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Performance Analysis and Comparative Study of a 467.2 kWp Grid-Interactive SPV System: A Case Study

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Abstract: This paper demonstrates the investigation of the acquired outcomes from consistent information observing a 467.2 kWp solar photovoltaic (SPV) framework commissioned on the roofs of three separate high-rise buildings, which are located at the location of 26.9585° N and 80.9992° E. Onside real-time performance for this system was investigated for three years, 2018–2020; this system contains 1460 SPV panels of 320 Wp each, having 20 PV panels per string, 09 DC/AC power conditioning units (PCU), and a SCADA (supervisory control and data acquisition) system for monitoring the other necessary parts of a grid-interactive SPV system. The outcomes of the different buildings are compared with each other to analyze the power output at the same input conditions. Hardware components of the plants with approximately the same ratings (P_2 ~ 108.8 kWp + P_3 ~ 128 kWp) are compared (with P_1 ~ 230.4 kWp). Simulation modeling of the year 2020 in PVsyst tool for generated energy, Performance Ratio (PR), and Capacity Utilization Factor (CUF) are carried out additionally and compared with the installed rooftop grid-interactive SPV system of 467.2 kWp (~P_1 + P_2 + P_3) at the site. Numerous performance parameters such as array efficiency, inverter efficiency, system efficiency, Performance Ratio (PR), and Capacity Utilization Factor (CUF) of the plant are evaluated and compared with already installed systems in different regions of the world. These points demonstrate great feedback to framework architects, workers, designers, and energy suppliers regarding the genuine limit and plausibility of the framework they can offer to clients. Moreover, one of the environmental benefits of the SPV plant is that the 467.2 kWp PV framework reduces the tremendous measure of CO_2, SO_2, and NO_X that is discharged into the air.

Keywords: grid-interactive SPV plant; Capacity Utilization Factor (CUF); Performance Ratio (PR); system performance; PVsyst

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Citation: Minai, A.F.; Usmani, T.; Alotaibi, M.A.; Malik, H.; Nassar, M.E. Performance Analysis and Comparative Study of a 467.2 kWp Grid-Interactive SPV System: A Case Study. *Energies* **2022**, *15*, 1107. https://doi.org/10.3390/en15031107

Academic Editor: Jesús Polo

Received: 2 January 2022
Accepted: 28 January 2022
Published: 2 February 2022

1. Introduction

The SPV power sector is developing at an enormous speed, with the government planning to accomplish the 100 GW objective set until 2022 in India. This drive has considered the government mandate to provide solar-oriented systems across the whole of India. SPV systems work with solar energy, which creates power from the obtained energy, relying upon the quality of radiation, cloud shading, the encompassing temperature, and module innovation. Today there is a need for information on weather identification/sun-oriented power generation determination as they assist the utility experts with long term investigations into sun-based energy production, O&M, with its significance and effect on grid dependability and load adjusting, its attendance to peak power requests, making use of the power range from sustainable power. An energy audit of solar plants is the key target for currently introduced SPV systems when they are viewed as the quality of their generation. Sun-oriented photovoltaic (PV) frameworks are a decent other option and a possible answer for the generation of power in India, particularly for grid-interactive frameworks.

India has an enormous potential for creating sunlight-based energy. The explanation for this is that the geological area obtains sun-oriented radiation nearly all of the time, which adds up to 3000 h of daylight [1]. Being situated in the tropical belt of the globe is a positive thing for India, receiving the best radiation from the sun of between 5.8 and 6.8 kWh/m^2/day. The same energy capacity is around six thousand million gigawatt hours of energy each year [2]. The improvement of environmentally friendly power advancements is generally perceived as an urgent part of presenting a coordinated answer to limiting ozone-depleting substance discharges [3]. The need for diminishing GHG outflows and a critical climb in the cost of ordinary energy uses has offered a chance for a large portion of the world's nations to outline new energy strategies. These arrangements were outlined for advancing environmentally friendly power sources in the energy area [4]. There are many explanations for a focus on these strategies, for example, innovation improvements, the lower expense of innovation, a higher amount of funding from the public authority for use in sustainable power sources, and ecological worries [5]. The appeal of new energy sources and the constraints of non-sustainable power sources has set off the specialists to foster new methods for power generation utilizing sun-oriented energy, which goes under the non-traditional wellspring of energy [6]. The measure of electricity that can be created by solar power relies upon the accessibility of the region [7]. The land area needed for a MW scale sun-powered plant is huge, but at minimal expense regardless of the sunlight-based light. However, although the productivity of sun-oriented PV plants is low, the wellspring of energy (from the sun) is uninhibitedly accessible [8]. Probably the most significant benefit of roof sun-oriented PV frameworks is that they can be allowed and introduced quicker than different kinds of environmentally friendly power sources. They cost less money, are assumed to be reliable, expand the access to energy, have support from the government, lessen carbon footprints, and have low upkeep costs [9]. Sun-based energy is the most quickly accessible wellspring of energy. Sun-powered energy is non-contaminating and upkeep-free, and it is turning out to be increasingly more appealing, particularly with regular changes in the supply of network power. A sun-based power plant depends on the conversion of the radiant energy of the sun into voltage, either direct by utilizing a photovoltaic (PV) cell, or in another way by utilizing concentrated sun-oriented power [10]. The capacity to foresee the production yield of power over a long period is of fundamental significance to developing the photovoltaic (PV) industry. Two main drivers are the productivity with which daylight is transformed into electrical energy and the behavior of this interrelation with time [11].

The dependability of PV modules, and the guarantee that they have a long lifetime, has been one of the main reasons for their increasing use. The producers of PV modules generally give assurance that they will last up to 20 years [12,13]. Sun-powered energy is one of the promising environmentally friendly power generation strategies [14,15]. Appropriate resource assessment is important to evaluate sunlight-based PV frameworks' plausibility on any site [16]. The study carried out on the size and improvement methods for solar photovoltaic frameworks recommends that the optimization of the SPV framework depends on meteorological factors, for example, sunlight-based energy, the surrounding temperature, and wind speed [17]. Thus, it becomes critical to have a severe investigation of different areas of the PV framework to ensure precise outcomes [18].

Accordingly, the fundamental objective of this paper is to analyze the installed systems and compare them with other installed systems at the same site and at the same insolation and temperature. In this paper, the considered SPV system is divided into three separate plants. Then, the comparison is made with the help of the energy values obtained from the SPV system through SCADA (recorded) and also compared with PVsyst software, used for assessment and forecasting energy. At the end, the Performance Ratio (PR) and

Capacity Utilization Factor (CUF) are calculated and compared. The SPV system is also compared with the various systems installed in different regions of the world in terms of array efficiency, inverter efficiency, system efficiency, Performance Ratio (PR), and Capacity Utilization Factor (CUF).

With the help of this paper, readers can understand the assessment process, the forecasting, and the response of the SPV power plants at the same input conditions considering different output parameters such as Performance Ratio, Capacity Utilization Factor and Degradation Factor as this study is the performance analysis of three working years (i.e., 2018, 2019, and 2020) of the solar PV plant.

2. Methodology

The assessment of the installed grid-interactive rooftop solar PV plant was carried out on account of its performance parameters. For this purpose, the necessary steps/methods followed are shown in Figure 1. For this, the complete SPV installation of 467.2 kWp was divided into three plants. This was easily achieved because the three plants were installed on three different buildings of the campus. Then, the daily, monthly, and yearly energy generation was recorded through SCADA from the installed SPV system, which helped in the accurate assessment and forecasting. A study was also conducted for the appliances' (hardware) requirements in a centralized and decentralized system of approximate equal ratings. This study was carried out for the years 2018, 2019, and 2020 at different monthly insolations and temperatures. Through this study, different performance parameters of the SPV plant were analyzed. One more study on the basis of the PR and CUF of the complete SPV system ($P_1 + P_2 + P_3$) of 467.2 kWp was performed using the values recorded through the installed SCADA system for the year 2020. Finally, a comparison was made with the other worldwide SPV systems installed in terms of array efficiency, inverter efficiency, system efficiency, PR, and CUF.

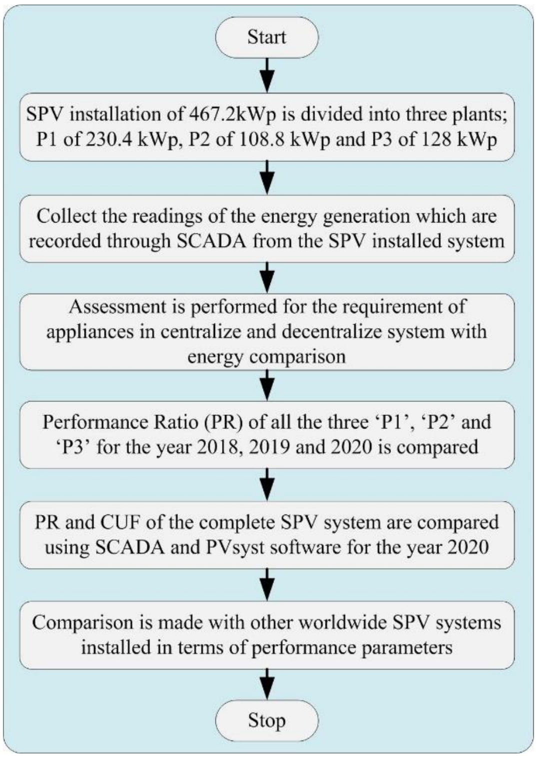


Figure 1. Methodology followed for assessment and comparison of SPV plant.

Performance Parameters of Globally Available SPV System

Following essential parameters (mainly, '% PR' and '%CUF') of Table 1, are used for the assessment of any SPV system.

Table 1. Performance parameters of globally available SPV system.

S. No.	Parameters and Its Expression	Reference
1.	Array yield (Y_A) = $E_{A,DC}/P_o$ Unit: kWh/kWp/d (or h/d). Where: $E_{A,DC}$ is Output Energy from an SPV array, P_o is Rated power output of installed array	[19]
2.	Reference yield (Y_R) = H_T/G_0 Unit: kWh/kWp/d (or h/d). Where: H_T is In-plane irradiance (Total), G_0 is Reference irradiance of PV	[19]
3.	Capacity Utilization Factor (CUF) = Y_F/24*366 Where: Y_F is Final yield	[20]
4.	Performance Ratio (PR) = 100 × (Y_F/Y_R) (%) Where: Y_F is Final yield, Y_R is Reference yield	[21]
5.	Final yield (Y_F) = E_{AC}/P_o Unit: kWh/kWp/d (or h/d). Where: E_{AC} is annually, monthly, or daily Output Energy (E_{AC}) of SPV system, P_o is Rated power output of installed array	[21]

3. Brief Detail of Developed SPV System

A 467.2 kWp grid-interactive solar PV plant, considered in this paper, is installed on three different buildings of Integral University, Lucknow. The exact geographical location of the plant is at coordinates 26.9585° N and 80.9992° E. The plant description is shown in Table 2.

Table 2. Installed Solar Plant description.

Building Name	Specifications	
Academic Block-1 (P_1)	Rating	230.4 kWp
	No. of SPV Panels	Total PV Panels: 720 Number of strings: 36
	PCU	3 of 66 kVA, (198 kW)
	Earthing	09
	LA	01
	AC Box	01
Academic Block-4 (P_2)	Rating	108.8 kWp
	No. of SPV Panels	Total PV Panels: 340 Number of strings: 17
	PCU	1 of 66 kVA 1 of 25 kVA (91 kW)
	Earthing	09
	LA	01
	AC Box	01
Medical Block Phase-1 (P_3)	Rating	128 kWp
	No. of SPV Panels	Total PV Panels: 400 Number of Strings: 20
	PCU	4 of 25 kVA(100 kW)
	Earthing	09
	LA	01
	AC Box	01

The specification of the complete BOS (balance of system) is given in Table 2. In this SPV system, the inverters are string type and there are, in total, 36 strings, 17 strings and 20 strings in academic block-1, academic block-4 and medical block phase-1, respectively.

The detailed description of the solar PV panels used in the system is given in Table 3, and the electrical scheme of the SPV system can be seen in Figure 2, while the aerial view of the SPV system can be seen through Figure 3.

Table 3. Detailed Specification of the solar panels used at the site.

Parameter	**Specification**
Make	Vikarm Solar Pvt.Ltd, Kolkata, India
Type	Eldora VSP.72.320.03.04. 72 cells, 320 Wp, Polycrystalline Solar PV module
P_{mpp}	320 W
V_{oc}	46.00 V
I_{sc}	9.03 A
V_{mpp}	37.70 V
I_{mpp}	8.50 A
FF	77.04%
η (%)	16.49%
$V_{max\ operating}$	1000 V
Dimension	1956 × 992 × 36 mm (77.01 × 39.06 × 1.42 inches)
A_1	3008.0106 inch ^{2} = 1.941 m^2
A_{1460}	2833.86 m^2
STC	2833.86 m^2 × 1000 W/m^2

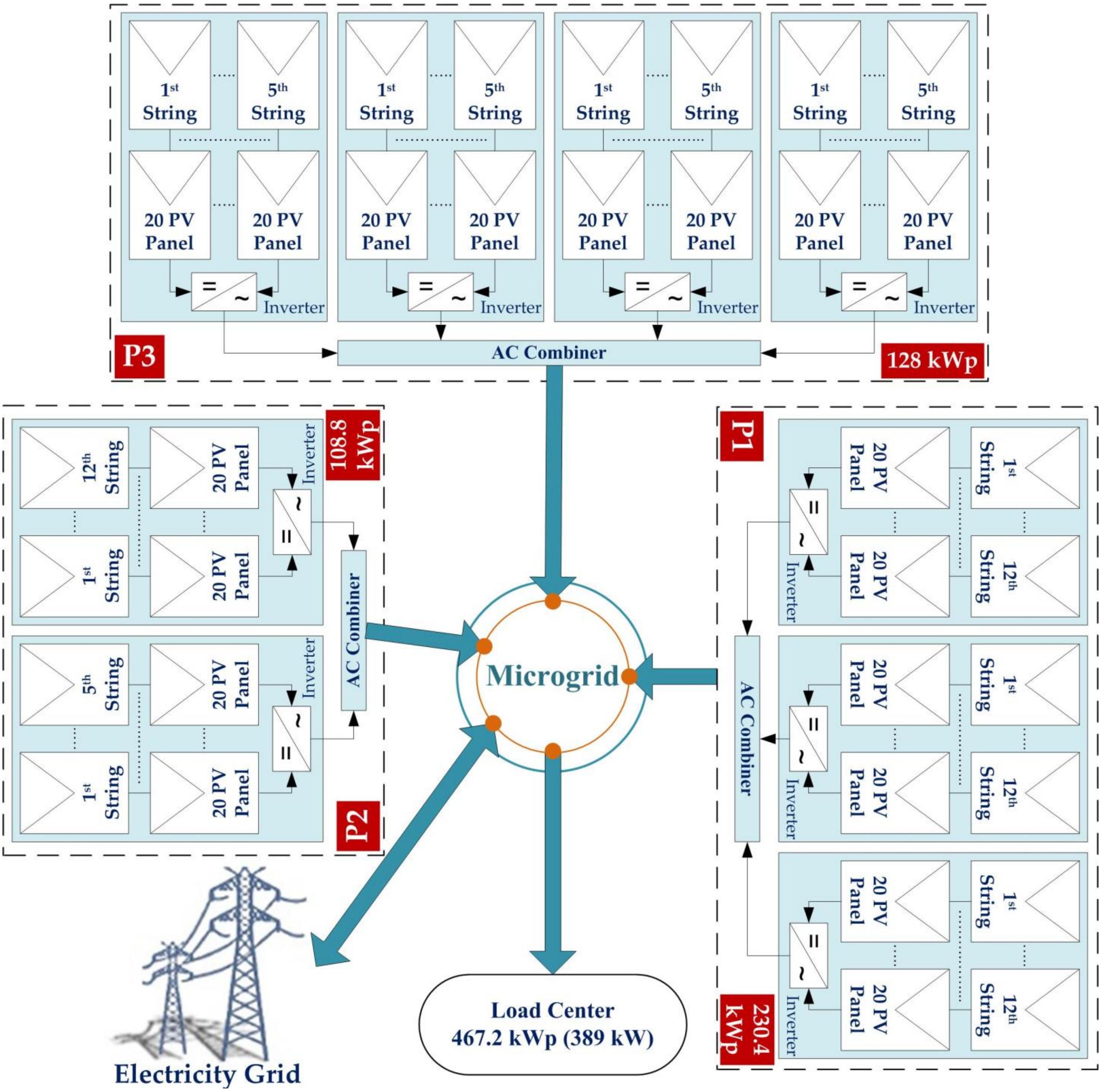


Figure 2. Developed electrical microgrid scheme based on solar PV system (1460 no. of PV panels (320 Wp) = 467.2 kWp (389 kW)).

(**a**)

(**b**)

(**c**)

(**d**)

Figure 3. (**a**) 230.4 kWp Rooftop Solar PV System (P_1); (**b**) 108.8 kWp Rooftop Solar PV System (P_2); (**c**) 128 kWp Rooftop Solar PV System (P_3). (**d**) Aerial view of the considered (P_1, P_2, and P_3) SPV Plant.

4. Result Demonstration and Discussion

There is sufficient proof that energy arrangements assume a focal part in supporting the reception of renewables [22]. Compared with centralized PV power, the decentralized PV power plant has positive possibilities because of its novel benefit that it is comparable in power generation and use, lessening or, in any event, wiping out the expense of power transmission [23]. In a decentralized SPV framework, every DC source can be associated with the DC supply without much of a stretch on the grounds that the primary need to control the DC voltage is to restrict the startup current [24]. The installation cost of the same rating SPV power generation plant on the rooftop of different buildings is greater than the centralized plant on a single rooftop. It is shown in Table 4, and Figure 4, that the number of PV panels is greater in the 236.8 kWp system but, due to the inverter rating, the 230.4 kWp system has a higher power rating. In the case of earth pits, 18 are used for the 236.8 kWp decentralized system, while 9 earth pits are used in the centralized installation of 230.4 kWp. Similarly, lightning arresters and AC combiners are required in double numbers for a decentralized system compared with a centralized system. However, of course, due to the limitation of space, decentralized installations are used, and there are also some advantages of these installations.

Table 4. Comparison of required electrical appliances in Plant 'P_2 + P_3' and Plant 'P_1'.

Specifications	P_2 + P_3 (kWp)	P_1 (kWp)
Total PV Panels	740	720
Inverters (kVA)	191	198
Earth Pits	18	9
Lightning Arrester	2	1
AC Combiner	2	1

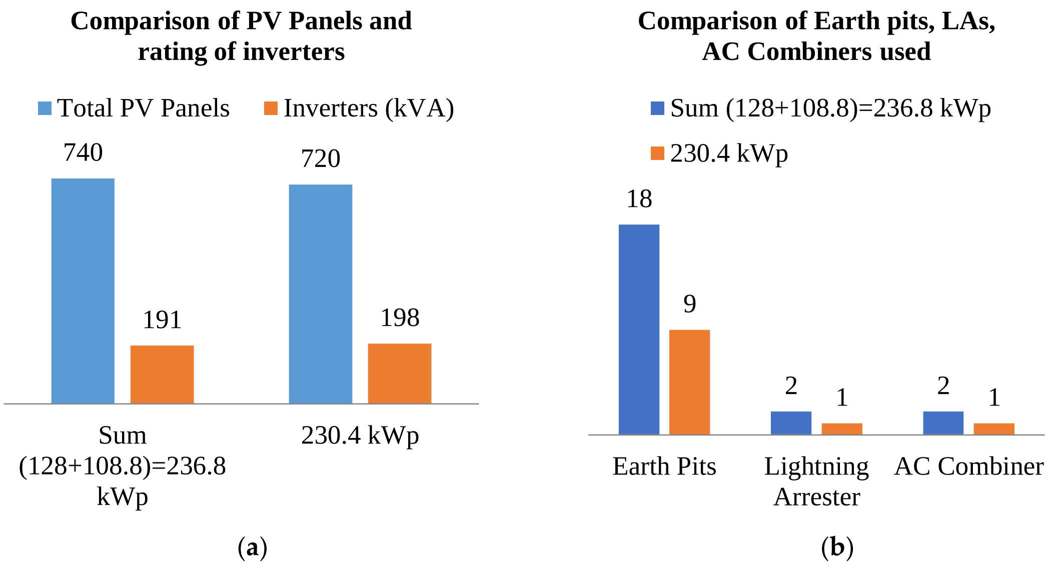


Figure 4. (**a**) Comparison of required rating of inverters, SPV panels in Plant 'P_2 + P_3' and Plant 'P_1'. (**b**) Comparison of required Earth Pits, Lightning Arresters, AC Boxes in Plant 'P2 + P_3' and Plant 'P_1'.

Thus, it can be seen from Figure 4, that the number of instruments needed are fewer in the case of a centralized system, and, therefore, the installation cost of the centralized system is less in comparison to the SPV system of the same rating.

Furthermore, the assessment of the rooftop grid-interactive SPV plants 'P_1', 'P_2', and 'P_3' is carried out in this paper individually, in pairs, and in total, in which comparisons are made and shown with the help of self-explanatory figures and tables.

As shown in Table 5 and Figure 5, the lowest insolation was achieved in January 2018, while the lowest temperature was achieved in December 2018, hence, the lowest generation was achieved in January 2018. Furthermore, the highest insolation was achieved in May

2018, while the highest temperature was in June 2018. Thus, the highest generation was achieved in the month of May 2018.

Table 5. Comparison of Generated Energy in 2018 (P_1 vs. $P_2 + P_3$).

Months (2018)	Insolation (Whr/m^2)	Temp (°C)	Energy (in MWhr) (P_1)	Energy (in MWhr) ($P_2 + P_3$)
Jan	3.548	13.531	16.65	19.1
Feb	4.293	20.72	27.27	26.78
Mar	5.888	27.725	33.68	35.06
Apr	6.373	33.307	29.89	34.86
May	6.503	38.149	35.33	36.76
Jun	6.078	38.746	29.82	29.74
Jul	3.954	31.963	24.51	23.63
Aug	3.725	28.192	22.72	22.83
Sep	4.507	26.82	26.5	25.78
Oct	5.005	23.368	29.56	29.41
Nov	3.94	18.587	23.38	23.87
Dec	3.553	13.467	22.6	24.05
Average	4.78	26.21	-	-
Total Energy (in MWhr)	-	-	321.91	331.87

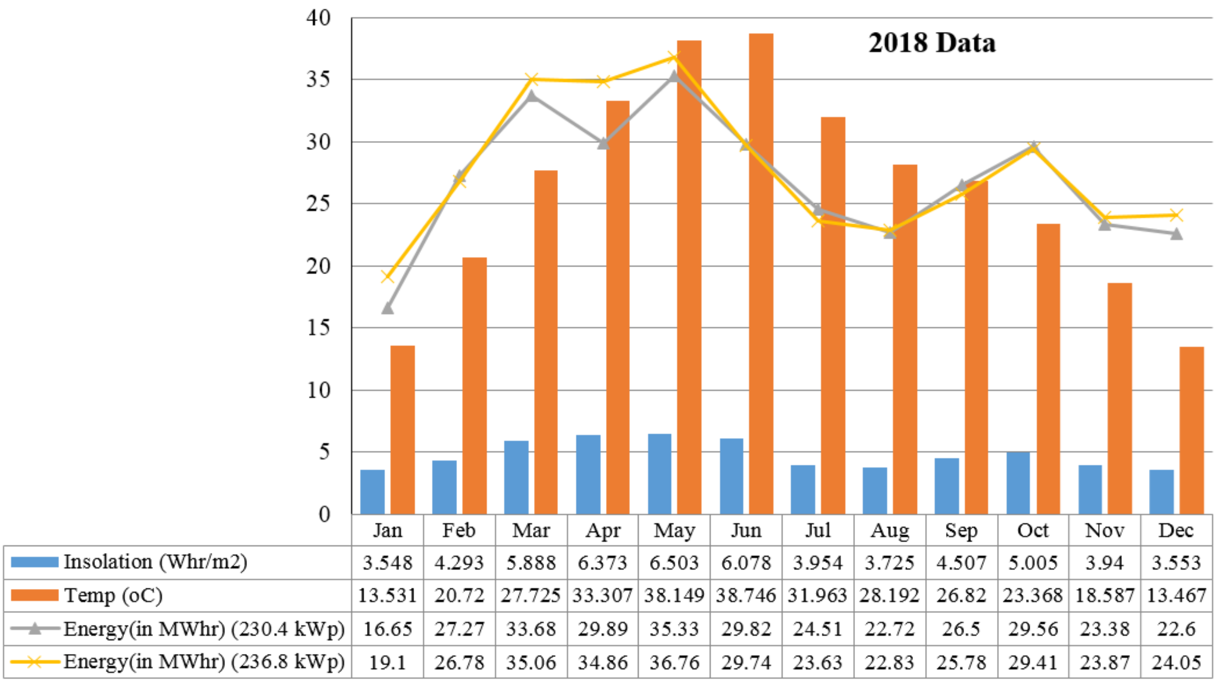


Figure 5. Comparison of Generated Energy in 2018 (P_1 vs. $P_2 + P_3$).

As shown in Table 6 and Figure 6, the lowest insolation was achieved in December 2019, while the lowest temperature was in December 2019. Thus, the lowest generation was achieved in December 2019. Furthermore, the highest insolation was in the month of May 2019 while highest temperature was in June 2019. Thus, the highest generation was achieved in May 2019.

Table 6. Comparison of Generated Energy in 2019 (P_1 vs. $P_2 + P_3$).

Months (2019)	Insolation (Whr/m^2)	Temp (°C)	Energy (in MWhr) (P_1)	Energy (in MWhr) ($P_2 + P_3$)
January	3.607	13.392	22.21	22.54
February	4.104	17.762	22.87	20.99
March	5.716	23.786	33.17	31.45
April	6.404	33.707	32.29	33.28
May	6.698	38.194	36.79	37.23
June	5.873	39.918	29.78	30.95
July	4.648	30.895	26.51	26.29
August	4.584	28.936	27.67	29.27
September	3.575	27.353	19.84	21.24
October	4.264	23.223	23.68	26.96
November	3.526	19.025	19.17	21.56
December	2.733	12.341	17.58	18.63
Average	4.64	25.71	-	-
Total	-	-	311.56	320.39

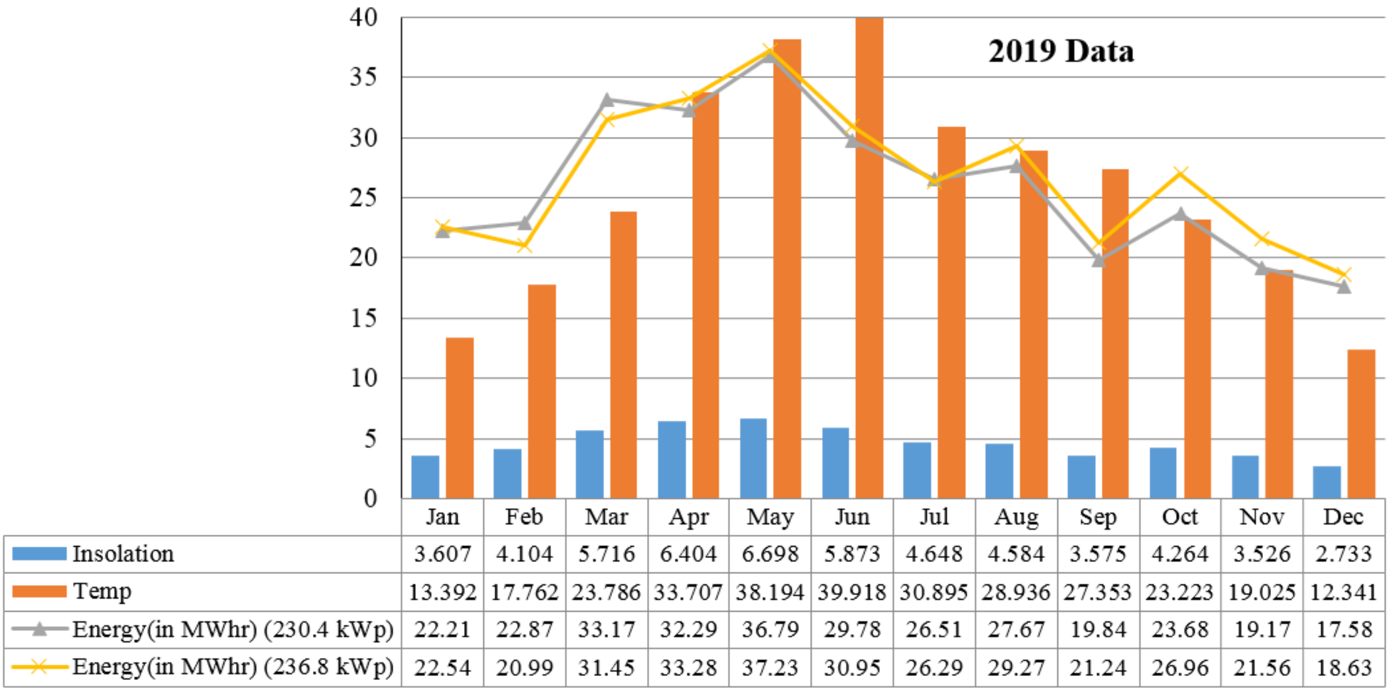


Figure 6. Comparison of Generated Energy in 2019 (P_1 vs. $P_2 + P_3$).

As shown in Table 7 and Figure 7, the lowest insolation was in January 2020, while the lowest temperature was in January 2020. Thus, the lowest generation was achieved in January 2020. Furthermore, the highest insolation was in the month of May 2020, while the highest temperature was in May 2020, so the highest units of generation were achieved in the months of May 2020 and October 2020.

Table 7. Comparison of Generated Energy in 2020 (P_1 vs. $P_2 + P_3$).

Months (2020)	Insolation (Whr/m^2)	Temp (°C)	Energy (in MWhr) (P_1)	Energy (in MWhr) ($P_2 + P_3$)
Jan	2.987	12.072	18.92	20.2
Feb	4.722	15.016	26.59	28.52
Mar	5.135	22.96	27.75	33.1
Apr	6.169	30.705	30.53	17.09
May	6.572	36.015	34.04	27.17
Jun	4.987	34.978	26.52	27.86
Jul	4.497	30.133	25.79	26.99
Aug	4.367	29.0154	25.67	28.3
Sep	4.9	28.651	25.87	27.82
Oct	4.922	26.7	27.87	28.83
Nov	3.861	20.058	23.31	24.81
Dec	3.338	15.94	20.36	21.86
Average	4.70	25.18	-	-
Total	-	-	313.22	312.55

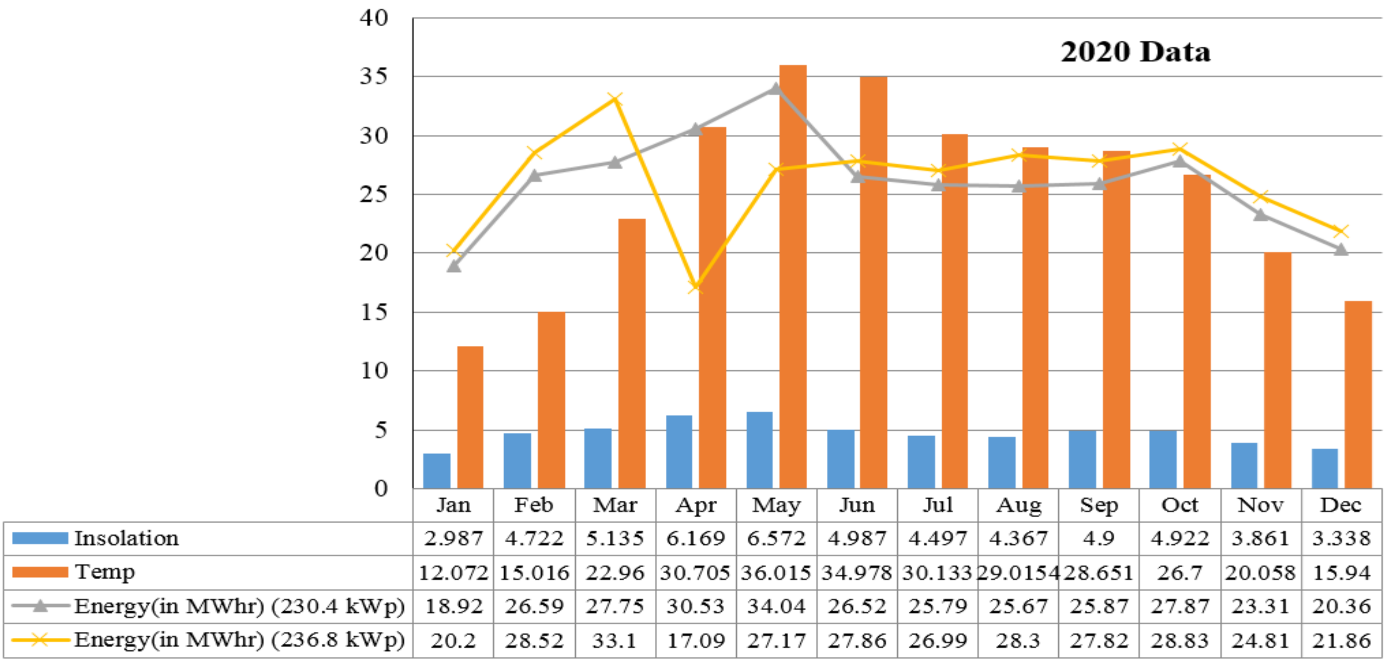


Figure 7. Comparison of Generated Energy in 2019 (P_1 vs. $P_2 + P_3$).

As shown in Table 8 and Figure 8, the findings are as follows: The lowest generation was in January 2018, while the lowest PR was in January 2018. Furthermore, the highest generation was achieved in May 2018, while the highest PR was achieved in February 2018. On the other hand, the lowest generation was in December 2019, while the lowest PR was in April 2019. The highest generation was in May 2019, while the highest PR was in December 2019. The lowest generation was in January 2020, while the lowest PR was in May 2020. The highest generation was achieved in May 2020, while the highest PR was in January 2020.

Table 8. Comparison of Generated Energy in 2018, 2019, and 2020 of 467.2 kWp Plant ($P_1 + P_2 + P_3$).

Months	2018		2019		2020	
	Energy (MWhr)	%PR	Energy (MWhr)	%PR	Energy (MWhr)	%PR
Jan	35.75	70.53	44.75	85.83	39.12	93.14
Feb	54.05	98.38	43.86	81.78	55.11	86.55
Mar	68.74	81.83	64.62	78.28	60.85	82.38
Apr	64.75	73.33	65.57	73.1	47.62	55.7
May	72.09	76.58	74.02	77.44	61.21	65.02
Jun	59.56	70.82	60.73	74.71	54.38	79.18
Jul	48.14	85.23	52.8	79.25	52.78	82.83
Aug	45.55	85	56.94	87.37	53.97	86.66
Sep	52.28	82.89	41.08	83.74	53.69	78.18
Oct	58.97	81.43	50.64	83.25	56.7	79.9
Nov	47.25	86.44	40.73	83.03	48.12	90.35
Dec	46.65	92.03	36.21	92.6	42.22	88.34
Average	-	82.04	-	81.69	-	80.68
Total	653.78	-	631.95	-	625.77	-

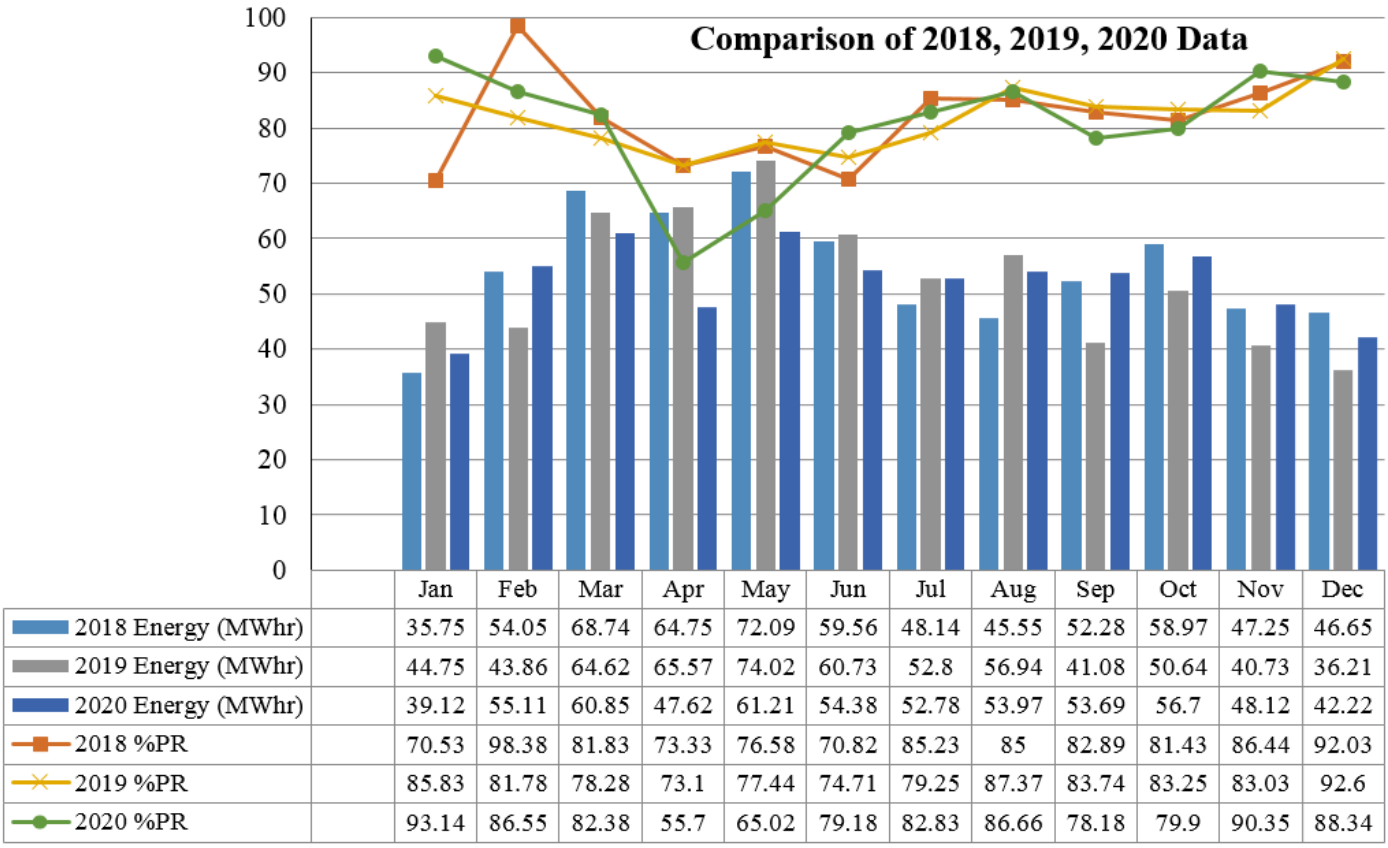


Figure 8. Comparison of Generated Energy in 2018, 2019, and 2020 of 467.2 kWp Plant ($P_1 + P_2 + P_3$).

The Performance Ratio of the last three years (i.e., 82.04 in 2018, 81.69 in 2019, and 80.68 in 2020) is shown in Figure 9. It can also be seen that the degradation of solar panels is about 0.35% to 1.01% yearly, i.e., a positive sign that the installed SPV system can be in working condition for the next 20 years.

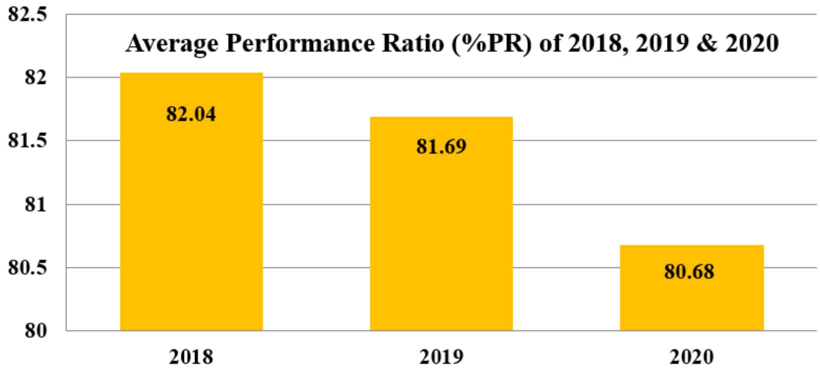
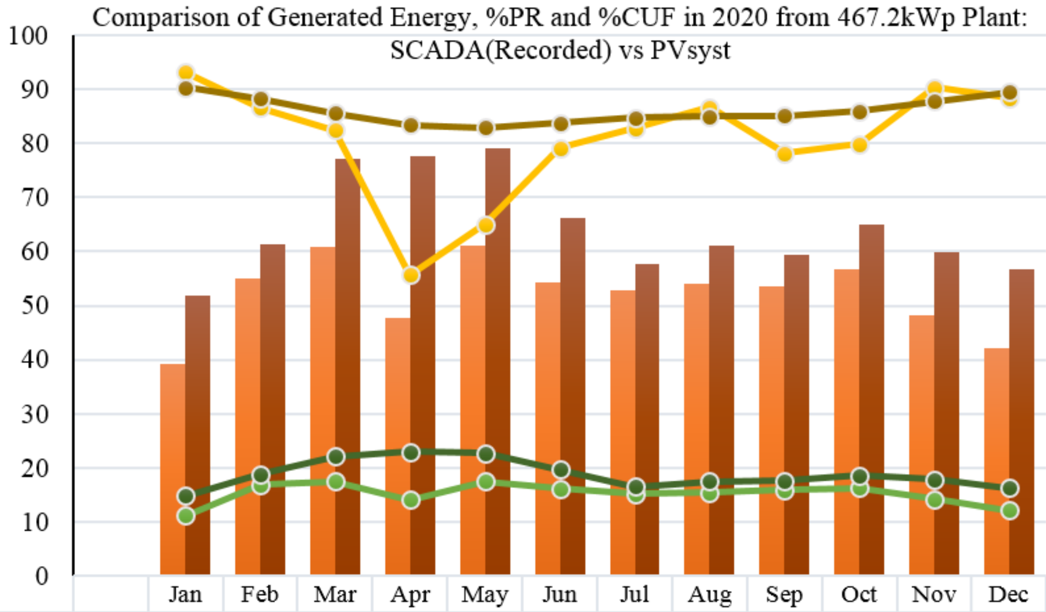


Figure 9. Comparison of PR in 2018, 2019, and 2020 of 467.2 kWp Plant ($P_1 + P_2 + P_3$).

With the help of Table 9 and Figure 10, it can be seen that the lowest Performance Ratio (PR) is in the month of April 2020 and is very low due to a technical error in an inverter, which was resolved in May 2020; otherwise, according to the weather conditions of 2020, the lowest PR is observed in the month of May, practically, and as can be seen with the help of the PVsyst simulation software. The lowest Capacity Utilization Factor (CUF) is observed in January 2020, and the highest is achieved in May 2020 in the case of the recorded date of SCADA, but it is highest in April in the case of the PVsyst software. It is assumed that in April 2020, the actual data (PR and CUF) deviates due to the inverter's inappropriate behavior, but after the maintenance in May 2020, the achieved results are up to the mark and it was fixed by just resetting the specific inverter. Other than the month of April 2020, it can be seen from Table 9 and Figure 10 that the system is in excellent working condition and is near to the desired value set by the PVsyst simulation software.

Table 9. Comparison of Generated Energy, %PR and %CUF in 2020 from 467.2 kWp Plant: SCADA (Recorded) vs. PVsyst.

Months	2020 (SCADA)			2020 (PVsyst)		
	Energy (MWhr)	%PR	%CUF	Energy (MWhr)	%PR	%CUF
Jan	39.12	93.14	11.25	51.80	90.3	14.90
Feb	55.11	86.55	16.94	61.27	88.3	18.84
Mar	60.85	82.38	17.50	77.07	85.6	22.17
Apr	47.62	55.7	14.15	77.59	83.4	23.06
May	61.21	65.02	17.60	79.17	82.9	22.77
Jun	54.38	79.18	16.16	66.33	83.7	19.71
Jul	52.78	82.83	15.18	57.63	84.8	16.58
Aug	53.97	86.66	15.52	61.06	85.0	17.56
Sep	53.69	78.18	15.96	59.43	85.1	17.66
Oct	56.7	79.9	16.31	64.99	85.9	18.69
Nov	48.12	90.35	14.30	60.01	87.8	17.84
Dec	42.22	88.34	12.14	56.82	89.5	16.34
Average	-	80.68	15.25	-	86.02	18.84
Total	625.77	-		773.23	-	



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2020 (SCADA) Energy (MWhr)	39.12	55.11	60.85	47.62	61.21	54.38	52.78	53.97	53.69	56.7	48.12	42.22
2020 (PVsyst) Energy (MWhr)	51.8	61.27	77.07	77.59	79.17	66.33	57.63	61.06	59.43	64.99	60.01	56.82
2020 (SCADA) %PR	93.14	86.55	82.38	55.7	65.02	79.18	82.83	86.66	78.18	79.9	90.35	88.34
2020 (SCADA) %CUF	11.25	16.94	17.5	14.15	17.6	16.16	15.18	15.52	15.96	16.31	14.3	12.14
2020 (PVsyst) %PR	90.3	88.3	85.6	83.4	82.9	83.7	84.8	85	85.1	85.9	87.8	89.5
2020 (PVsyst) %CUF	14.9	18.84	22.17	23.06	22.77	19.71	16.58	17.56	17.66	18.69	17.84	16.34

Figure 10. Comparison of Generated Energy, %PR and %CUF in 2020 from 467.2 kWp Plant: SCADA (Recorded) vs. PVsyst.

With the help of Table 10, it can be seen that the performance of the installed SPV system improved day by day and highly depends upon the size, climatic conditions, and geographic location of the plant. In 2006, [25] the PR of the 13 kWp system installed in Ireland was in the range of 60%–62%, while the system efficiency was about 6%–9%. It is also reported that the array efficiency was 7.5%–10% and the efficiency of the inverter was 87%. In 2007, [26] it was reported that the PR of the 200 kWp system installed in Spain was 62.7%, while the system efficiency was 7.8% and the inverter efficiency and array efficiency were 88.1% and 8.9%, respectively. In 2009, a 171.36 kWp SPV system was reported in [27]. The location of the plant was Greece. The PR and CUF were 67.36% and 15.26%, respectively. The array efficiency and inverter efficiency were 8%–11% and 89%, respectively.

Table 10. Performance parameters of SPV plants reported in published literature compared with installed site at Integral University.

Location	PV Type	System Size	Array Eff. (%)	Inverter Eff. (%)	System Eff. (%)	PR (%)	CUF (%)	Reference
Lucknow	p-si	5 kWp	11.34	88.38	10.02	76.97	16.39	[19] 2018
Roorkee	p-si	1816 kWp	12	97	8.7	63.68	13.85	[20] 2016
Ireland	p-si	1.72 kWp	14.9	89.2	13.3	81.50	10.10	[21] 2011
Ireland	p-si	13 kWp	7.5–10	87	6.0–9.0	60–62	–	[25] 2006
Spain	p-si	200 kWp	8.9	88.1	7.8	62.7	–	[26] 2007
Greece	p-si	171.36 kWp	8–11	89	–	67.36	15.26	[27] 2009
Singapore	p-si	142.5 kWp	13.7	94.8	11.2	81	15.7	[28] 2012
Thailand	p-si	11 kWp	11.2	93	10.41	73.45	14	[29] 2012
Turkey	p-si	2.73 kWp	9.54	96.8	-	72	23.2	[30] 2013
Karnataka	p-si	3 MWp	10.1–13.25	97	–	72	15.69	[31] 2013
Khatkar Kalan	p-si	190 kWp	10–14	95	8.3	74	9.27	[32] 2013
Abu Dhabi, UAE	p-Si	111.4 kWp	14.2	97.3		80		
	p-Si	50.4 kWp	14.2	97.1	-	81	-	[33] 2015
	m-Si	215.7 kWp	18.4	96.1		70		
Malaysia	p-si	3 kWp	10.11	95.15	–	77.28	15.7	[34] 2015
Algeria	p-si	3.2 kWp	13.72	88.1	–	64.3	20.41	[35] 2015
Norway	p-si	2.07 kWp	12.7	88.8	11.6	83.03	10.58	[36] 2015
Shivgangai, TN, India	TFa-Si	5 MWp	6.08	88.2	5.08	85.5–92.3	–	[37] 2015
Bhubaneswar	p-si	11.2 kWp	13.42	89.83	12.5	78	15.27	[38] 2017
Ås, Norway	mc-Si	5 kWp	11.46	98	-	74.59	12.69	[39] 2019
Jeddah, Saudi Arabia	mc-Si	12.25 kWp	21.49	96.318	-	78	22	[40] 2019
Kovilpatti, India	p-Si	1 kWp	12.14	95.6	11.07	78.48	17.99	[41] 2019
Haryana, India	p-Si	186 kWp	14.77	93.14	13.76	82.7	17.8	[42] 2019
Turkey	p-si	2130.7 kWp	14.1	98.8	13.18	81.15	18.86	[43] 2020
Adrar, South of Algeria	p-si	20 MW	15.1	98	10.82	71.71	20.76	[44] 2020
Serpong, South Tangerang	p-si	10.6 kWp	15.29	96.63	14.77	82.42	14.07	[45] 2020
East Poland	p-Si	21.25 kWp	15.4	97.8	14.5	80	-	[46] 2020
Kuantan, Malaysia	mc-Si	20 MWp	13–20	98	11.54	76.88	15.22	[47] 2020
Nouakchott, Mauritania	p-Si	48 kWp	11.22	84.60	9.49	77.76	19	[48] 2021
Our developed SPV power plant	p-si	467.2 kWp	16.49	98.7 (66 kVA) 98 (25 kVA)	15.47	80.68	15.25	Present study 2020

mc-si or m-si: mono-crystalline silicon, p-si: Polycrystalline silicon, TFa-Si: Thin Film amorphous Silicon.

In 2011, [21] the PR and CUF of the 1.72 kWp system installed in Ireland were 81.5% and 10.10 respectively, while the system efficiency was about 13.3%. It was also reported that the array efficiency was 14.9% and the efficiency of the inverter was 89.2%. In 2012, [28] it was reported that the PR of the 142.5 kWp system installed in Singapore was 81%, while the system efficiency was 11.2% and the inverter efficiency and array efficiency were 94.8% and 13.7%, respectively. The reported CUF was 15.7. In 2012, an 11 kWp SPV system was reported in [29]. The location of the plant was in Thailand. The PR and CUF were 73.45% and 14%, respectively. The array efficiency, inverter efficiency, and system efficiency were 11.2%, 93%, and 10.41%, respectively.

In 2013, [30] the PR and CUF of the 2.73 kWp system installed in Turkey was 72% and 23.2, respectively. It was also reported that the array efficiency was 9.54% and the efficiency of the inverter was 96.8%. Again in 2013, [31] it was reported that the PR of the 3 MWp system installed in Karnataka was 72%, while the inverter efficiency and array efficiency were 97% and in the range of 10.1–13.25%, respectively. The reported CUF was 15.69. In 2013, a 190 kWp SPV system was reported in [32]. The location of the plant was Khatkar Kalan, India. The PR and CUF were 74% and 9.27%, respectively. The array efficiency, inverter efficiency, and system efficiency were 10%–14%, 95%, and 8.3%, respectively.

In 2015, [33] the PRs of the 111.4 kWp, 50.4 kWp, and 215.7 kWp systems installed in Abu Dhabi, UAE were 80%, 81%, and 70%, respectively. It was also reported that the array efficiencies were 14.2%, 14.2% and 18.4%, respectively, while the efficiencies of the inverters were 97.3%, 97.1%, and 96.1%, respectively. In 2015, [34] it was reported that the PR of the 3 kWp system installed in Malaysia was 77.28%. The inverter efficiency and array efficiency were 95.15% and 10.11%, respectively. In 2015, a 3.2 kWp SPV system was reported in [35]. The location of the plant was Algeria. The PR and CUF were 64.3% and 20.41%, respectively. The array efficiency and inverter efficiencies were 13.72% and 88.1%, respectively. In 2015, [36] the PR and CUF of the 2.07 kWp system installed in Norway were 83.03% and 10.58%, respectively, while the system efficiency was about 11.6%. It was also reported that the array efficiency was 12.7% and the efficiency of the inverter was 88.8%. In 2015, [37] it was reported that the PR of the 5 MWp system installed in Tamil Nadu, India was in the range of 85.5–92.3%, while the system efficiency was 5.08% and the inverter efficiency, array efficiency were 88.2% and 6.08%, respectively.

In 2016, an 1816 kWp SPV system was reported in [20]. The location of the plant was Roorkee, India. The PR and CUF were 63.68% and 13.85%, respectively. The array efficiency, inverter efficiency, and system efficiency were 12%, 97%, and 8.7%, respectively. In 2017, [38] the PR and CUF of the 11.2 kWp system installed in Bhubaneshwar, India were 78% and 15.27%, respectively, while the system efficiency was about 12.5%. It was also reported that the array efficiency was 13.42% and the efficiency of the inverter was 89.83%. In 2018, [19] it was reported that the PR of the 5 kWp system installed in Lucknow, India was 76.97%, while the system efficiency was 10.02% and the inverter efficiency and array efficiency were 88.38% and 11.34%, respectively. In 2019, a 5 kWp SPV system was reported in [39]. The location of the plant was in Norway. The PR and CUF were 74.59% and 12.69%, respectively. The array efficiency and inverter efficiency were 11.46% and 98%, respectively. In 2019, [40] the PR and CUF of the 12.25 kWp system installed in Jeddah, Saudi Arabia were 78% and 22%, while it was also reported that the array efficiency was 21.49% and the efficiency of the inverter was 96.31%. In 2019, [41] it was reported that the PR of the 1 kWp system installed in Kovilpatti, India was 78.48%, while the system efficiency was 11.07% and the inverter efficiency and array efficiency were 95.6% and 12.14%, respectively. In 2019, a 186 kWp SPV system was reported in [42]. The location of the plant was Haryana, India. The PR and CUF were 82.7% and 17.8%, respectively. The array efficiency, inverter efficiency, and system efficiency were 14.77%, 93.14%, and 13.76%, respectively.

In 2020, [43] the PR and CUF of the 2130.7 kWp system installed in Turkey were 81.15% and 18.86%, respectively, while the system efficiency was about 13.18%. It was also reported that the array efficiency was 14.1% and the efficiency of the inverter was 98.8%. In 2020, [44] it was reported that the PR of the 20 MWp system installed in Algeria was 71.71%, while the system efficiency was 10.82% and the inverter efficiency and array efficiency were 98% and 15.1%, respectively. In 2020, a 10.6 kWp SPV system was reported in [45]. The location of the plant was Serpong. The PR and CUF were 82.42% and 14.07%, respectively. The array efficiency, inverter efficiency, and system efficiency were 15.29%, 96.63%, and 14.77%, respectively. In 2020, [46] the PR of the 21.25 kWp system installed in East Poland was 80%, while the system efficiency was about 14.5%. It was also reported that the array efficiency was 15.4% and the efficiency of the inverter was 97.8%. In 2020, [47] it was reported that the PR of the 20 MWp system installed in Malaysia was 76.88%, while the system efficiency was 11.54% and the inverter efficiency and array efficiency were 98% and 13%–20%, respectively. In 2021, a 48 kWp SPV system was reported in [48]. The location of the plant was Nouakchott, Mauritania. The PR and CUF were 77.76% and 19%, respectively. The array efficiency, inverter efficiency, and system efficiency were 11.22%, 84.60%, and 9.49%, respectively.

Our developed SPV system, which was installed in 2017, also had good performance in 2020 (present study). The PR and CUF of the 467.2 kWp system installed in Lucknow were 80.68% and 15.25%, respectively, while the system efficiency was about 15.47%. It was also reported that the array efficiency was 16.49% and the efficiency of the inverter was about 98%. It can be seen in this study that the developed plant is working in a very good manner when it is compared with other installed SPV plants worldwide with the approximately same ratings (reported in Table 10).

5. Conclusions

India profoundly relies upon coal-based power generation stations, which discharge an immense measure of greenhouse gasses (GHGs) into the air. In one unit (kWh) from a coal-based power generation plant, a normal amount of 980 g CO_2, 1.24 g SO_2, 2.59 g NO_X, and 68 g ash is discharged. The SPV plant places a positive effect on the climate and changes to unnatural weather patterns by diminishing the discharge of greenhouse gasses. A 467.2 kWp rooftop SPV power plant has been introduced in this paper and assessment has been conducted for the last three years (i.e., 2018, 2019, and 2020). The impact of solar insolation and temperature on the plant has been seen and compared with other plants worldwide. It is likewise assessed that the 467.2 kWp PV framework reduces the tremendous measures of CO_2, SO_2, and NO_X that are discharged into the air.

Furthermore, apart from the environmental benefits, in the considered case study, performance predictions are made for understanding the energy outputs. The major findings are:

- The installation cost of the same rating SPV plant on the rooftops of different buildings is greater than the centralized plant on a single rooftop (as shown in Table 4 and Figure 4).
- The comparison of the 230.4 kWp and 236.8 kWp plants is made for the years 2018, 2019, and 2020. It can be seen from Table 5, Table 6, Table 7, and Figure 5, Figure 6, and Figure 7 that the difference in the generated energy is not as much as the installation cost. The difference in the rating of the SPV plant is 6.4 kWp, but the difference in the generation is 9.96 MWHr in 2018, 8.83 MWHr in 2019, and -0.67 MWHr in 2020 (due to a fault in the inverter of one of the buildings taken for study in the month of April 2020)
- A comparison of the monthly PR with respect to the power generation of years 2018, 2019, and 2020 of the 467.2 kWp SPV plant is made with discussion and results are shown in Table 8, Figure 8, and Figure 9.
- For the year 2020, the PR and the CUF analysis of the 467.2 kWp (389 kW) plant is made with a discussion and results shown in Table 9 and Figure 10.
- A worldwide performance comparison in terms of array efficiency, inverter efficiency, system efficiency, PR, and CUF with the 467.2 kWp (389 kW) plant is reported in Table 10.

Thus, with the help of this paper, readers can understand the assessment, benefits, and evaluation of the solar PV plant. Since this is the study of three working years of the plant (i.e., 2018, 2019, and 2020), readers can understand the solar PV plant's effectiveness, relative performance, and degradation.

Author Contributions: Conceptualization, A.F.M., T.U., H.M. and M.A.A.; methodology, A.F.M., T.U., H.M. and M.A.A.; software, A.F.M., T.U., H.M., M.E.N. and M.A.A.; validation, A.F.M., T.U., H.M., M.E.N. and M.A.A.; formal analysis, A.F.M., T.U., H.M. and M.A.A.; investigation, A.F.M., T.U., H.M. and M.A.A.; resources, A.F.M., T.U., H.M., M.E.N. and M.A.A.; data curation, A.F.M., T.U., H.M., M.E.N. and M.A.A.; writing—original draft preparation, A.F.M., T.U., H.M. and M.A.A.; writing—review and editing, A.F.M., T.U., H.M., M.E.N. and M.A.A.; visualization, A.F.M., T.U., H.M., M.E.N. and M.A.A.; supervision, T.U. and M.E.N.,; project administration, H.M. and M.A.A.; funding acquisition, H.M. and M.A.A. All authors have read and agreed to the published version of the manuscript.

Funding: The authors extend their appreciation to the Researchers Supporting Project at King Saud University, Riyadh, Saudi Arabia, for funding this research work through the project number RSP-2021/278.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to acknowledge the support from King Saud University, Saudi Arabia. The authors would like to acknowledge the support from Intelligent Prognostic Private Limited Delhi, India Researcher's Supporting Project. The authors would like to acknowledge the support from Integral University, Lucknow, India for providing the data and accessing the site used in this study. The statements made herein are solely the responsibility of the authors.

Conflicts of Interest: The authors declare no conflict of interest.

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