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# Performance of a 35.2 kWp Roof Top Grid-Connected Solar Photovoltaic Power Plant in Tribal Region of Gujarat

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**Abstract:** In India, rooftops and underutilized lands are increasingly being harnessed for solar photovoltaic (PV) installations to generate electricity. A prominent example is the 35.2 kW$_p$ grid-connected solar PV power plant installed on the rooftop of the College of Agricultural Engineering and Technology at Navsari Agricultural University (NAU), Dediapada (located at 21.66°N and 73.59°E), in May 2018. Situated on the top floor at approximately 10 meters above ground with a 20° tilt, this project aimed to evaluate the performance and efficiency of the solar PV system in Gujarat's tribal region. This study assesses the system's performance from January 2019 to December 2022, during which all generated electricity was fed into the state grid. Key performance parameters analyzed include final yield, reference yield, array yield, system losses, array capture losses, cell temperature losses, PV module efficiency, system efficiency, inverter efficiency, performance ratio, and capacity factor. Over the monitoring period, the system produced a total of 202.3 MWh of electricity, with the PV modules achieving an efficiency of 12%, the inverter operating at 95% efficiency, and a performance ratio of 0.7.

**Key words**: Solar electricity, 35.2 kW$_p$ PV system, yields, system efficiencies, capacity utilization factor, performance ratio.

India's energy demand, driven by economic growth, has outpaced supply, necessitating a shift from fossil fuels, which contribute to greenhouse gas emissions and environmental degradation, to renewable sources like solar, which offers consistent radiation and reduces carbon footprints. It is approximated that about 60% of the country's total power generation capacity will be achieved through renewable sources and transition to 100% renewable energy by 2050 (Poonia *et al.,* 2022). Globally, India's solar photovoltaic (PV) capacity is expected to reach 200 GW by 2025, with India adding approximately 24 GW in the fiscal year 2024-25, ranking third largest solar power generator worldwide, supported by the Jawaharlal Nehru National Solar Mission targeting 280 GW by 2030 (Renewables, 2016).

Previous research has highlighted the effectiveness of such systems. For example, Poonia *et al*. (2024) carried out performance validation and feasibility assessments of these

*Table 1. Meteorological observations of the site [Jan to Dec 2022 and Average of year 2019, 2020, 2021 and 2022]*

| Month | Ambient temperature (°C) | Humidity (%) | Wind speed (m $s^{-1}$) | Solar irradiation in plane of array (kWh $m^{-2}$ $d^{-1}$) |
|---|---|---|---|---|
| January | 19.6 | 45.7 | 1.1 | 5.3 |
| February | 25.0 | 32.0 | 1.3 | 6.5 |
| March | 29.2 | 26.6 | 1.9 | 6.3 |
| April | 33.6 | 24.0 | 1.5 | 6.2 |
| May | 32.5 | 40.2 | 2.5 | 6.4 |
| June | 32.1 | 40.9 | 2.2 | 5.9 |
| July | 27.1 | 73.4 | 1.3 | 3.7 |
| August | 27.4 | 72.5 | 0.8 | 4.1 |
| September | 29.4 | 69.8 | 0.7 | 5.3 |
| October | 25.6 | 54.3 | 0.9 | 5.3 |
| November | 25.9 | 36.5 | 0.9 | 5.4 |
| December | 22.7 | 47.2 | 1.3 | 4.6 |
| Data of year 2022 | | | | |
| Average | 27.5 | 46.9 | 1.4 | 5.4 |
| Data of year 2021 | | | | |
| Average | 26.5 | 48.2 | 2.3 | 5.3 |
| Data of year 2020 | | | | |
| Average | 28.7 | 44.8 | 1.6 | 6.3 |
| Data of year 2019 | | | | |
| Average | 32.1 | 45.1 | 1.4 | 6.9 |

plants of 375 kWp rooftop photovoltaic plant from April 1, 2022, to March 31, 2023, generating 543666 kWh annually for the grid. The calculated the energy payback time to 4.5 years (post- C-credit inclusion) and over a 25-year lifespan, the embodied energy of the PV plant would thouch 2552265 kWh. Sharma and Chandel (2013) reported a 190 $kW_P$ system in Punjab, which achieved a final yield of 1.45-2.84 kWh $kW_P^{-1}$ $day^{-1}$ and a performance ratio ranging from 55% to 83%. Mondol *et al.* (2006) studied a 13 $kW_P$ system that demonstrated efficiencies of 4.5-9.2% for PV modules, 3.6–7.8% for the overall system, and inverter efficiencies between 50% and 87%. Tarigan and Kartikasari (2015) observed that a 1 $kW_P$ system in Indonesia could reduce approximately 1,296 kg of $CO_2$ annually. Pundir *et al.* (2016) recorded a performance ratio of 63.68% and a capacity factor of 8.77% for a system installed at IIT Roorkee. Additionally, Peerapong and Limmeechokchai (2014) compared various systems in Thailand, demonstrating their economic viability through favorable feed-in tariffs. These research works underscore the vital role of rooftop PV systems in addressing energy shortages, reducing greenhouse gas emissions, and promoting sustainable energy adoption in urban environments, especially amidst land constraints.

Solar photovoltaic (PV) systems, particularly grid-connected rooftop installations, represent a sustainable energy solution with significant potential in India, especially in Gujarat, due to high solar irradiance and the availability of rooftops and open land. The Ministry of New and Renewable Energy (MNRE) has advanced these initiatives, utilizing approximately 10 $m^2$ of space per 1 $kW_P$ system to generate around 100 to 120 units of electricity a month and around 1200 to 1500 units annually, which can offset electricity costs via net metering while minimizing transmission losses. This study evaluates the performance of a 35.2 $kW_P$ grid-connected rooftop PV system installed on May, 2019, at a CAET, NAU, Dediapada, focusing on final yield, performance ratio, and system efficiency over four-year period.

## Materials and Methods

*Location and meteorological data*: The solar photovoltaic power plant is situated on the rooftop of the College of Agricultural Engineering and Technology, Navsari

Agricultural University located in Dediapada, Gujarat, India. Solar irradiation data in the plane of the array were collected using a pyranometer and datalogger, which recorded irradiance at 15 min intervals throughout the study period. Ambient temperature measurements were obtained with a T-type thermocouple placed inside a Stevenson screen. Additional meteorological parameters, such as monthly mean wind speed and relative humidity, were measured using a cup-type anemometer and a hygrometer, respectively. Rainfall data were collected from a nearby meteorological observatory. Table 1 presents the monthly mean values for ambient temperature (°C), relative humidity (%), wind speed (m s$^{-1}$), and solar irradiation in the plane of the array (kWh m$^{-2}$ day$^{-1}$). According to Table 1, the highest solar irradiation in the plane of the array was recorded from February to May 2022, while the lowest was observed in July 2022. The annual average solar irradiation values were 6.9, 6.3, 5.3, and 5.4 kWh m$^{-2}$ day$^{-1}$ for the years 2019, 2020, 2021, and 2022, respectively. Relative humidity peaked between 54% and 73% from July to October 2022, with the highest wind speed of 2.5 m s$^{-1}$ recorded in May 2022. Figure 1 details the monthly mean normal rainfall (mm) and the number of normal rainy days.

*Technical description of 35.2 kW$_p$ grid connected solar roof top PV system*: A Vadodara-based company was contracted to supply, install, commission, and provide a five-year comprehensive maintenance contract for a 35.2 kWp grid-connected solar photovoltaic system at the CAET, Dediapada, Narmada District, Gujarat, India. A net metering interconnection agreement was signed on March 23, 2018, between CAET, Dediapada, and Dakshin Gujarat Vij Company Limited (DGVCL), Surat. The system was fully installed, commissioned, and operational at the site by May, 2018. The system comprises key components, including solar PV modules, mounting structures, inverters, and associated accessories such as an array junction box, AC distribution board, and energy meter.

*Solar power plant rating*: Located at 21.66°N and 73.59°E, the solar PV system has a nominal capacity of 35.2 kW$_P$ under standard test conditions (STC). It delivers a three-phase output of 415V at 50 Hz, connected to the nearest utility grid point.

*Solar module*: The system utilizes Goldi 320PM modules, each with a 320 Wp capacity, consisting of 72 polycrystalline silicon solar cells arranged in 12 rows and 6 columns. Each module has an open-circuit voltage of 46.20 V and a short-circuit current of 9.00 A at STC. The system configuration includes 10 modules connected in series to form a single string, with 11 such strings connected in parallel, resulting in a total of 110 modules. The 35.2 kW$_P$ system covers a surface area of 206 m$^2$. To minimize soiling losses, the PV module surfaces were cleaned with water every seven days during the monitoring period. A PV array consists of environmentally sealed PV modules, which are collections of PV cells that convert sunlight into electricity. Each module measures approximately 900 × 380 × 40 mm and weighs between 20 and 22 kg. Commercial module

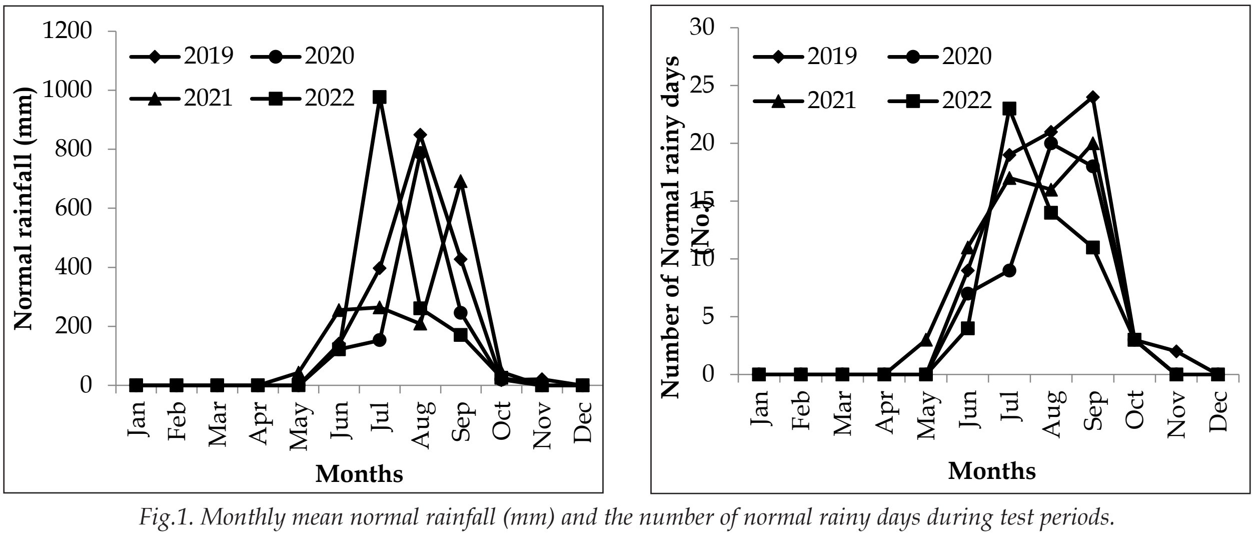

Fig.1. Monthly mean normal rainfall (mm) and the number of normal rainy days during test periods.

*Table 2. Solar panel specification*

| Parameters | Specification |
|---|---|
| Type of material | Polycrystalline |
| Make | Goldi Green Technologies Pvt. Ltd. |
| Model | GOLDI320PM |
| Maximum power $P_{max}$ | 320 W |
| Open circuited voltage $V_{oc}$ | 46.20 V |
| Short circuited current $I_{sc}$ | 9.00 A |
| Maximum power voltage $V_{max}$ | 37.10 V |
| Maximum power current ($I_{max}$) | 8.63 A |
| No. of cells in a module | (12 rows × 6 columns) 72 nos. |
| Module dimensions (mm) | 1920 (L) × 975 (W) × 40 (T) |
| Area of single module | 1.872 $m^2$ |
| No. of Solar modules | 110 |
| Net area required for solar array | 206 $m^2$ [without considering the space between two row and two panel, geometric constraint, corners of the buildings] |
| Capacity of each module | 320 W |
| System generation capacity at STC | 35.2 $kW_p$ |
| No. of modules per kW | 3.125 per kW |
| No. of modules in a panel | 10 |
| No. of panels in a array | 11 |
| Total no. of arrays | 1 |
| Details of series / parallel combination | 10 nos. in series with 11 rows in parallel |
| Operating Temperature | Min 15° and Max 40°C |
| Title angle (slop) of PV module | 20° |
| Wind speed rating | 150 km $h^{-1}$ |
| Mounting | Fixed type |
| Output of the PV array to be connected to the PCU | Nominal 35 kW |
| Weight/module, kg | About 20 to 22 kg |
| Protective device | 400 volts under voltage relay |
| Other devices | Junction boxes, meters, distribution boxes, wiring materials, mounting materials, etc. |

efficiencies typically range from 11% to 15%, with an average surface area requirement of 8 to 10 $m^2$ $kW_p^{-1}$. Detailed specifications of the PV modules are provided in Table 2.

*Solar module mounting structure*: The solar panels are supported by hot-dip galvanized mild steel mounting structures with a material thickness of approximately 2.5 mm. These structures are engineered with multiple components to ensure durability against harsh weather conditions while requiring minimal maintenance. The entire photovoltaic (PV) system is mounted on metal frames anchored to concrete pillars. Stainless steel fasteners secure the structures, which are further reinforced with 25 cm × 25 cm × 15 cm reinforced cement concrete blocks to withstand high winds. The design allows for an optimal tilt angle tailored to the site's geographical location, typically set equal to the latitude of the area. For this system, located in Dediapada, the solar PV panels are tilted at 20° facing south with an azimuth angle of 0° to maximize solar radiation capture and avoid shading. The structure maintains a clearance of 170 cm at the upper side and 12 cm at the lower side from the roof level. The long legs of the structure measure 125 cm in height, while the short legs are 19 cm. A figure illustrates the PV system at its installation site.

*Inverter system*: The system employs 3-phase transformer-based DC/AC inverters with capacities of 20 kW and 15 kW from KSTAR (Table 3). These inverters perform two key functions: converting DC power from the PV

*Table 3. Inverter specifications*

| Parameters | Specifications |
|---|---|
| Model | KSG-20K and KSG-15K |
| No. of Inverter | Two |
| Maximum PV array open circuit voltage | 1000 V DC |
| Type | Grid Export Condition (GEC) |
| Efficiency | Almost 90 to 95 % |
| No. of Phases | 3 - φ |
| Nominal input voltage | 620 V DC |
| PV input operating voltage range | 250-950 V DC |
| Maximum operating PV input current | 21 A DC × 2 |
| Maximum total PV array short-circuit current | 23 A DC × 2 |
| Nominal AC output voltage | 3/N/PE 400 V AC / 230 V AC |
| Nominal AC output frequency | 50 Hz |
| Maximum AC output over current protection | 32 A AC |
| Maximum continuous AC output current | 29 A AC |
| Maximum continuous AC output power | 22 KVA |
| Power factor range | 0.8 under-excited to 0.8 over-excited |
| Ingress protection | IP65 |

arrays to AC power and tracking the maximum power point (MPPT) of the modules. The AC power output is suitable for operating AC appliances or feeding directly into the utility grid. The 20 kW and 15 kW inverters have an MPPT voltage range of 250–950 V DC, with maximum continuous AC output power of 22 kVA and 16 kVA, respectively, and an output voltage of 415 V AC, three-phase, 50 Hz. The nominal apparent power is 20 kVA for the 20 kW inverter and 15 kVA for the 15 kW inverter. The inverters achieve a rated efficiency ranging from 90% to 95% (Table 3).

*Metering and connection accessories*: The system is equipped with meters to monitor its performance, with certain meters capable of tracking household energy consumption. Beyond the solar modules and inverters, connection accessories play a critical role in the system's functionality. These include an array junction box, AC distribution board, PVC copper cables of varying sizes and lengths as needed, multi-contact male and female cable couplers, nuts, bolts, screws, sockets, earthing wires, and cable ties.

*Integration of SPV power with grid*: The solar PV system generates DC power, which is fed into the inverter for conversion to AC power. This AC power is then synchronized and supplied to the Gujarat state grid. In the event of grid failure or abnormal voltage levels (either too low or too high), the solar PV system automatically disconnects from the grid for safety. A data logger records the DC voltage and current input to the inverter, as well as the energy output from the inverter. The system's

*Table 4. Specifications of grid and solar photovoltaic power plant*

| Grid details | |
|---|---|
| No. of phases | 3 - ϕ |
| Voltage rating | 400 Volts AC |
| Frequency | 50 Hz |
| Solar photovoltaic power plant | |
| Plant capacity | 35.2 kW |
| Voltage output | 250 Volts DC o/p OCV |
| Current output | 16A DC |
| No. of Modules | 110 nos. |
| Area | Approximate 350 m² |

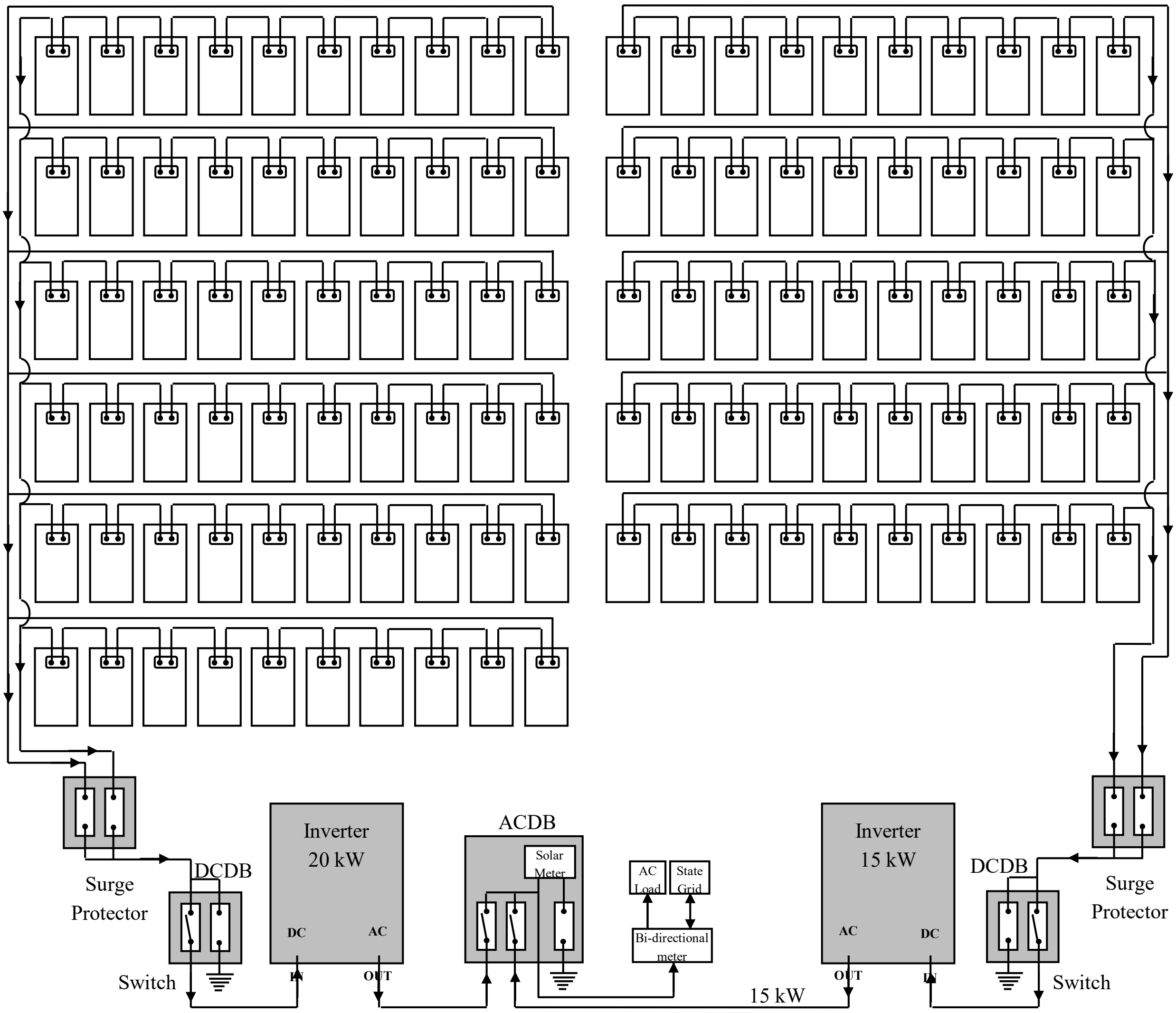

*Fig. 2. Schematic layout of installed system.*

schematic layout is depicted in Fig. 2 and 3, while the installed system is illustrated in Fig. 4 and 5.

Earthing the positive or negative conductor of the panels, or back-contact panels, is essential to protect against voltage corrosion and ensure

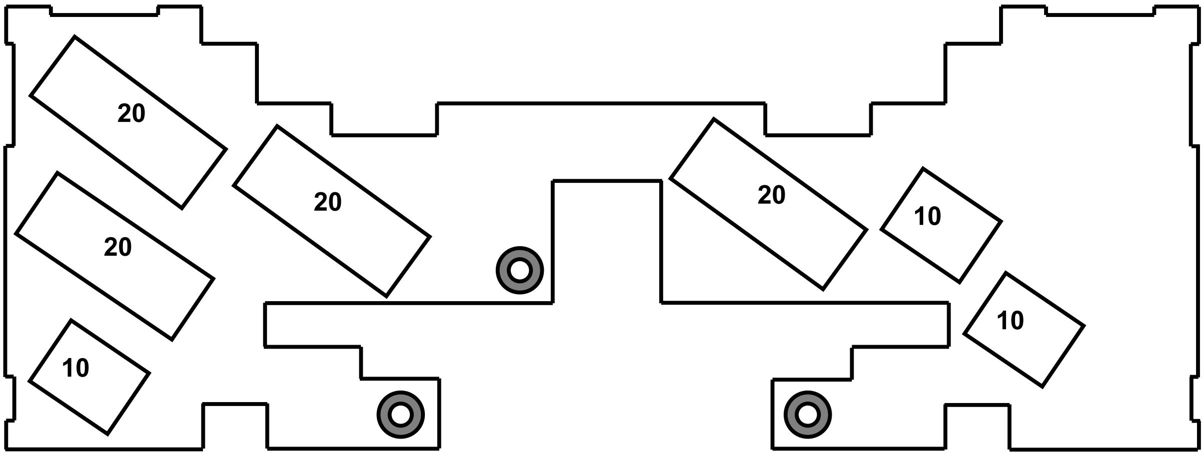

*Fig. 3. Layout of the terrace (Number of SPV modules arranged on one structure).*

*Fig. 4. 35.2 kWp rooftop grid interactive solar PV system and GI supporting structures with concrete pillars.*

electrical safety. Earthing safeguards system components from surges, such as those caused by lightning strikes. The PV panel frame, typically part of the earth-fault current path (negative polarity of the DC circuit), must be electrically bonded to the installation's earthing system. Earthing bonds for PV module frames are prone to corrosion and weathering, necessitating careful material selection (e.g., avoiding dissimilar metal contact between aluminium and copper) to ensure durability.

*Performance analysis*: The International Electrotechnical Commission (IEC) established the IEC 61724 standard in 1998, outlining parameters for assessing photovoltaic system performance (Photovoltaic, 2010). This standard was adopted by the Bureau of Indian Standards (BIS, 2010) in the same year. Data collection for this project commenced in January 2019. To evaluate the electrical performance of the grid-connected photovoltaic system, key parameters such as array yield, final yield, reference yield, PV module efficiency, inverter efficiency, system efficiency, performance ratio, capacity utilization factor, and energy losses were analysed using data gathered over a 12-month period from January 1, 2019, to December 31, 2022. These parameter values for the assessment period were also compared with the average values from the preceding three years.

*Array yield*: The array yield ($Y_a$) [Eq. 1] is defined as the ratio of the energy output from the PV array over a specific period (daily, monthly, or yearly) to the rated PV power (Ppv, rated = 35.2 $kW_p$), as described by Ayompe *et al*. (2011). Here, $P_{DC,\ daily}$ represents the total daily DC energy output (kWh).

*Final yield*: The final yield ($Y_{FD}$) [Eq. 2] is the ratio of the net AC energy output of the entire PV system—supplied by the array over a daily, monthly, or annual period—to the rated power of the installed PV array, as outlined by Ayompe *et al*. (2011). Here, $P_{AC,d}$ denotes the total daily AC energy output (kWh).

*Reference yield*: The reference yield (Yr) [Eq. 3] is calculated as the total daily in-plane solar irradiation $G_t$ (kWh m$^{-2}$) divided by the reference irradiation Gi-ref (1 kWh m$^{-2}$), representing the number of peak sun-hours per day (h/d), as specified by Ayompe *et al*. (2011).

$$Y_a = P_{(DC,daily)} / P_{(pv,rated)} \quad \ldots 1$$

*Fig. 5. 20 kW and 15 kW DC/AC 3-phase inverters, solar meter and bi-directional meter.*

$Y_{FD}=P_{(AC,d)}/P_{(pv,rated)}$ …2

$Y_r=G_t/G_{(i,ref)}=(G_t\ kWh/m^2)/(1\ kW/m^2)$ …3

*PV module efficiency*: The instantaneous PV module efficiency (ηpv) [Eq. 4] is calculated as per Ayompe *et al*. (2011), with the PV module area ($A_m$) set at 206.00 m².

Inverter efficiency: The instantaneous inverter efficiency ($\eta_{inv}$) [Eq. 5] and monthly inverter efficiency ($\eta_{inv}$, month) [Eq. 6] are defined by Ayompe *et al*. (2011). Here, $P_{AC,D}$ and $P_{DC,D}$ represent the monthly average daily total AC output (kWh) and DC output (kWh), respectively.

$\eta_{pv}=[P_{DC}/(G_t{*}A_m)]\times 100$ …4

$\eta_{inv}=P_{AC}/P_{DC}$ …5

$\eta_{(inv,m)}=(P_{AC,D}/P_{DC,D})\times 100$ …6

*System efficiency*: The instantaneous PV system efficiency (ηsys, %) [Eq. 7] is determined by multiplying the PV module efficiency (ηpv, %) by the inverter efficiency (ηinv, %), as described by Ayompe *et al*. (2011) and Drif *et al*. (2007). System efficiency is also expressed by [Eq. 8], where PAC,d is the total daily AC energy output (kWh).

$\eta_{sys}=\eta_{pv}\times\eta_{inv}$ …7

$\eta_{sys,d}=P_{AC,d}/(G_t\times A_m)$ …8

*Capacity utilisation factor*: The capacity utilization factor (CUF) [Eq. 9] is the ratio of the actual annual energy generated by the PV system ($E_{AC,a}$) to the energy it would produce if operating at its full rated power for 24 hours per day over a year, as outlined by Ayompe *et al*. (2011) and Vasisht *et al*. (2016). It can also be expressed as CUF = [(Peak sun h $d^{-1}$) (24 h $d^{-1})^{-1}$]. A system operating continuously at full rated power would have a CUF of 100%. The CUF is location-specific and does not account for environmental factors such as year-to-year irradiance variations or panel degradation. Higher CUF values indicate better system performance. In India, rooftop solar PV systems typically achieve a CUF of 16–17% (Pundir *et al*., 2016). Here, $E_{AC,a}$ is the annual AC energy output, and Ppv, rated is the rated PV power.

$CUF= [(E_{AC,a})/(P_{(pv,rated)}\times 24\times 365)]\times 100$ …9

*Performance ratio:* The performance ratio (PR) reflects the cumulative impact of losses on the system's rated output, including losses from PV module temperature, incomplete use of incident solar radiation, inverter inefficiencies, wiring mismatches, soiling, or component failures. PR is a dimensionless metric, typically higher in winter than in summer due to temperature-related losses. Values generally range from 0.6 to 0.8, depending on location, solar irradiance, and climatic conditions (Marion *et al*., 2005). PR does not directly indicate energy production, as a system with a low PR in a high-irradiance area may generate more energy than a high-PR system in a low-irradiance region. It quantifies total losses during DC-to-AC conversion and is used to monitor long-term performance changes, with decreasing PR values over time indicating performance degradation. PR is defined as the ratio of the energy fed to the grid (YF = final yield, $kWhk^{-1}W_pd^{-1}$) to the energy the system could produce at DC rated power for the peak sun hours per day (YR = reference yield, $kWhk^{-1}W_pd^{-1}$), expressed as:

$PR=Y_F/Y_R$ ...10

*Energy losses*: The photovoltaic (PV) system experiences various losses, including array capture loss, system losses, and total losses.

*Capture Loss ($L_c$):* Defined by Ayompe *et al*. (2011), capture loss is calculated as the difference between the reference yield (YR) and the array yield (YA):

$L_c=Y_R-Y_A$ ...11

*System Losses (Ls):* These occur during the conversion of DC to AC by the inverter, as described by Kymakis *et al*. (2009):

$L_s=Y_A-Y_F$ ...12

*Inverter loss (Linv)*: Inverter loss is calculated using the equation:

$L_{inv}=1-(P_{AC}/P_{DC})$ ...13

Inverter losses are influenced by factors such as DC input power, voltage fluctuations, inverter temperature, and grid voltage, making them complex to quantify. Reported conversion losses range from 13% (Mondol *et al*., 2006), 9.62-17.7% (Baltus *et al*., 1997), to 6.3-16.8% (Alonso-Abella *et al*., 2005). For high-quality inverters, losses are typically around 5% (Hegedus and Luque, 2011).

Total loss: $L_T=Y_R-Y_F= L_c+L_s$ …14

*Table 5. Various yield calculated for each month (Year 2022)*

| Month | Average solar radiation in kWh m$^{-2}$ | Energy at inverters in kWh | Energy at meters in kWh | Array yield | Final yield | Reference yield |
|---|---|---|---|---|---|---|
| January | 5.3 | 139.8 | 134.7 | 4.0 | 3.8 | 5.3 |
| February | 6.4 | 153.6 | 148.2 | 4.4 | 4.2 | 6.5 |
| March | 6.3 | 152.7 | 146.9 | 4.4 | 4.2 | 6.3 |
| April | 6.2 | 159.4 | 153.4 | 4.6 | 4.4 | 6.2 |
| May | 6.5 | 139.0 | 134.6 | 4.0 | 3.8 | 6.4 |
| June | 5.9 | 148.1 | 142.6 | 4.2 | 4.1 | 5.9 |
| July | 3.7 | 110.7 | 106.6 | 3.2 | 3.0 | 3.7 |
| August | 4.1 | 064.3 | 060.8 | 1.8 | 1.7 | 4.3 |
| September | 5.3 | 151.6 | 143.0 | 4.3 | 4.1 | 5.3 |
| October | 5.3 | 143.0 | 134.7 | 4.1 | 3.8 | 5.3 |
| November | 5.4 | 148.2 | 142.1 | 4.2 | 4.1 | 5.4 |
| December | 4.6 | 160.6 | 150.4 | 4.6 | 4.3 | 4.8 |
| Average | 5.4 | 139.3 | 133.2 | 4.0 | 3.8 | 5.5 |
| Data of year 2021 | | | | | | |
| Average | 5.3 | 133.8 | 128.2 | 3.8 | 3.7 | 5.3 |
| Data of year 2020 | | | | | | |
| Average | 6.3 | 160.3 | 154.0 | 4.6 | 4.4 | 6.3 |
| Data of year 2019 | | | | | | |
| Average | 6.9 | 171.8 | 160.4 | 4.9 | 4.6 | 6.9 |

Average array yield = 4.325 kWhk$^{-1}$W$_p$d$^{-1}$
Average final yield = 4.125 kWhk$^{-1}$W$_p$d$^{-1}$
Average reference yield = 6.000 kWhk$^{-1}$W$_p$d$^{-1}$

## Results and Discussions

### *Energy production, efficiency and losses*

The array yield, final yield, and reference yield were computed and are presented in Table 5. Monthly average solar radiation on the tilted PV array was lowest in July 2022 (3.7 kWh m$^{-2}$ d$^{-1}$) and highest in May 2022 (6.5 kWh m$^{-2}$ d$^{-1}$). The annual average monthly yields for array, final, and reference yields were 4.9, 4.6, and 6.9 h d$^{-1}$ for 2019; 4.6, 4.4, and 6.3 h d$^{-1}$ for 2020; 3.8, 3.7, and 5.3 h d$^{-1}$ for 2021; and 4.0, 3.8, and 5.5 h d$^{-1}$ for 2022, respectively (Table 5). The highest final yield of 4.4 kWhk$^{-1}$W$_p$d$^{-1}$ was recorded in April 2022, attributed to clear skies, while the lowest final yield of 1.7 kWhk$^{-1}$W$_p$d$^{-1}$ occurred in August 2022 due to reduced energy production. The annual average final yield was 3.8 kWhk$^{-1}$W$_p$d$^{-1}$, equivalent to 1,387.0 kWh kW$_p$$^{-1}$ yr$^{-1}$, which is notably high. This final yield surpasses values reported in earlier Indian studies (Table 6), likely due to

*Table 6. Performance summary of grid connected P-Si PV systems in India.*

| Reference | System size(kWp) | Final yield (kWhk$^{-1}$ W$_p$d$^{-1}$) | PV module efficiency (%) | Inverter efficiency (%) | Performance ratio (%) |
|---|---|---|---|---|---|
| Present study (2019-2022) | 35.2 | 4.125 | 12.53 | 95.25 | 68.85 |
| Sharma and Goel (2017) | 11.2 | 3.67 | 13.42 | 89.83 | 78.00 |
| Vasisht *et al.* (2016) | 20.0 | 4.1 | 13.71 | - | 85.00 |
| Pundir *et al.* (2016) | 1816 | - | 08.76 | - | 63.58 |
| Sundaram and Babu (2015) | 5000 | 4.81 | 06.08 | 88.2 | - |
| Kumar and Sudhakar (2015) | 10000 | 1.96-5.07 | 13.30 | 97.0 | 86.12 |
| Sharma and Chandel (2013) | 190 | 2.23 | - | - | 74.00 |
| Padmavathi and Daniel (2013) | 3000 | 3.75 | - | - | 00.70 |
| Kamalapur and Udaykumar (2011) | 50 | - | - | - | 55-89 |

*Table 7. Various efficiencies calculated for each month (Year 2022)*

| Month | Total solar radiation in kWh m$^{-2}$ | DC power in kW | Instantaneous PV module efficiency | Instantaneous inverter efficiency | Monthly inverter efficiency | Instantaneous PV system efficiency | System efficiency |
|---|---|---|---|---|---|---|---|
| January | 5.3 | 139.8 | 12.7 | 96.1 | 96.3 | 12.2 | 12.3 |
| February | 6.5 | 153.6 | 11.9 | 96.5 | 96.5 | 11.5 | 11.1 |
| March | 6.3 | 152.7 | 12.6 | 97.1 | 96.2 | 12.2 | 11.4 |
| April | 6.2 | 159.4 | 12.6 | 96.3 | 96.3 | 12.1 | 12.1 |
| May | 6.4 | 139.0 | 10.3 | 96.8 | 96.8 | 10.0 | 10.2 |
| June | 5.9 | 148.1 | 12.5 | 96.2 | 96.2 | 12.0 | 11.8 |
| July | 3.7 | 110.7 | 11.5 | 96.2 | 96.3 | 11.9 | 11.1 |
| August | 4.1 | 064.3 | 12.1 | 95.8 | 95.5 | 11.4 | 10.8 |
| September | 5.3 | 151.6 | 13.4 | 94.7 | 94.3 | 12.7 | 13.0 |
| October | 5.3 | 143.0 | 13.5 | 91.9 | 94.2 | 12.4 | 12.4 |
| November | 5.4 | 148.2 | 13.3 | 94.2 | 95.9 | 12.6 | 12.8 |
| December | 4.6 | 160.6 | 12.8 | 95.3 | 95.7 | 12.8 | 12.3 |
| Average | 5.4 | 139.3 | 12.4 | 95.6 | 95.8 | 12.0 | 11.8 |
| Data of Year 2021 | | | | | | | |
| Average | 5.3 | 133.8 | 12.4 | 95.7 | 95.8 | 11.9 | 11.7 |
| Data of Year 2020 | | | | | | | |
| Average | 6.3 | 160.3 | 12.8 | 95.6 | 96.0 | 12.2 | 12.1 |
| Data of Year 2019 | | | | | | | |
| Average | 6.9 | 171.8 | 12.5 | 94.4 | 93.4 | 11.8 | 11.2 |

a higher average daily in-plane irradiance of 4.73 kWh m$^{-2}$ d$^{-1}$. Compared to studies from 2013 with lower irradiance (2.30-3.53 kWh m$^{-2}$ d$^{-1}$) (Sharma and Chandel, 2013), the final yield is higher, but it aligns with a 4.1 kWhk$^{-1}$ W$_{p}$d$^{-1}$ yield reported in 2016 studies in India (Vasisht *et al.,* 2016).

The efficiencies of the PV module, inverter, and overall system were computed and are presented in Table 7. During the testing period from January 2019 to December 2022, the PV module efficiency, inverter efficiency, and system efficiency were recorded as 12.53%, 95.25%, and 11.70%, respectively. The annual average monthly efficiencies for the PV module, inverter, and system were 12.5%, 93.4%, and 11.2% for 2019; 12.8%, 96.0%, and 12.1% for 2020; 12.4%, 95.8%, and 11.7% for 2021; and 12.4%, 95.8%, and 11.8% for 2022, respectively (Table 7). These values surpass those reported in earlier Indian studies by Sundaram and Babu (2015) with 6.08% and Pundir *et al.* (2016) with 8.76%, but are lower than those reported by Sharma and Goel (2017) with 13.42%, Vasisht *et al.* (2016) with 13.71%, and Kumar and Sudhakar (2015) with 13.30%.

*Capacity utilization factor (CUF) and Performance ratio (PR)*: The annual average capacity utilization factor (CUF) was determined for the testing period from January 2019 to December 2022. In 2022, the annual AC energy output was 48,674.8 kWh, with the system's rated PV power at 35.2 kW$_{p}$. The highest CUF value of 17.1% was recorded in 2019, while the lowest value of 15.8% was observed in both 2020 and 2021. The average CUF across the period was 16.1%. This is lower than the 17.68% CUF reported by Shudhakar and Shiva Kumar (2015). In India, CUF for PV plants typically ranges from 12.29% to 18.80% based on one year of operation, with variations attributed to system losses influenced by local climatic conditions. However, the average CUF of 17.1% for this plant closely aligns with values reported for other solar PV plants in India (MNRE, 2011).

The data indicate that the PV system maintained relatively stable performance over the four-year period from 2019 to 2022, with minor fluctuations in CUF and PR. In 2019, CUF was 17.1% and PR was 0.6667, indicating moderate capacity use and efficiency. For 2020, CUF decreased to 15.8% while PR increased to 0.6984, suggesting stable output with

*Table 8. Different losses occurred during the experiment (Year 2022)*

| Month | Capture loss $L_c = Y_R - Y_A$ | System losses $L_s = Y_A - Y_F$ | Loss in inverter $L_{inv} = 1 - (P_{AC}/P_{DC})$ | Total loss $L_s = Y_R - Y_F$ |
|---|---|---|---|---|
| January | 1.3 | 0.2 | 0.0394 | 1.5 |
| February | 2.1 | 0.2 | 0.0347 | 2.3 |
| March | 1.9 | 0.2 | 0.0289 | 2.1 |
| April | 1.6 | 0.2 | 0.0371 | 1.8 |
| May | 2.4 | 0.2 | 0.0316 | 2.6 |
| June | 1.7 | 0.1 | 0.0383 | 1.8 |
| July | 0.5 | 0.2 | 0.0377 | 0.7 |
| August | 2.5 | 0.1 | 0.0420 | 2.6 |
| September | 1.0 | 0.2 | 0.0534 | 1.2 |
| October | 1.2 | 0.3 | 0.0810 | 1.5 |
| November | 1.2 | 0.1 | 0.0578 | 1.3 |
| December | 0.2 | 0.3 | 0.0470 | 0.5 |
| Average | 1.5 | 0.2 | 0.0441 | 1.7 |
| Data of year 2021 | | | | |
| Average | 1.5 | 0.2 | 0.0431 | 1.7 |
| Data of year 2020 | | | | |
| Average | 1.4 | 0.5 | 0.0669 | 1.9 |
| Data of year 2019 | | | | |
| Average | 2.0 | 0.3 | 0.1000 | 2.4 |

improved efficiency. In 2021, CUF remained at 15.8% and PR was 0.6981, reflecting consistent performance. In 2022, CUF slightly increased to 15.9% and PR decreased to 0.6909, with an average CUF of 16.1% and PR of 0.6885 over the period. The CUF ranged from 15.8% to 17.1%, with an average of 16.1%, suggesting moderate utilization of the system's rated capacity. The PR ranged from 0.6667 to 0.6984, with an average of 0.6885, reflecting consistent but sub-optimal energy conversion efficiency, likely influenced by environmental or operational factors. These metrics provide insights into the system's operational reliability and potential areas for optimization, such as addressing losses to improve PR or increasing energy output to enhance CUF. The average CUF across the four years is 16.1%, reflecting the overall operational efficiency of the PV system during this period. The average PR over the period is 0.6885, indicating that, on average, the system operated at approximately 68.85% of its ideal performance.

The data presented in Table 8 quantifies the various energy losses in a 35.2 $kW_p$ grid-connected rooftop solar photovoltaic (PV) system during the experimental period spanning 2019 to 2022, with a detailed monthly breakdown for the year 2022. The table includes four types of losses: Capture Loss ($L_c$), System Losses ($L_s$), Inverter Loss ($L_{inv}$), and Total Loss ($L_t$). These losses reflect inefficiencies at different stages of energy conversion and transmission within the PV system.

For the year 2022, monthly data reveal variations in losses influenced by environmental and operational factors. Capture Loss ($L_c$), which represents the energy lost due to factors like shading, soiling, or module degradation, ranged from 0.2 in December to 2.5 in August, averaging 1.5 across the year. System Losses ($L_s$), attributed to the conversion of DC to AC by the inverter, remained relatively stable, varying between 0.1 (June, August, November) and 0.3 (October, December), with an annual average of 0.2. Inverter Loss ($L_{inv}$), indicating the inefficiency of the inverter, fluctuated between 0.0289 in March and 0.0810 in October, averaging 0.0441, with higher values in September and October. Total Loss ($L_{t)}$, the cumulative effect of capture and system losses, ranged from 0.5 in December to 2.6 in May and August, averaging 1.7 for the year.

Annual average data from 2019 to 2021 provide a comparative perspective. In 2019, the average Capture Loss was higher at 2.0,

*Table 9. Monthly energy generation by PV plant and unit supplied to Grid*

| Month | Energy generation by PV plant, kWh | | | | Unit supplied to grid, kWh | | | |
|---|---|---|---|---|---|---|---|---|
| Year | 2019 | 2020 | 2021 | 2022 | 2019 | 2020 | 2021 | 2022 |
| January | 5324.8 | 4680.5 | 4165.8 | 4873.4 | 4293.8 | 3968.8 | 4073.5 | 5124.2 |
| February | 4994.5 | 4583.1 | 3921.7 | 4504.4 | 3984.3 | 3844.8 | 3746.2 | 4771.5 |
| March | 6089.9 | 5725.7 | 5355.1 | 5195.0 | 4979.2 | 4939.2 | 5038.6 | 4782.1 |
| April | 5399.4 | 5423.1 | 4427.0 | 4895.2 | 4426.6 | 4820.6 | 4368.0 | 3632.7 |
| May | 5724.9 | 4975.6 | 4668.1 | 4328.0 | 4582.8 | 4226.1 | 4423.9 | 3654.4 |
| June | 4052.7 | 3993.2 | 4092.2 | 4104.5 | 3443.6 | 3235.0 | 3919.7 | 4277.6 |
| July | 3411.0 | 3474.5 | 3378.5 | 2595.8 | 3064.2 | 2805.7 | 3285.9 | 2803.0 |
| August | 2181.7 | 2597.2 | 3100.8 | 3325.2 | 1983.7 | 2154.0 | 3055.4 | 3088.5 |
| September | 3121.2 | 3793.9 | 2876.1 | 1262.3 | 2592.9 | 3281.7 | 2786.7 | 2947.6 |
| October | 4498.1 | 4103.3 | 4707.0 | 4584.7 | 3749.1 | 3583.2 | 4507.8 | 4176.5 |
| November | 4013.6 | 4191.4 | 4129.7 | 4490.6 | 3331.2 | 3578.6 | 4024.5 | 4205.1 |
| December | 3538.8 | 4313.7 | 3658.6 | 4515.7 | 2870.5 | 3807.6 | 3612.4 | 3746.4 |
| | Annual energy generation (kWh) | | | | Annual energy supplied to grid (kWh) | | | |
| | 52350.6 | 51855.2 | 48480.6 | 48674.8 | 43301.9 | 44245.3 | 46842.6 | 47209.6 |
| | Average energy generation 50340.3 kWh<br>Total energy generation 201361.0 kWh | | | | Average energy supplied to Grid 45399.9 kWh<br>Total energy supplied to Grid 181599.0 kWh | | | |

System Losses were 0.3, Inverter Loss was significantly higher at 0.1000, and Total Loss was 2.4, indicating less efficiency compared to later years. In 2020, Capture Loss decreased to 1.4, but System Losses increased to 0.5, Inverter Loss reduced to 0.0669, and Total Loss was 1.9. For 2021, the averages were 1.5 ($L_c$), 0.2 ($L_s$), 0.0431 ($L_{inv}$), and 1.7 (Lt), showing improved inverter performance compared to 2020. The consistency in average Total Loss (1.7) for 2021 and 2022 suggests stable overall system performance despite monthly variations. The relatively low Inverter Loss values in 2021 and 2022 (0.0431 and 0.0441) compared to 2019 (0.1000).

## *Environment benefits*

*Monthly energy generated and supplied*: The PV modules convert solar energy into electrical energy, with power output primarily influenced by weather conditions such as solar irradiance, wind speed, and ambient temperature. Daily power output from the PV modules varies depending on the availability of solar radiation. During the rainy season, cloudy days, or periods of low solar irradiance, the PV plant may experience reduced or halted power generation. The average power output, monthly energy production, and annual energy generation of the plant are detailed in Tables 12 and 13. Energy generation data were recorded using a solar meter installed downstream of the 15 kW and 20 kW inverters. The units supplied to the grid were measured by a bi-directional meter placed immediately after the solar meter, with meter readings collected daily at 5:30 PM.

Electricity generation from photovoltaic (PV) systems or other renewable energy sources significantly benefits the environment. In contrast, coal-based thermal power plants emit substantial quantities of greenhouse gases (GHGs) such as carbon dioxide ($CO_2$), nitrogen oxide (NOx), sulfur dioxide ($SO_2$), and ash. The annual energy output from the solar power

*Table 10. Greenhouse gasses reduction by 35.2kWp PV system for the year 2019 to 2022*

| GHG from coal fired thermal power plant | Emission per kWh of electricity (g $kWh^{-1}$) | Total emission reduction | | | | Reference |
|---|---|---|---|---|---|---|
| | | Year 2019 (kg 52350.6 $kWh^{-1}$) | Year 2020 (kg 51855.2 $kWh^{-1}$) | Year 2021 (kg 48480.6 $kWh^{-1}$) | Year 2022 (kg 48674.8 $kWh^{-1}$) | |
| $CO_2$ | 980.00 | 51303.59 | 50818.10 | 47510.99 | 47701.30 | Vasisht *et al.* (2016) |
| $SO_2$ | 1.24 | 64.91 | 64.30 | 60.11 | 60.36 | Tarigan and Kartikasari (2015) |
| NOx | 2.59 | 135.59 | 134.30 | 125.56 | 126.07 | |
| Ash | 68.00 | 3559.84 | 3526.15 | 3296.68 | 3309.89 | |

*Table 11. Actual energy supplied from solar to GEB (Data from Electricity bill (CAET) during Jan 2019 to Dec 2022*

| Month | Monthly energy unit exported/supplied to GEB (kWh) | | | | Monthly energy unit imported/consumed from GEB (kWh) | | | | Monthly surplus energy unit (kWh) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | 2019 | 2020 | 2021 | 2022 | 2019 | 2020 | 2021 | 2022 | 2019 | 2020 | 2021 | 2022 |
| January | 2932 | 3190 | 4920 | 4842 | 980 | 150 | 155 | 620 | 1952 | 3040 | 4765 | 4222 |
| February | 4655 | 3750 | 3949 | 4473 | 1270 | 144 | 194 | 513 | 3385 | 3606 | 3755 | 3960 |
| March | 3230 | 4080 | 4248 | 3734 | 1210 | 145 | 152 | 540 | 2020 | 3935 | 4096 | 3194 |
| April | 4720 | --- | 6449 | 5151 | 420 | 0 | 286 | 927 | 4300 | --- | 6163 | 4224 |
| May | 5416 | 10610 | 6294 | 3060 | 800 | 324 | 178 | 1440 | 4616 | 10286 | 6116 | 1620 |
| June | 3450 | 3352 | 4784 | 4819 | 180 | 269 | 226 | 1261 | 3270 | 3083 | 4558 | 3558 |
| July | 3360 | 3357 | 5295 | 3255 | 85 | 158 | 280 | 932 | 3275 | 3199 | 5015 | 2323 |
| August | 2175 | 2228 | 5593 | 2767 | 55 | 153 | 416 | 827 | 2120 | 2075 | 5177 | 1940 |
| September | 2384 | 3198 | 5555 | 4324 | 140 | 147 | 523 | 836 | 2244 | 3051 | 5032 | 3488 |
| October | 3610 | 8356 | 5781 | 1845 | 280 | 193 | 530 | 1300 | 3330 | 8163 | 5251 | 545 |
| November | 3352 | 4375 | 4752 | 4958 | 210 | 135 | 391 | 645 | 3142 | 4240 | 4361 | 4313 |
| December | 3390 | 4756 | 4087 | 3468 | 190 | 210 | 631 | 742 | 3200 | 4546 | 3456 | 2726 |
| Total | 42671 | 51252 | 61707 | 46696 | 5820 | 2028 | 3962 | 10583 | 36851 | 49224 | 57745 | 36113 |
| Total of four years | 2,02,326 kWh | | | | 22,393 kWh | | | | 1,79,933 kWh | | | |

plant was recorded as 52,350.6 kWh in 2019, 51,855.2 kWh in 2020, 48,480.6 kWh in 2021, and 48,674.8 kWh in 2022. Over the four-year period, this system achieved an average annual reduction of approximately 49,333 kg of CO$_2$, 62 kg of SO$_2$, 130 kg of NOx, and 3,423 kg of ash from the atmosphere, as detailed in Table 10.

Monthly electricity bills from the Gujarat Electricity Board (GEB) were used to calculate the actual energy generated by the 35.2 kW$_p$ solar photovoltaic (SPV) system, the energy supplied to GEB, the energy received from GEB, and the energy consumed to power the college building. Over the four-year period from January 2019 to December 2022, the total energy exported to GEB was 202,326 kWh, while the total energy imported from GEB was 22,393 kWh, as recorded in the GEB electricity bills for the College of Agricultural Engineering and Technology (CAET). Table 11 indicates that surplus energy was available each month, with total surplus units of 36,851, 49,224, 57,745, and 36,113 kWh accumulated with GEB during the 12-month periods of 2019, 2020, 2021 and 2022, respectively. These results in a total surplus energy of 179,933 kWh supplied to GEB. Notably, the inverter underwent repairs due to a circuit issue during September and October 2022, rendering the system non-operational during this period. Consequently, the surplus energy recorded in these months was significantly lower compared to other months in 2022.

### *System costing and consumer refund credit*

The total cost of the 35.2 kWp grid-connected rooftop solar photovoltaic (SPV) system, encompassing all components such as mounting structures, 110 solar PV modules, two inverters, cables, metering devices, earthing kits, and various connection accessories, was Rs. 17,60,150 after subsidies. In 2017, the approximate cost per kW was Rs. 50,000. This cost included taxes, levies, duties, packing, forwarding, freight, insurance, loading, unloading, supply, installation, commissioning, and all associated charges for successful system deployment at the site. Following the system's installation in May 2018, consumer refund credits of Rs. 1,04,012 and Rs. 61,553 (totalling Rs. 1,65,565) were deposited into the college's bank account in May 2021 and April 2022, respectively, as part of the solar consumer refund credit billing.

## Conclusions

The performance of a 35.2 kWp photovoltaic system, installed on a reinforced cement concrete (RCC) flat roof of a college building approximately 10 meters tall in Dediapada, Narmada District, Gujarat (latitude 21.63°N, longitude 73.59°E), was monitored from January 2019 to December 2022. All electricity generated was supplied to the low-voltage grid serving the college building. The evaluated performance parameters included final yield, reference yield, array yield, system losses, array capture losses, cell temperature losses, PV module efficiency, system efficiency, inverter efficiency, performance ratio, and capacity utilization factor. The total annual energy output was 50,581.5 kWh for the 35.2 kWp system, equivalent to 1,437 kWh $kW_P^{-1}$. The annual average daily values for final yield, reference yield, and array yield were 4.125 $kWhk^{-1}W_Pd^{-1}$, 6.000 $kWhk^{-1}Wpd^{-1}$, and 4.325 $kWhk^{-1}Wpd^{-1}$, respectively. The annual average daily efficiencies for the PV module, system, and inverter were 12.5%, 11.2%, and 94.4% in 2019; 13.5%, 12.1%, and 93.3% in 2020; 12.4%, 11.7%, and 95.8% in 2021; and 12.4%, 11.8%, and 95.8% in 2022. The performance ratio of the 35.2 $kW_P$ solar PV plant averaged 100.0% over 12 months, indicating the overall efficiency of the system. The capacity utilization factor was 15.9%. The annual average system losses, capture losses, inverter losses, and total losses were 0.2, 1.5, 0.04, and 1.7, respectively.

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