, preventing building heat, generating income for households, and reducing transmission and distribution costs. This article focuses on a comprehensive long-term analysis conducted on 51 roof-top GCPV systems in the tropical monsoon climate of Hue City, Viet Nam, during the period from 2019 to 2023. The analysis findings reveal that roof-top GCPV systems with a capacity of 3-6 kW are well-suited for households in the central region of Viet Nam, characterized by a tropical monsoon climate. These systems exhibit an average sizing ratio of 1.03. The annual average daily final yield peaked at 3.28 kWh/kWp/day in 2021 and reached its lowest point at 2.97 kWh/kWp/day in 2022. Notably, the typical slope of the yield gradually increases with the installed capacity and the studied year. Furthermore, the monthly average daily final yield demonstrates a seasonal pattern, with higher yields observed from March to August and lower yields from September to January, aligning with the climate of the study area. As the years progress, the capacity factor and performance ratio of roof-top GCPV systems display a declining trend. Throughout the entire study period, these systems successfully mitigated 664 metric tons of CO2 emissions. The evaluation of long-term yield data offers valuable insights for photovoltaic installers, operators, and system owners, aiding in system maintenance and optimizing load utilization across different time periods. Long-term performance can be used by energy managers and owners of roof-top GCPV systems to identify supply shortfalls and initiate countermeasures.

Keywords: Long-term performance, roof-top, photovoltaic, tropical monsoon

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1. Introduction

The photovoltaic (PV) technology is a central pillar for the global energy transition to achieve climate change mitigation goals and work towards as a net zero emission target (Das et al., 2023; Hafner et al., 2021). In recent years, the PV systems of different sizes and capacities have installed globally. By the conclusion of 2021, the cumulative global installed capacity of solar PV is estimated to reach 866 GWp. It is further projected to increase by approximately 189 GWp by 2022, resulting in a total installed capacity of solar power reaching 1055 GWp. In the context of Viet Nam, the total installed solar capacity is anticipated to reach 18.5 GWp in 2022, marking a rise from 16.7 GWp in 2021 (IRENA, 2023).

According to calculations by many groups, including the World Bank Group (WBG), Viet Nam is considered to have the high solar energy potential with many hours of sunshine per year due to its proximity to the equator results in a substantial number of sunshine hours per year (Riva Sanseverino et al., 2020). The development of solar power in Viet Nam began in 2015 with the implementation of Decision 2068/QD-TTg, which approved the Renewable Energy Development Strategy of Viet Nam until 2030 with a vision towards 2050 (Government of Vietnam, 2015). Subsequently, the solar power sector experienced a surge in growth following the introduction of feed-in tariffs (FiT). The initial FiT, known as FiT1, was set at 9.35 US cents per kilowatt-hour (Decision 11/2017/QD-TTg (Government of Vietnam, 2017)). This was followed by FiT2, which offered a tariff of 8.38 US cents per kilowatt-hour (Decision 13/2020/QD-TTg (Government of Vietnam, 2020), further stimulating the expansion of solar power systems in the country.

Roof-top grid-connected PV (GCPV) systems exhibit remarkable efficiency in urban areas due to several advantages: they occupy no land, contribute to reduced monthly electricity bills, mitigate building heat, generate income for households, and minimize transmission and distribution costs (Awan *et al.,* 2020; Duman, Güler, 2020). The combined impact of two mechanisms, FiT1 and FiT2, has resulted in a rapid increase in the installed capacity of roof-top solar power in Viet Nam. At the culmination of FiT2, the total installed capacity reached 9,296 MWp, which has remained stable at 9,580 MWp to date (Ky *et al.*, 2021; Ngo, Do, 2022).

Figure 1 illustrates the total system and installed capacity of the roof-top GCPV systems in Viet Nam from 2019 to the present (Ngo, Do, 2022). Recently, the Vietnamese government issued Decision No. 500/QD-TTg, approved by the Prime

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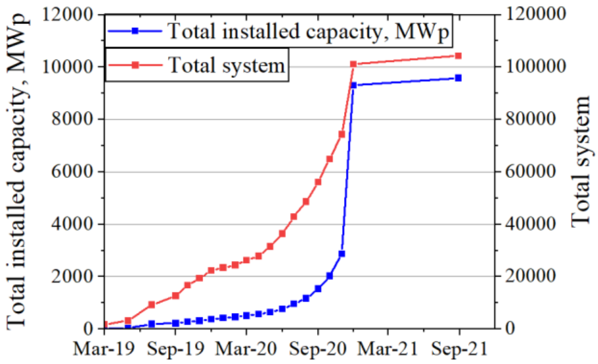

Fig. 1. Total installed capacity of roof-top GCPV system.

Minister, which outlines the national electricity development plan for the period of 2021-2030, with a long-term vision to 2050 (referred to as Power Plan 8) (Ha-Duong, 2023). Notably, this decision called "Power Plan 8" places significant emphasis on the robust development of renewable energy sources for electricity generation. By 2030, the renewable energy is projected to contribute approximately 30.9% to 39.2% of the total power supply. Furthermore, Viet Nam aims to achieve a target of 50% of office buildings and 50% of residential houses utilizing self-sufficient roof-top solar power for on-site consumption, rather than selling electricity back to the national grid, by 2030 (Ha-Duong, 2023).

Many researchers have presented comprehensive analyses and evaluations of PV systems in different areas. These include a 1.32 kWp roof-top GCPV system for residential buildings in Central Vietnam (Ngo *et al.*, 2022); a 41 kWp GCPV system at the medical faculty building in An-Najah National University, Nablus, Palestine (Ibrik, 2020); a 7.8 kWp GCPV system at a residential house in Malaysia (Anang *et al.*, 2021); and a 232.5 kWp GCPV system at Monash University, Malaysia (Saleheen et al., 2021); Additionally, studies have examined an 8.36 kWp roof-top solar power system in a family home in Thu Dau Mot City, Vietnam (Nguyen, Van, 2021); the 5 MW Kupang solar power plant in Indonesia (Nugroho, Sudiarto, 2021); nine PV installations of prosumers in South-Eastern Poland (Gulkowski, 2022); and 50 roof-top GCPV systems with 5896 kWp across two typical climate zones in Vietnam (Ngo, Do, 2022); Furthermore, assessments have been conducted on over 1564 PV systems in France in 2014 (Gromaire, te Heesen, 2015); as well as over 10,000 PV systems in France and Belgium in 2010 (Leloux *et al.*, 2011). It is important to note that a limitation of these assessments is the relatively short analysis period, typically spanning only one year of study.

Several research groups have conducted systematic analyses, focusing on the long-term evaluation and performance of PV systems. These studies examine the performance ratio and final yield of these systems using comprehensive data. Noteworthy assessments have been conducted in various countries, including a study of PV systems in the challenging environment of Qatar over a two-year period (Touati et al., 2017); an analysis of PV systems in Germany from 2014 to 2016 (H te Heesen *et al.*, 2017); an examination of 466 PV systems in the Netherlands in 2014, 2015, and 2016 (Tsafarakis *et al.*, 2017), a study of over 23,000 roof-top PV systems in Germany spanning seven years from 2012 to 2018 (Henrik te Heesen *et al.,* 2019); an assessment of six different PV systems in the Unit ed Kingdom and Australia over a decade from 2008 to 2017 (Dhimish, Alrashidi, 2020); and an analysis of 8,400 PV systems in Europe from 2010 to 2016 (Lindig *et al.*, 2021). These studies

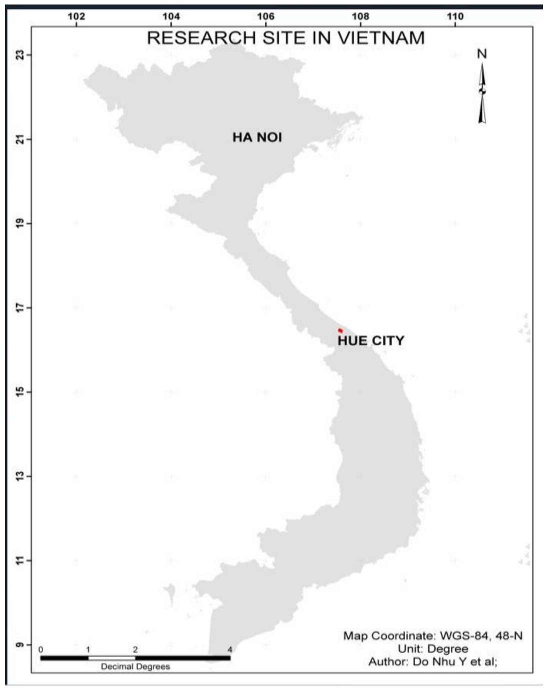

Fig. 2. The location of Hue city - Research site in Vietnam.

primarily focus on regions in Europe where connectivity and monitoring systems are well-developed. However, it is evident that there is a lack of long-term studies in other regions and countries, such as Viet Nam.

Hue City, located in central Vietnam, experiences a tropical monsoon climate. The location of Hue city is shown in Figure 2. As per the statistics provided by Thua Thien Hue Electricity Company, there are currently 438 operational roof-top solar power systems with capacities under 100 kW in the city. These systems have a combined installed capacity of 4,455.05 kWp as of January 4, 2021 (Thua Thien Hue Electricity Company, 2021). This article focuses on conducting a long-term analysis of the performance of 51 roof-top GCPV systems in Hue City from 2019 to 2023 with a total installed capacity of 300 kWp (accounting for 6.7% of the above capacity). This is the first time that long-term yield data from dozens of systems in Viet Nam has been analyzed. The primary objective of this study is to assess the distribution of yield over time and explore the variations in monthly and annual yield data. The article proceeds by presenting case studies in Section 2, followed by the presentation of results from the analysis and evaluation of the data in Section 3. Finally, the conclusions drawn from the study are presented in Section 4.

2. Case study

2.1 Overwiew

Viet Nam has an area stretching across the Northern Hemisphere, divided into 3 regions: North, Central, and South with distinctly different climates from North to South (Ngo, Do, 2022). Central Viet Nam was selected as the study area, and Hue City - the center of Thua Thien-Hue province was selected as the representative site. The climate of Hue city is considered as a tropical monsoon climate, where there is a cold wet rainy season and hot dry summer, with a rainy season from September to January and a dry season from March to August.

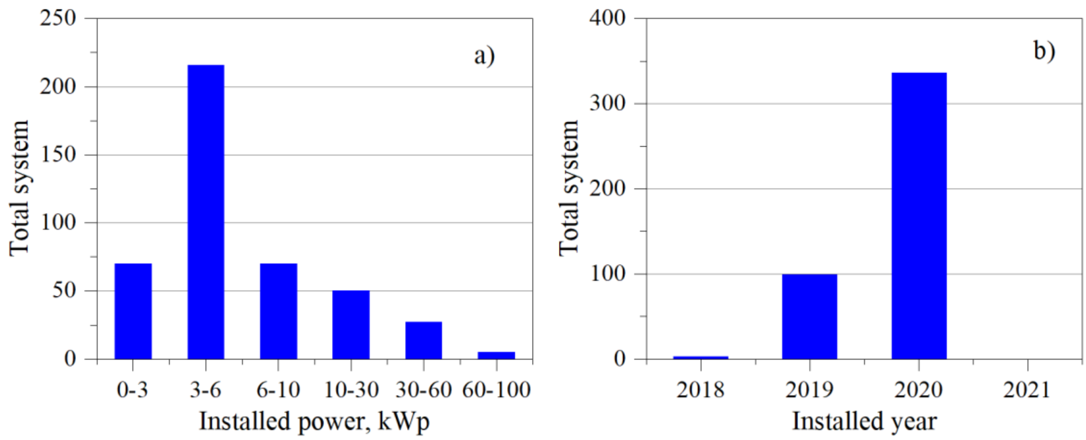

Fig. 3. Histogram of installed systems with capacity less than 100kWp by capacity (a) and year (b).

The average annual temperature is about 25°C and the annual rainfall is about 3,000 mm (Dang *et al.*, 2016).

Figure 3 shows a histogram presenting the distribution of installed systems in Thua Thien-Hue province. It can be seen tha t the most prevalent systems have capacities ranging from 3 kWp to 6 kWp, with a concentrated installation period in 2020. This indicates that systems within this capacity range are well-suited for households with electricity consumption in the city. Furthermore, it is worth noting that after 2020, the government's FiT2 program, which facilitated the installation of these systems, has concluded. Consequently, no further installations of roof-top systems under the FiT2 program will take place.

The study focuses on analyzing long-term data on the performance of 51 roof-top GCPV systems (accounting for 11.6% of the total system) in Hue city from June 2019 to June 2023 with total installed capacity of 300 kWp (accounting for 6.7% of installed capacity). The yield data from GCPV systems is measured directly from the inverter's data logger, which is uploaded to the server platform for storage on the home page of the solarman monitoring system.

To facilitate the evaluation process, various data configurations of each roof-top GCPV system are considered. These configurations include information such as the grid connection time, installation location, PV module orientation (s) and inclination (s), capacity, and daily yield data. Additionally, irradiance values at the installation sites are obtained from Solcast, an open-source platform dedicated to providing accurate solar radiation data (Solcast). Effects such as shading are not taken into account for this particular publication since the focus is primarily on analyzing and visualizing the yield and performance of the PV systems.

2.2 Performance of roof-top GCPV system

The performance of roof-top GCPV system is usually considered through final yield, reference yield and performance ratio.

The final yield is the AC power output of the roof-top GCPV system divided by the maximum DC power of the GCPV system installed under standard test conditions (solar irradiance of 1 kW/m² and module temperature of 25°C) (Cuong *et al.*, 2021). In this study, the final yield and average daily final yield are computed as follows:

$$Y_f = \frac{E_{out}}{P_0} \tag{1}$$

$$\bar{Y}_f = \frac{E_{out}}{P_0 . n} \tag{2}$$

where, E_{out} is the AC power output (kWh), P_0 is the peak DC power of the installed PV system (kWp); n is the number of days (day), Y_f is the final yield (kWh/kWp), $\bar{Y}_f$ is the average daily final yield (kWh/kWp/day).

The reference yield (or peak sunshine hours) is the total solar irradiance in the plane divided by the reference irradiance. In this research, the reference yield and average daily reference yield are defined as:

$$Y_r = \frac{H_t}{G_{i,ref}} \tag{3}$$

$$\bar{Y}_r = \frac{H_t}{G_{i,ref} . n} \tag{4}$$

where H_t is the total in-plane solar irradiance (kWh/m²), $G_{i,ref}$ is the reference irradiance (1 kW/m²), n is the number of days (day), Y_r is the reference yield (kWh/kW) and $\bar{Y}_r$ is the average daily reference yield (kWh/kW/day).

The performance of a roof-top GCPV system is influenced by several factors, including radiation intensity, temperature, cloudiness, and the quality of key components such as PV panels and inverters. Additionally, factors like shading and dust accumulation can also impact the overall system performance (Ngo, Do, 2022; Ngo *et al.*, 2020). The performance ratio (PR) serves as a metric to assess the efficiency of a GCPV system. It is calculated by considering the electrical energy generated in relation to the amount of irradiance received and the DC array power rating of the system. The PR is typically expressed as an annual value and is calculated following the guidelines outlined by the International Electrotechnical Commission (IEC, 2016):

$$PR = \frac{Y_f}{Y_r} . 100 \tag{5}$$

where, PR is the performance ratio (%), Y_f is the final yield (kWh/kWp), Y_r is the reference yield (kWh/kW).

2.3 Capacity factor

The power factor is a widely used metric for power plants, including PV systems, that enables comparisons with other

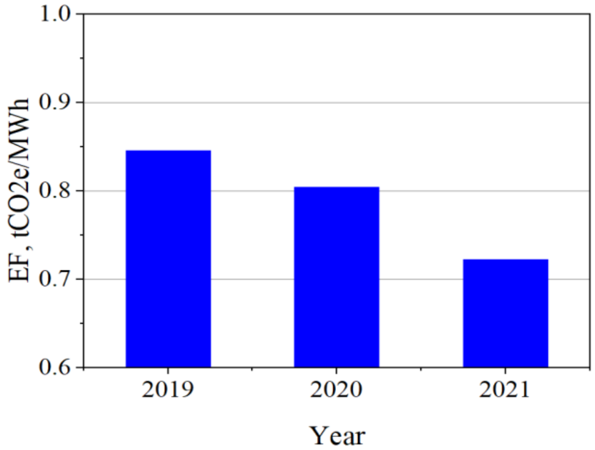

Fig. 4. Statistical data on CO2 emission factor of Vietnam's power grid.

types of power plants. It is calculated by considering the factory AC rating, which is determined as the lower value between the array DC power rating and the total inverter rating in the system, as defined in IEC 61724-1 (IEC, 2017). This metric measures the energy fraction of electricity generated by the PV system in comparison to what the plant would generate if it operated at its rated AC power continuously.

$$CF = \frac{E_{out}^{annual}}{P_{0,AC}.\,24.\,n^{\text{annual}}}.100 \qquad (6)$$

where CF is the capacity factor (%), E_{out}^{annual} is the AC energy output in year (kWh), $P_{0,AC}$ is the AC rating power (AC power of inverter) (kW), n^{annual} is the number of days of year, typically 365 or 366 (day).

2.4 Impacts on Environment

The PV energy is well known as a clean and environmentally friendly power source, with a significantly lower impact on air quality and climate change compared to traditional forms of power generation. In contrast to fossil fuel-based systems, the PV systems do not emit carbon dioxide, methane, sulfur oxides, or nitrogen oxides during their operation. As a result, their contribution to air pollution and global warming is minimal (Olabi and Abdelkareem, 2022). To evaluate the environmental performance of a roof-top GCPV system, the CO_2 factor is employed. This factor quantifies the amount of carbon dioxide emissions reduced through the utilization of solar energy. The calculation method for the CO2 factor is as follows (Haffaf *et al.*, 2021; Ngo *et al.*, 2022):

$$(CO2) = E_{out}^{annual}\frac{EFgrid}{1000} \qquad (6)$$

where, $(CO2)$ is the amount of carbon dioxide emission reduction (t CO2), E_{out}^{annual} is the AC energy output in year (kWh), $EFgrid$ is the carbon dioxide emission factor of electricity grid in Viet Nam, where GCPV systems are installed (tCO2e/MWh).

The annual carbon dioxide emission factor for the Vietnamese power grid is released on a yearly basis by the Department of Climate Change, under the Ministry of Natural Resources and Environment of Viet Nam. These emission factors are documented and presented in Figure 4 (Department of climate change Vietnam, 2023). For the calculations pertaining to 2022 and 2023, the values are assumed to be equal to the most recent available year.

3. Results and discussion

3.1 Data quality

The data quality of the analyzed roof-top GCPV systems is pointed out in Figure 5. Each data point represents the final annual output of a GCPV system, alongside the number of days in which data transmission occurred. Additionally, a histogram is included to display the distribution of days with available data. It is evident that GCPV systems with a total of over 350 days of data per year exhibit the highest frequency. Notably, there is a prominent peak in the range of 150-200 days, primarily concentrated in the 2023 data.

A histogram of the studied GCPV system by capacity and year of installation is presented in Figure 6. The total number of studied systems installed was mainly concentrated in 2020, with 48 GCPV systems, which can be explained by the government's FiT2 program which ended at the end of 2020. The studied roof-top GCPV system has a main capacity of less than 10kWp, which proves that this capacity range is suitable for consumers in the tropical monsoon climate in central Viet Nam. These results are similar to those of the European study (Henrik te Heesen *et al.*, 2019).

Due to the relatively low cost of PV modules, installing a PV array with a rated DC power (measured under Standard Test Conditions) greater than the rated AC output power of the inverter can be a valuable tool for system designers looking to provide the maximum amount of energy at the lowest possible specific cost. By that way, the total energy output can be increased under weak solar radiation conditions (Sangwongwanich *et al.*, 2018). Figure 7 shows the sizing ratio (ratio of rated DC power of PV array to AC rating power of inverter) according to AC rating power. It can be seen that the studied GCPV systems have sizing ratio in the range from 1 to 1.2, the sizing ratio is high for systems with AC rating power less than 10. The average sizing ratio achieved a value of 1.03, indicating an optimal ratio that allows for increased power output at a relatively low cost.

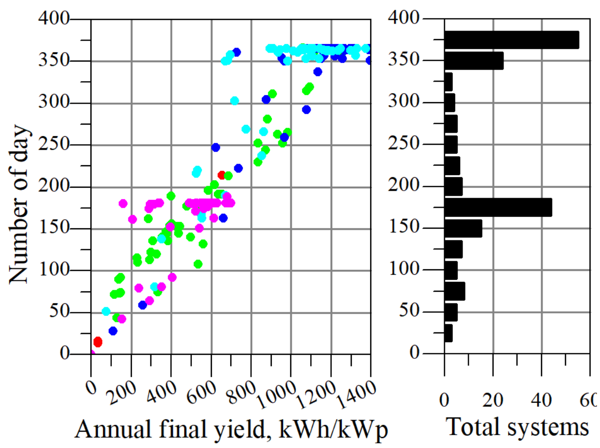

Fig. 5. Data quality of the studied GCPV systems

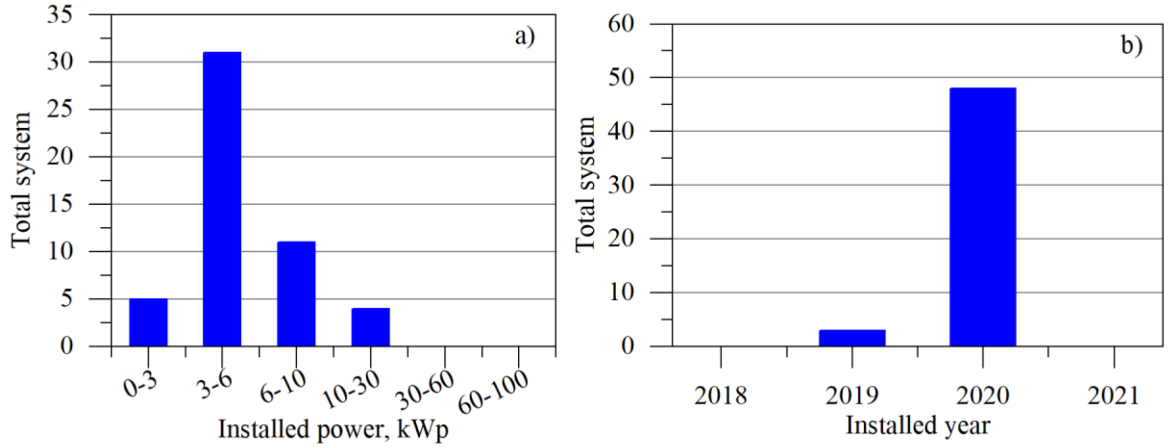

Fig. 6. Histogram of studied system GCPV by capacity (a) and installed year (b).

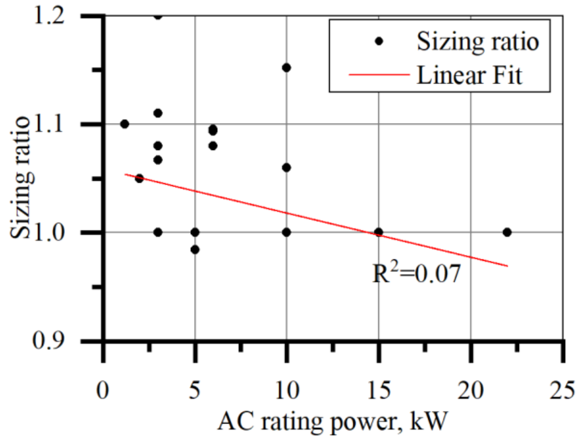

Fig. 7. Sizing ratio according to AC rating power.

3.2 Weather data for the studied period

The global horizontal irradiance boxplot of Hue city during the study period is indicated in Figure 8. The monthly minimum, maximum and average air temperatures are presented in Figure 9. These graphs clearly show that in Hue city, from about March to September of the year, the temperature and the large global horizontal irradiance represent the hot dry season. In the remaining months, the low temperature represents the rainy season, and the Global horizontal irradiance decreases completely. The global horizontal irradiance is highest at 7.50 kWh/m^2/day in May 2021, and the lowest is 0.26 kWh/m^2/day

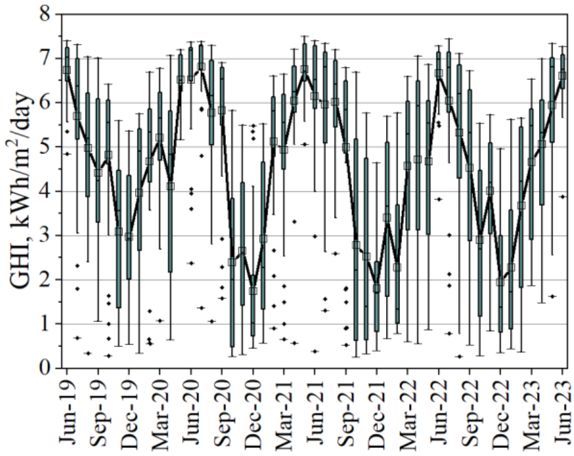

Fig. 8. Global horizontal irradiance Box-plot of Hue city during the studied period.

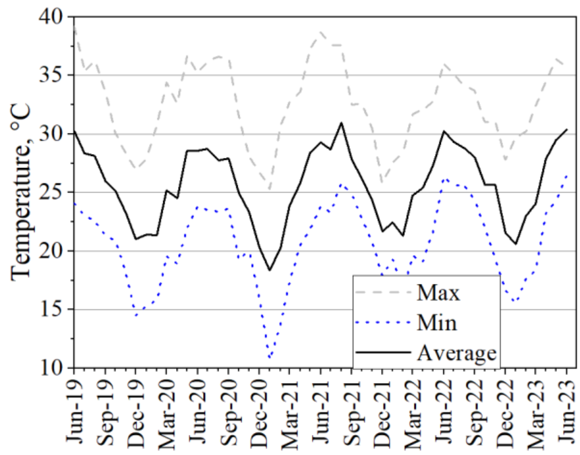

Fig. 9. Monthly air temperature during the studied period.

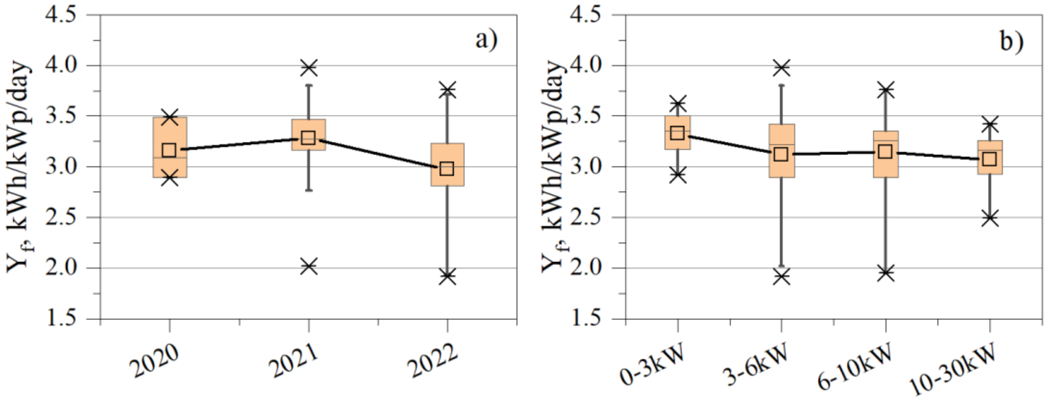

Fig. 10. Annual average daily final yield according to survey year (a) and installed capacity (b).

in October 2021. The highest temperature is 39.2 °C in June 2019, and the lowest temperature is 10.7 °C in January 2021.

3.3 Long-term annual final yield analysis

The distribution of average daily final yield of roof-top GCPV systems in central Viet Nam by survey year and installed capacity is shown in Figure 10. In this section, the yield data of all GCPV systems with more than 350 days of data per year is used to analyse.

In 2020, it can be seen as the first year of the GCPV system with more than 350 data to evaluate. During that year, the GCPV system with a capacity of 3 kW achieved the highest annual average daily final yield, reaching 3.49 kWh/kWp/day. However, in 2022, there were notable variations in the annual average daily final yield among different systems.

The analysis clearly demonstrates that, on average, the annual average daily final yield for all GCPV systems reached its highest point in 2021 at 3.28 kWh/kWp/day, while it reached its lowest in 2022 at 2.97 kWh/kWp/day. When considering the distribution based on capacity, GCPV systems with a capacity less than 3 kW exhibited the highest average annual average daily final yield, with a value of 3.32 kWh/kWp/day, whereas systems with capacities between 3-6 kW had the lowest average yield of 3.11 kWh/kWp/day.

The analysis clearly demonstrates that, on average, the annual average daily final yield for all GCPV systems reached its highest point in 2021 at 3.28 kWh/kWp/day, while it reached its lowest in 2022 at 2.97 kWh/kWp/day. When considering the distribution based on capacity, GCPV systems with a capacity less than 3 kW exhibited the highest average annual average daily final yield, with a value of 3.32 kWh/kWp/day, whereas systems with capacities between 3-6 kW had the lowest average yield of 3.11 kWh/kWp/day.

Overall, it is noteworthy that the typical trend observed in the analysis is an increase in the average daily final yield with increasing installed capacity and survey year. However, this yield decrease is attributed to factors such as inadequate system maintenance and insufficient cleaning of PV panels. These factors can lead to durability issues in the PV panels, resulting in the generation of hotspots and subsequently reducing the overall yield. This aspect is extensively discussed in the study (Dhimish and Badran, 2023).

3.4 Seasonal yield analysis

The seasonal yield data provide more precise insight into the variation of energy production during the study period relative to the tropical monsoon climate in central Viet Nam. In this section the yield data of all GCPV systems with more than 28

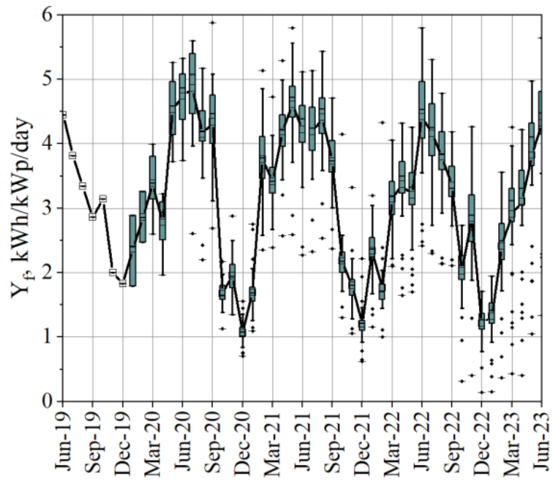

Fig. 11. Monthly average daily final yield.

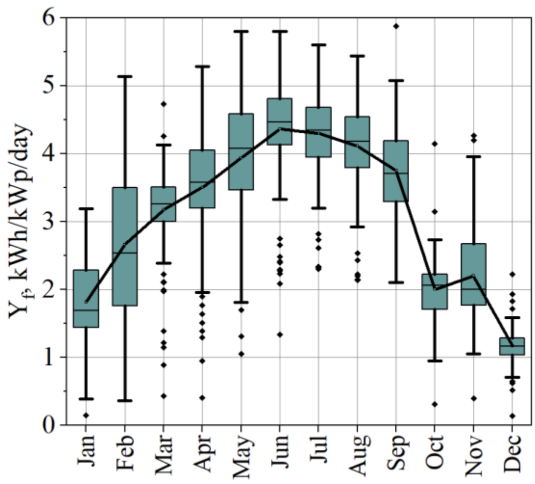

Fig. 12. Monthly average daily final yield by month of the year.

days of data (including the days with the last recorded zero yield) per month are used for analysis.

In Figure 11, the monthly average daily final yield is depicted over the study period. The highest recorded value of monthly average daily final yield was 5.88 kWh/kWp/day in September 2020, while the lowest was 0.14 kWh/kWp/day in December 2022. On average, considering all GCPV systems, the monthly average daily final yield reached its peak at 4.86 kWh/kWp/day in July 2020, and it dropped to the lowest point at 1.07 kWh/kWp/day in December 2020.

To further analyze the variation of GCPV systems according to climatic season characteristics, values for the same month are aggregated. Figure 12 shows monthly average daily final yield by month of the year. It can be seen that the monthly average daily final yield gradually increases from January to June, and peaks in June, then decreases gradually from June to December. On average for all GCPV systems, the monthly average daily final yield hits a high of 3.17 - 4.36 kWh/kWp/day from March to August, and a low of 1.17 - 2.66 kWh/kWp/day from September to January. The typical seasonal yield behavior consistent with the tropical monsoon climate in central Viet Nam is presented in section 2.

3.5 Capacity factor analysis

Figure 13 illustrates the capacity factor of the GCPV systems under study. The capacity factor ranges from 8.0% to 16.6%, and its average value shows a declining trend over the years. The average capacity factor in 2020, 2021, and 2022 is recorded as 13.95%, 14.11%, and 12.79%, respectively. These values are lower than the capacity factor values typically observed in tropical climates, which range from 14.69% to 17.51% with a mean of 15.70% (Farhoodnea *et al.*, 2015; Saleheen *et al.*, 2021).

3.6 Performance ratio analysis

The PR analysis is conducted on 02 roof-top GCPV systems installed in 2019 and 2020. In Figure 14, the average daily final yield is plotted against the average daily reference yield for each operating time of the rooftop GCPV systems. The data points on the PR curve represent a PR value of 100%, indicating an ideal GCPV system where no electrical energy is lost. The closer a data point lies below the PR=100 line, the lower the PR of the corresponding GCPV system. On the other hand, data points above the PR=100 line indicate cases of system misconfiguration or errors. In Figure 14 (a), the data points of the GCPV system installed in 2020 are found adjacent to the PR=78 line. In Figure 14 (b), the data points of the GCPV system installed in 2019 are adjacent to the PR=65 line.

Figure 15 depicts the PRs of the two systems above. The data points correspond to a year with more than 350 data days. The PR1-PR of the GCPV system installed in 2020, which has an approximate value of 78%, which tends to decrease year by year. The PR2-PR of the GCPV system installed in 2019, which achieved its target of 65% in 2021 and also exhibited a decreasing trend over time.

These results align with a study conducted on the Annual Performance Ratio of a PV system in Germany spanning 9 years. The study revealed a significant decline in PR over time, with a possible explanation being the degradation effect on PV cells (Nordmann *et al.*, 2014).

Comparison of GCPV system from different regions is presented in Table 1. It is clear that the annual average daily final yield ranges from 2.52 to 4.86 kWh/kWp/day, while the performance ratio ranges from 57.83 to 90 %. depending on year and study location. Rooftop GCPV systems in Hue City are at an average level.

Table 1
Comparison of GCPV system from different regions.

Location	Number of systems	Survey time	Annual average daily final yield (kWh/kWp/day)	PR (%)	CF (%)	Reference
Hue, Vietnam	51	2020 2021 2022	3.16 3.28 2.97	62.26 65.06 / 78.36 57.83 / 78.20	13.95 14.11 12.79	This study
Terengganu, Malaysia	1	2018-2019	3.30-3.78	65-71	13.71-15.72	(Anang *et al.*, 2021)
Kupang, Indonesia	1	3/2016 to 12/2019	3.02-3.95	70-90	10.73-16.70	(Nugroho, Sudiarto, 2021)
Europe	8,400	2010 to 2016	2.62	76.7	N/A	(Lindig *et al.*, 2021)
Netherlands	466	2014 2015 2016	4.73 4.86 3.56	75.0 ± 9.5, 75.4 ± 7.9, 74.6 ± 10.2	N/A	(Tsafarakis *et al.*, 2017)
Germany	23,000	2012 2013 2014 2015 2016 2017 2018	2.68 ± 0.41 2.47 ± 0.34 2.62 ± 0.38 2.70 ± 0.39 2.56 ± 0.37 2.57 ± 0.40 2.80 ± 0.41	72-78	N/A	(Henrik te Heesen *et al.*, 2019);
Australia	25 (DC power of 1-10kWp)	2008-2012	4.60 ± 0.61	79 ± 0.1	N/A	(Nordmann *et al.*, 2014)
Italy/North	17 (DC power of 1-10kWp)	2008-2012	3.10 ± 0.12	74.1 ± 0.01	N/A	(Nordmann *et al.*, 2014)

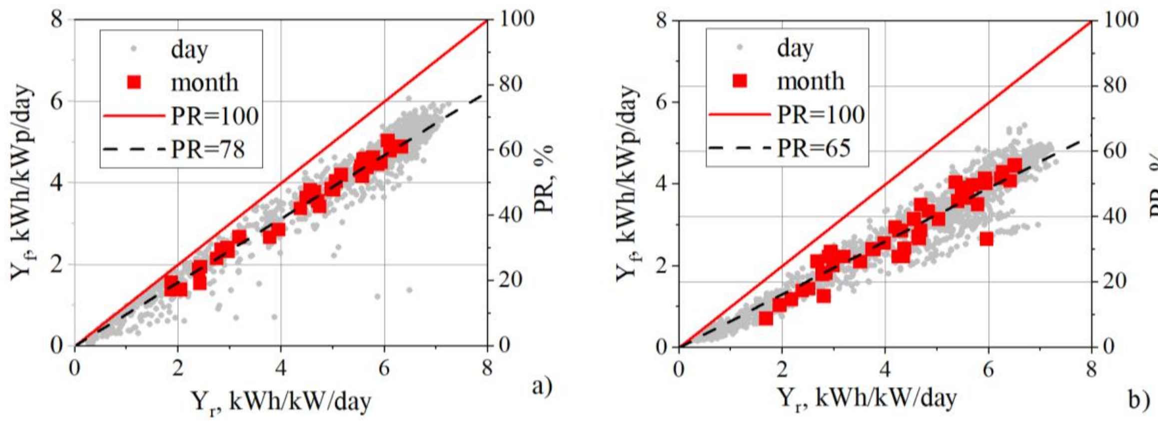

Fig. 14. Average daily final yield is plotted against the average daily reference yield of the roof-top GCPV system. a) 2020 installations; b) 2019 installation system.

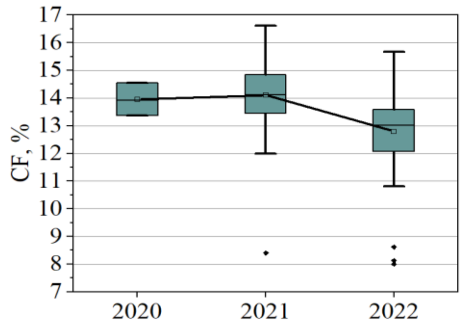

Fig. 13. Capacity factor of studied GCPV systems.

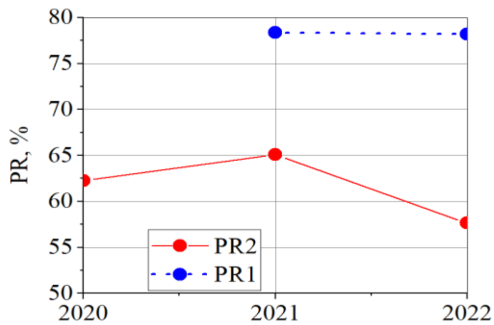

Fig. 15. Performance ratio of 2 systems by year.

3.7 Environmental analysis

In Table 2, the carbon dioxide emission reduction amounts are showcased. This section includes the output data from the rooftop GCPV systems collected throughout the study. The highest annual yield of all rooftop GCPV systems occurred in 2021, resulting in a reduction of 238 t CO_2. Throughout the entire study period, the rooftop GCPV systems collectively contributed to a total reduction of 664 t CO_2. This is a substantial achievement in terms of environmental protection.

Table 2
Amount of carbon dioxide emission reduction.

Year	Annual yield, kWh	Amount of carbon dioxide emission reduction, t CO2
2019	2393	2
2020	142483	115
2021	329623	238
2022	285635	206
2023	142760	103
Sum	902893	664

4. Conclusions

This paper provides a long-term analysis of roof-top GCPV systems in the tropical monsoon region of central Viet Nam, assessing the influence of climate on the performance of roof-top GCPV systems. The analysis utilizes daily yield data collected from 51 roof-top GCPV systems, spanning the period from 2019 to 2023, while considering the configuration of each system. The data has been aggregated over time and capacity to facilitate analysis. The primary focus of the analysis is on the final yield of the roof-top GCPV systems.

The analysis and evaluation results have shown that the studied roof-top GCPV systems with a capacity of 3-6 kW are suitable for households in the tropical monsoon climate in central Viet Nam. The studied roof-top GCPV systems have a sizing ratio in the range of 1 to 1.2. On average, these systems achieve a sizing ratio of 1.03, which is considered an appropriate ratio for enhancing power output while keeping costs low.

In addition, the average daily final yield in 2021 is the highest with 3.28 kWh/kWp/day, in 2022 the lowest with 2.97 kWh/kWp/day. Analyzing the distribution based on capacity, roof-top GCPV systems with a capacity of less than 3 kW exhibited the highest average daily final yield at 3.32 kWh/kWp/day. Notably, there is a noticeable trend of the average daily final yield gradually increasing with the installed capacity and survey year.

The monthly average daily final yield exhibits a gradual increase from January to June, reaching its peak in June. Subsequently, it gradually decreases from June to December. The monthly average daily final yield reaches a high of 3.17-4.36 from March to August, and a low of 1.17-2.66 from September to January. Typical seasonal yield behavior consistent with the tropical monsoon climate of central Viet Nam.

Furthermore, the capacity factor of the studied roof-top GCPV systems ranges from 8.0% to 16.6%, its mean value tends to decrease year by year. The PR of the roof-top GCPV system installed in 2020 is approximately 78%. The PR of the roof-top GCPV system installed in 2019 reached its highest point at 65% in 2021. However, The PR values tend to decrease year by year. Throughout the entire study period, the examined roof-top GCPV systems collectively contributed to a reduction of 664 t CO_2. This is a noteworthy achievement in terms of environmental protection.

Evaluation of long-term performance will facilitate the comparison of GCPV systems that differ in design, technology, or geographical location. Similar studies need to be performed for different locations, and further studies are needed to identify faulty GCPV system components.

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