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# Performance evaluation of three grid-connected monocrystalline silicon solar photovoltaic systems in Nepal

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**Abstract**

This study evaluates three grid-connected solar photovoltaic (PV) systems using four criteria: final yield, performance ratio, capacity utilization factor, and system efficiency. The PV systems were installed on the rooftop of the Nepal Telecom office at Sundhara, Pokhara, and Biratnagar. The generation data was collected through the web interface of the data logger installed at the sites. Long-term comparison (four years) of the plant at Sundhara and the same system comparison of plants at Pokhara and Biratnagar were performed. Long-term analysis of the plant at Sundhara found that the final yield decreased from 2.91 kWh/kW$_p$ in 2019 to 2.21 kWh/kW$_p$ in 2022. Similarly, the performance ratio decreased from 91.0% in 2019 to 67.3% in 2022, capacity utilization factor decreased from 12.1% in 2019 to 9.2% in 2022, and system efficiency decreased from 16.8% in 2019 to 12.5% in 2022. The same system installed at Pokhara and Biratnagar had slightly varied performance owing to the variation in meteorological parameters. The average air temperature at Biratnagar (26.7$^0$C) was higher than at Pokhara (13.1$^0$C) while the amount of solar radiation at Biratnagar was just higher by 4%. This led to the reduction of final yield by 9% at Biratnagar than at Pokhara as higher temperatures at Biratnagar caused more reduction in the power output from the solar panels. Finally, this study provides insights to researchers, PV installers, and panel manufacturers on the actual performance of grid-connected solar PV in Nepal.

***Keywords***: comparison; monocrystalline; grid-connected photo voltaic; long-term analysis; Nepal Telecom solar plants; performance parameter

## Introduction

Nepal's energy needs are mostly dependent on traditional sources like fuelwood. However, in the recent years, the use of commercial and renewable energy sources has been on the rise. The consumption of traditional fuel has decreased from nearly 90% to less than 70 % in 15 years while the consumption of commercial fuels, like petroleum, electricity and coal, has increased from nearly 10% to 30% during the same interval (Kathmandu University et al., 2022). Among the commercial sources, consumption of petroleum products, electricity, and other modern energy like coals, stood at 65%, 15%, and 20% respectively. However, the portion of modern renewable energy, solar and wind, is still less than 3% (Lohani et al., 2022).

Nepal has good sunshine for about 300 days a year and the solar radiation varies from 3.6 – 6.2 kWh/m$^2$/day (Water and Energy Commission Secretariat [WECS], 2010), with a national average of 4.66 kWh/m$^2$/day (Adhikari et al., 2013). After the 680.4 kW$_p$ solar photovoltaic (PV) plant at Kathmandu Upatyaka Khanepani

Limited (KUKL), Sundarighat, Lalitpur was connected to the national grid on Sept. 28, 2012, a lot of grid-tied projects have been commissioned in the recent years. A grid-tied or grid-connected PV system generates electricity through a solar PV power system and is connected to the utility grid. Its components include solar panels, grid inverters, power conditioning units, and grid connection equipment. July 2008 assessment of solar and wind energy in Nepal gives the commercial potential for grid connection of solar power to be about 2,100 MW (Nepal Electricity Authority [NEA], 2014). Recently, Nepal Electricity Authority has called for proposals to set up grid-tied solar plants through competitive bidding (Shrestha, 2022). They plan to buy a maximum of 100 MW of power from such solar plants at 16 locations across the country. This is the first time that NEA is buying power through bids. Earlier, it was fixed at Rs. 7.30 per unit based on the "Working Procedure on Grid Connected Alternative Electric Energy Development – 2017" formulated in February 2018, which was later capped at Rs. 5.94 per unit in March 2022. Bidding would require NEA to sign a power purchase agreement (PPA) with developers who pass the technical evaluation and offer competitive bids below the maximum price ceiling. As various technologies, such as mono-crystalline, poly-crystalline, and thin-film solar cells have been used in building the plants, it is necessary to consider their performance so that the developers can use the information to design their systems, be it for selling to NEA or other purposes.

This study considers the grid-connected plants with solar panels made from monocrystalline Silicon technology and evaluates their performance. Cells in monocrystalline panels are formed by making silicon into bars and cutting them into wafers (American Solar Energy Society, 2021). This process differs from the polycrystalline where the fragments of silicon are melted together to form the wafers. Because of this process, monocrystalline solar cells have a uniform dark appearance and rounded edges square with small spaces between each cell, while polycrystalline solar cells have a bluish hue and no rounded edges. Performance analysis requires a comparison of parameters such as final yield, performance ratio, capacity utilization factor, and system efficiency. There are various comparative studies of the performance of grid-connected PV plants globally. **Ameur et al.** (2022) performed long-term performance and degradation analysis of three silicon-based PV technologies including amorphous silicon, poly-crystalline silicon, and mono-crystalline silicon in Morocco. They found that crystalline silicon technologies were better than amorphous PV system based on performance ratio analysis with the values of 84.25% for mono, 84.32% for poly, and 79.14% for amorphous. Ayadi et al. (2022) investigated experimentally the performance of mono-crystalline, poly-crystalline, and thin-film solar panels under sunny climatic conditions. They found that mono-crystalline PV systems had better performance than other technologies in terms of specific yield per unit area (267 $kWh/m^2$), performance ratio (80.5%), and efficiency (12.8%), whereas thin-film systems performed somewhat better in specific yield per installed capacity compared to mono-crystalline due to its low-temperature coefficient. Bahanni et al. (2022) compared two mini-grid connected PV plants based on mono-crystalline, poly-crystalline and amorphous technologies located in Beni Mellal and El Jadida, Morocco. They found that ambient temperature had a greater impact on the performance ratio of mono-crystalline as for every $8^0$C rise in temperature, the PR decreased by 2.5%, 2%, and 1% for monocrystalline, polycrystalline, and amorphous technologies at Bemi Mellal. The values were 5.5%, 5.2%, and 3% at El Jadida. Bajracharya & Maharjan (2019) conducted a techno-economic analysis of a 64.6 kWp grid-tied mono-crystalline solar PV system installed at Nepal Telecom, Sundhara, and found that the performance ratio and capacity utilization factor was 85.9% and 14.09%, respectively. Elshazly et al. (2021) studied effect of high temperature and dust accumulation on solar panels in natural outdoor conditions at El-Sherouk City, Egypt and found that increase in temperature of monocrystalline panels by $10^0$ resulted in a degradation of panel's efficiency by approximately 7% and accumulation of dust on the surface of panels could reduce the efficiency by 30%. Owolabi et al. (2022) compared a 5 kWp grid-tied mono-crystalline silicon (m-si) solar PV system and a 4.6 kWp grid-tied poly-crystalline silicon (p-si) solar PV system installed on the rooftop of the Engineering building at Kyungpook National University, Republic of Korea and found that m-si solar cell technology performed better than the p-si solar cell annually when considering the final energy output, system yield, capacity factor, and system efficiency. But, the p-si solar cell outperformed the m-si solar technology in performance ratio. Satsangi et al. (2018) studied a 40 kW grid-interactive monocrystalline PV system installed at Dayalbagh Educational Institute, Agra, India and found that PV efficiency decreased as cell temperature increased. PV efficiencies were highest in rainy season due to the natural cleaning of panels and in winter due to lower temperatures. **Zain et al.** (2013) compared the performance of mono-crystalline and poly-crystalline PV plants using the performance ratio as an indicator. They found that the PR for monocrystalline was 77% and for polycrystalline, it was 80%; though the efficiency for mono was 11.8% compared to 11.5% for poly. This showed that a higher performance ratio just indicated higher energy yield compared to expected energy yield under STC and needs to be taken as relative data.

This study has the main objective of comparing the performance of monocrystalline Silicon (m-Si) PV plants installed at Nepal Telecom offices located at Biratnagar, Pokhara, and Sundhara with the following specific objectives.

- Long-term comparison of a system (NTC Sundhara).

- Comparison of system with the same components (NTC Pokhara and Biratnagar).

**Overview of the grid-tied solar photovoltaic systems**

Three grid-tied solar PV systems installed at Nepal Telecom offices at Sundhara, Biratnagar, and Pokhara were considered for this study. The PV systems follow the system archetype (Owolabi et al., 2022) as shown in Figure 1, where the solar panels and grid-tied inverter are the central components of the system. Variables like air temperature, wind speed, and solar irradiation are measured, which affects the performance of solar panels. The measured solar irradiation gives the reference yield based on which the yield of solar panels can be compared. The DC output of the panel gives the array yield, while the AC output gives the final yield; which is always less than the array yield because of inverter efficiency. The final energy output can be used to determine performance parameters such as performance ratio, capacity utilization factor, system efficiency, and final yield.

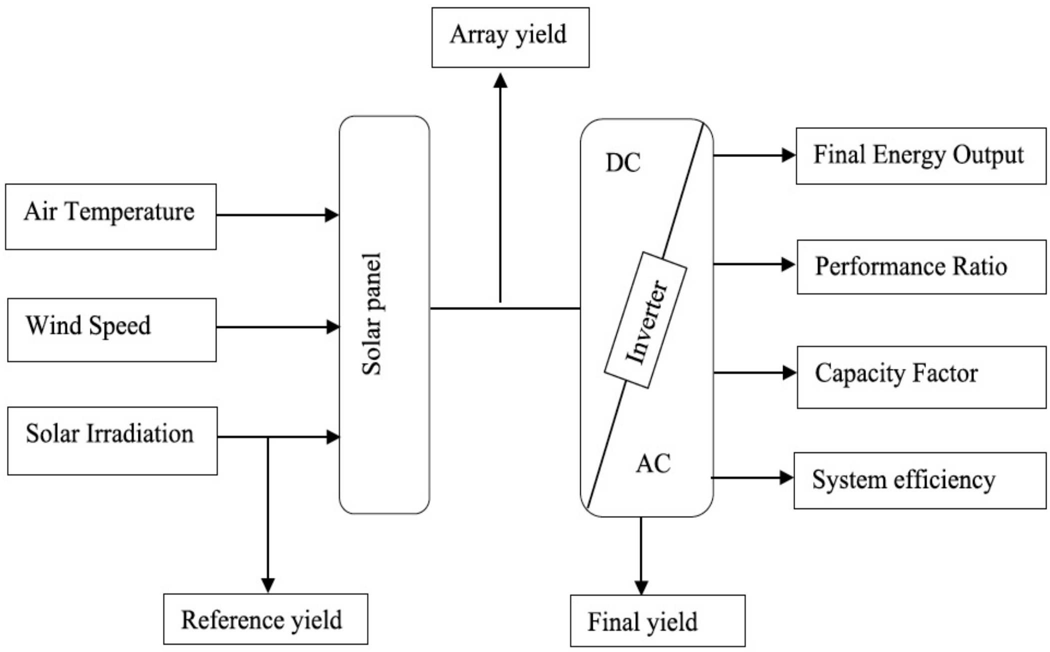


Figure SEQ Figure * ARABIC 1 Archetype of solar photovoltaic system

**Nepal Telecom, Sundhara**

The 64.6 $kW_p$ solar plant at Sundhara is located at the latitude of $27.70^0$ N and longitude of $85.31^0$ E in the Kathmandu District of Bagmati Province in Nepal which was commissioned in March 2019. The system consists of 10 strings of solar panels (each string consisting of 19 solar panels in series), a single grid-tied inverter, protection and measuring devices, and a data logger. The description of the solar panel and inverter is mentioned below:

a) **Solar panel:** 340 $W_p$ solar panels composed of 72 pieces of mono-crystalline silicon (m-si) solar cells manufactured by Vikram Solar are used in the system. The panel has a dimension of 1,956 x 992 x 36 mm with efficiency of 17.52%. The panel has a linear power warranty of 27 years with 3% degradation in the 1$^{st}$ year and 0.65% degradation from year 2 to year 27. The electrical parameters of the solar panel are as shown in Table 1.

b) **Inverter:** A single 80 kW Delta grid-tied transformerless solar inverter has been used in the system. It connects up to 18 strings with a recommended DC power of 95 $kW_p$ in the 400/415 $V_{AC}$ range. It operates at a nominal voltage of 620 V with a maximum input current of 140 A. It can operate in a temperature range of -25$^0$C – 40$^0$C at full power. The technical data of the inverter is shown in table 2.

**Nepal Telecom, Pokhara**

The 45.32 $kW_p$ solar plant at Pokhara is located at the latitude of 28.22$^0$ N, longitude of 84.00$^0$ E and altitude of 822 m in Kaski district of Gandaki province in Nepal which was commissioned on April 23, 2021. The system consists of 2 strings of solar panels with 14 panels in series and 5 strings with 15 panels in series, two grid-tied inverters, protection and measuring devices, and a data logger. The description of the major components is given below:

**a) Solar panel.** Longi 440 $W_p$ solar panels composed of mono-crystalline silicon (m-si) solar cells are used in the system. The solar panel has two identical parts with cells half the size of ordinary solar cells, so it has 144 cells than the usual 72 cells. Single panel dimension is 2,094 x 1,038 x 35 mm with an efficiency of 20.2%. The panel has a linear power warranty of 25 years with 2% degradation in the 1$^{st}$ year and 0.55% degradation from year 2 to year 25. The electrical parameters of the solar panel are as shown in table 1.

**b) Inverter.** Two Solis inverters of capacities 20 kW and 25 kW have been used for the system. Solis-25K-5G (25 kW) transformerless inverter has four Maximum Power Point Tracker (MPPT) designs with a precise algorithm that reduces string mismatch and has over 98.8% maximum efficiency. It can handle maximum input power of 33 kW can start as low as 180 V and handle as high as 1100 V of input voltage. Solis-3P20K-4G (20 kW) transformerless inverter has a dual MPPT design with a precise MPPT algorithm and has over 98.7% maximum efficiency. It can handle maximum input power of 24 kW. The technical data of the inverters are shown in table 2.

**Nepal Telecom, Biratnagar**

The 45.32 $kW_p$ solar plant at Biratnagar is located at latitude of 26.46$^0$ N, longitude of 87.29$^0$ E and altitude of 80 m in Morang district of Koshi province in Nepal which was commissioned on October 16, 2020. The components of the system are like the one installed at Nepal Telecom, Pokhara.

**Table 1 Electrical specification of solar panels**

| Electrical parameter at Standard Test Condition (STC*) | Vikram Solar 340 $W_p$ module | Longi 440 $W_p$ module |
|---|---|---|
| Model | VSM.72.AAA.03.04 | LR4-72HPH-440M |
| Maximum power, $P_{max}$ ($W_p$) | 340 | 440 |
| Cells | m-Si (72 pcs) | PERC m-Si (144 pcs) |
| Voltage at maximum power, $V_{mpp}$ (V) | 37.98 | 41.1 |
| Current at maximum power, $I_{mpp}$ (A) | 8.98 | 10.71 |
| Open circuit voltage, $V_{oc}$ (V) | 47.10 | 48.9 |
| Short circuit current, $I_{sc}$ (A) | 9.42 | 11.46 |
| Module efficiency, $\eta$ (%) | 17.52 | 20.2 |

** STC means solar irradiance of 1000 W/m$^2$, Air mass of 1.5, and air temperature of 25$^0$C.*

**Table 2 Technical data of inverters**

| Technical parameter | Solis-3P20K-4G | Solis-25K-5G | Delta 80 kW |
|---|---|---|---|
| Maximum DC power ($kW_p$) | 24 | 33 | 95 |
| Maximum DC input voltage (V) | 1000 | 1100 | 1100 |
| MPPT voltage range (V) | 160 - 850 | 200 – 1000 | 200 – 1000 |
| Maximum operating input current (A) | 44 | 52 | 140 |
| Rated/Maximum output power (kW) | 20 / 22 | 25 / 27.5 | 69 / 76 |
| Rated/Maximum output current (A) | 28.9 / 31.8 | 36 / 41.8 | 96 / 106 |
| Nominal AC voltage (V) | 3-ø, 400 | 3-ø, 400 | 3-φ, 400 |
| Maximum efficiency (%) | 98.7 | 98.8 | 98.8 |
| Self-consumption at night (W) | < 1 | < 1 | < 3 |

## Materials and Methods

This is a quantitative study where after identifying the problem and conducting relevant literature study, the performance data from the sites were collected. Data related to energy generation from solar plants was collected from the website that displayed the data from the data logger installed at the sites. Radiation and temperature data were then obtained from the National Solar Radiation Database portal available online at the website of the National Renewable Energy Laboratory. The data was entered in MS Excel to calculate the parameters (final yield, capacity utilization factor, performance ratio, and system efficiency) on a monthly, seasonal, and yearly basis. Long-term analysis of the system at Sundhara and performance analysis of systems (Pokhara and Biratnagar) with the same components were done. Charts were made to visualize the differences in the parameters among the various sites. Conclusion and recommendation were written based on the results obtained. Figure 2 below shows the research methodology flowchart followed for this study.


Figure 2 Research Methodology Flowchart

**Array yield**

Array yield is the ratio of direct current energy output from the PV array over a certain period to its rated power. It indicates the number of hours that the PV array must operate at its nominal power to generate the energy produced (Owolabi et al., 2022). It is given by,

$$Y_a = \frac{E_{DC}}{P_{STC}} \text{ (kWh/kW}_p\text{)},$$

where $E_{DC}$ is the direct energy (DC) energy output from the PV array and $P_{STC}$ is the installed power at STC.

**Final yield**

Final yield is the ratio of the net energy output of the entire PV system to its rated power. It indicates the duration of hours the PV system must operate at its rated power to produce the recorded amount of energy. It is given by

$$Y_f = \frac{E_{AC}}{P_{STC}} \text{ (kWh/kW}_p\text{)},$$

where $E_{AC}$ is the net energy output and $P_{STC}$ is the installed power at STC conditions. Usually, the specific yield (array yield and final yield) [kWh/kW$_p$] is used to evaluate the solar PV system performance but it does not consider the footprint of the system. As rooftop area comes as a design constraint in most cases, specific yield per unit area (kWh/m$^2$) is also used as an important indicator for comparing solar PV systems (Ayadi et al., 2022).

**Reference yield**

Reference yield is the ratio of total in-plane solar radiation, $H_t$ (kWh/m$^2$) to the reference irradiance at STC, $G_{STC}$ (kW/m$^2$). It is given by $Y_r = \frac{H_T}{G_{STC}}$ (kWh/kW$_p$). It represents an equivalent duration in hours that the system needs to operate at the reference irradiance (Roumpakias & Stamatelos, 2017) and defines the solar radiation resource for the PV system (Marion et al., 2005).

**Performance ratio**

Performance ratio (PR) measures the quality of a solar photovoltaic and is also called the quality factor that is independent of location (Verma & Singhal, 2015). It indicates how close a PV system is to its ideal performance during actual operation and it also allows comparison of PV systems independent of location, tilt angle, orientation and rated power capacity (Sharma & Goel, 2017). It is given by, $PR = \frac{Y_f}{Y_r}\, x\, 100\%$. Normalization with irradiance provides the cumulative effect of losses on the rated output due to wiring losses, inverter inefficiency, reflection from the front surface, system down-time, PV module temperature, dust accumulation, and component failures (Marion et al., 2005). By itself, it doesn't represent the total energy produced as a system having low PR in a location with high solar resources might produce more amount of energy than a system having high PR in a location with low solar resources.

**Capacity utilization factor**

Capacity utilization factor (CUF) is the ratio of AC energy produced by the PV system over a given period (usually one year) to the possible amount of energy produced if the system were operated at full capacity during that period (Adaramola & Vagnes, 2015). It is given by, $CUF = \frac{E_{AC}}{P_{STC}\, x\, 8760}\, x\, 100\%$

### 3.6. System efficiency

System efficiency is the ratio of AC output energy generated to the total possible energy generation from the surface area of the solar panel. It is given by,

$$_{sys} = \frac{E_{AC}}{H_T \; x \; A_m} \; x \; 100\%,$$

where $A_m$ is the module area in $m^2$.

**PV Cell Temperature**

It is the temperature of the surface of the PV array. At night, the value is same as the ambient temperature, while at day, the value can exceed the ambient temperature by $30^0C$ or more. Using the energy balance equation for PV array given by Duffie and Beckman, the PV cell temperature can be given as (HOMER ENERGY, n.d.):

$$T_c = \frac{T_a + \left(T_{c,NOCT} - T_{a,NOCT}\right)\left(\frac{G_T}{G_{T,NOCT}}\right)\left[1 - \frac{\eta_{mp,STC}\left(1 - \alpha_P T_{c,STC}\right)}{\tau\alpha}\right]}{1 + \left(T_{c,NOCT} - T_{a,NOCT}\right)\left(\frac{G_T}{G_{T,NOCT}}\right)\left(\frac{\alpha_P \eta_{mp,STC}}{\tau\alpha}\right)}$$

where,

$T_c$ = PV cell temperature

$T_{c,\,NOCT}$ =Nominal operating cell temperature

$T_{c,\,STC}$ = Cell temperature under standard test condition = $25^0C$

$T_a$ = Ambient temperature

$T_{a,\,NOCT}$ = Ambient temperature at which the NOCT is defined = $20^0C$

$G_T$ = Solar radiation striking the PV array [$kW/m^2$]

$G_{T,\,NOCT}$ = Solar radiation at which NOCT is defined = 800 $W/m^2$

$\eta_{mp,\,STC}$ = Maximum power point efficiency under standard test condition

$\alpha_p$ = temperature coefficient of power

$\tau$ = solar transmittance of any cover over the PV array

$\alpha$ = solar absorptance of the PV array

The loss in power generation is then calculated using the relation:

$P_{corrected} = P_{rated} \{1 + \alpha_p (T_c - T_{c,\,STC})\}$

where,

$P_{rated}$ = rated power of the solar panel

$P_{corrected}$ = Corrected power of the solar panel after the temperature is considered.

## Results and Discussion

This section discusses the results obtained from the data analysis. It is divided into two sections;

a) a long-term comparison of a system (NTC Sundhara), and

b) a comparison of systems with the same components (NTC Pokhara and Biratnagar).

### Long-term comparison of a system

The **final yield** (kWh / $kW_p$) has been constantly decreasing since 2019. The value of 2.91 kWh per $kW_p$ in 2019 has decreased by 24% in 2022 (see fig. 3). Besides, the per square meter energy generation also has decreased from 0.54 kWh/m$^2$ in 2019 to 0.41 kWh/m$^2$ in 2022. Although the solar manufacturer has mentioned linear power warranty for 27 years with 3% degradation in the 1st year and 0.65% degradation from year 2 to year 27, the actual decrease is relatively high compared to this. As Kazem et al. (2022) also found that just 35 days of dust accumulation caused a decrease in power from monocrystalline panels by 20%, this huge decrease seems mainly because of dust accumulation. Similarly, Salimi et al. (2019) had also found that the output power of a panel with dust covering was approximately 8 – 12% less per month compared to the clean panel. A new tower is being built nearby, alongside the fallen Dharahara, and the dust from the construction works coats the panels with a layer of dust. This would require regular cleaning of the panels. However, the panels do not get cleaned regularly and the accumulated dust reduces the incident solar energy

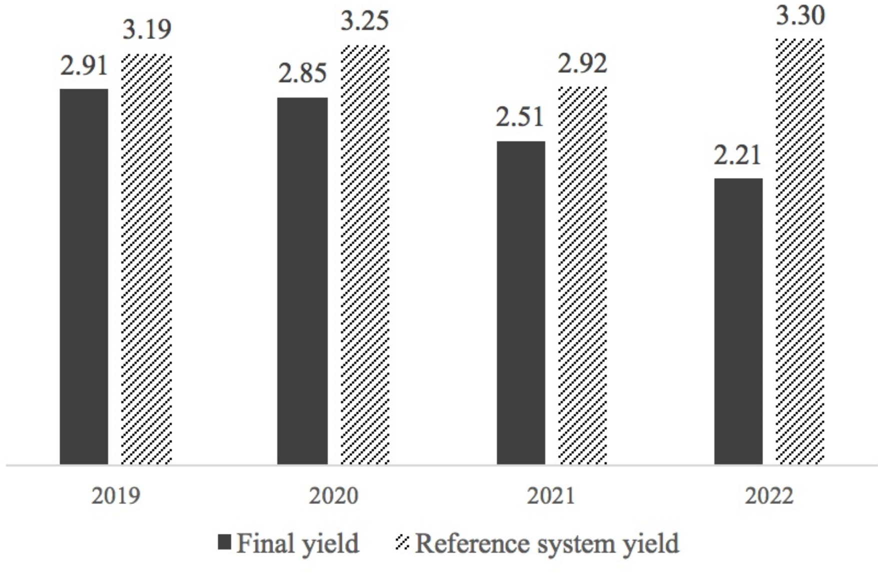


Figure 3 Yearly average final yield and reference system yield (kWh/kWp) at NTC Sundhara

that the panels can get for electricity production. Besides, there are some strings in the system that were at considerable shading zones. Bajracharya (2020) performed shading analysis for summer morning at 9:00 AM, summer noon, summer afternoon at 3:00 PM, winter morning at 9:00 AM, winter noon, and winter afternoon at 3:00 PM, and found that there was considerable shading in the winter for three strings in any time of the day, whereas there was some shading in the summer morning in one of the strings. This shading by building structures reduced the generation resulting in the lower value of final yield. Shading simulation in PVsyst showed that the annual generation without shading and with shading condition would generate 117.5 MWh and 96 MWh of electricity, respectively, causing overall loss of 18.3% energy in a year (Bajracharya, 2020). The shading loss was more pronounced in winter than summer (see fig. 4).

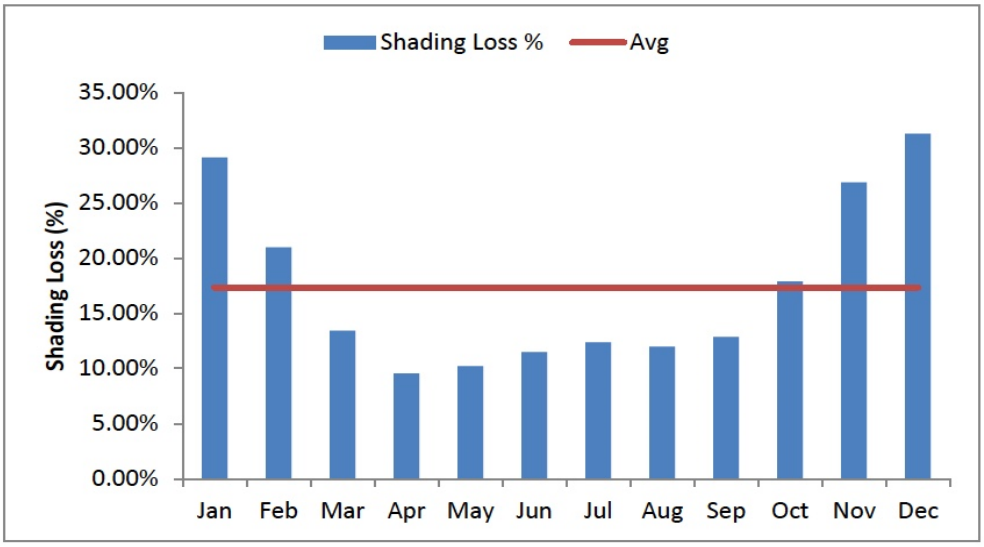


Figure 4 Shading losses (simulated) in the solar plant at NTC Sundhara

The performance ratio was 91.0% in 2019 and 87.8% in 2020 and 2021, but it drastically dropped to 67.3% in 2022 (fig. 5). The final yield continuously decreased as expected. But, the reference yield dipped in the year 2021 compared to the other years. This was because of the lesser value of solar radiation in the spring (March–May) of that year.

This dip resulted in a higher value of performance ratio in the year 2021 causing a drastic decrease from 2021 to 2022. As the energy output continuously decreased over the years, the capacity utilization factor also continuously decreased from 12.1% in 2019 to 9.2% in 2022. And, the system efficiency dropped drastically

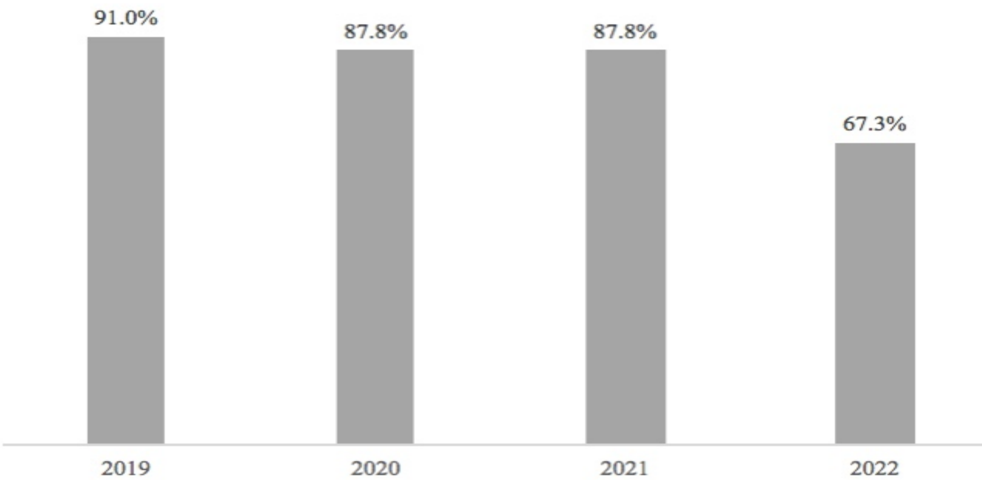


Figure 5 Yearly performance ratio of the solar plant at NTC Sundhara

from 16.3% in 2021 to 12.5% in 2022, due to the lesser value of solar irradiance in spring 2021.

**Comparison of systems with the same components**

The systems installed at Pokhara and Biratnagar consisted of the same components (45.32 $kW_p$ solar system consisting of 103 numbers of 440 $W_p$ Longi solar panels and two SOLIS inverters of capacities 20 kW and 25 kW). Pokhara lies in the hilly region of Nepal while Biratnagar lies in the Terai region (fig. 6). The impact of temperature and radiation on the various parameters was conducted.

| | Pokhara | Biratnagar |
|---|---|---|
| **Latitude** | $28.22^0$ N | $26.46^0$ N |
| **Longitude** | $84.00^0$ E | $87.29^0$ E |
| **Altitude** | 822 m | 80 m |
| **Solar irradiance** | 4.83 kWh/$m^2$/day | 5.01 kWh/$m^2$/day |

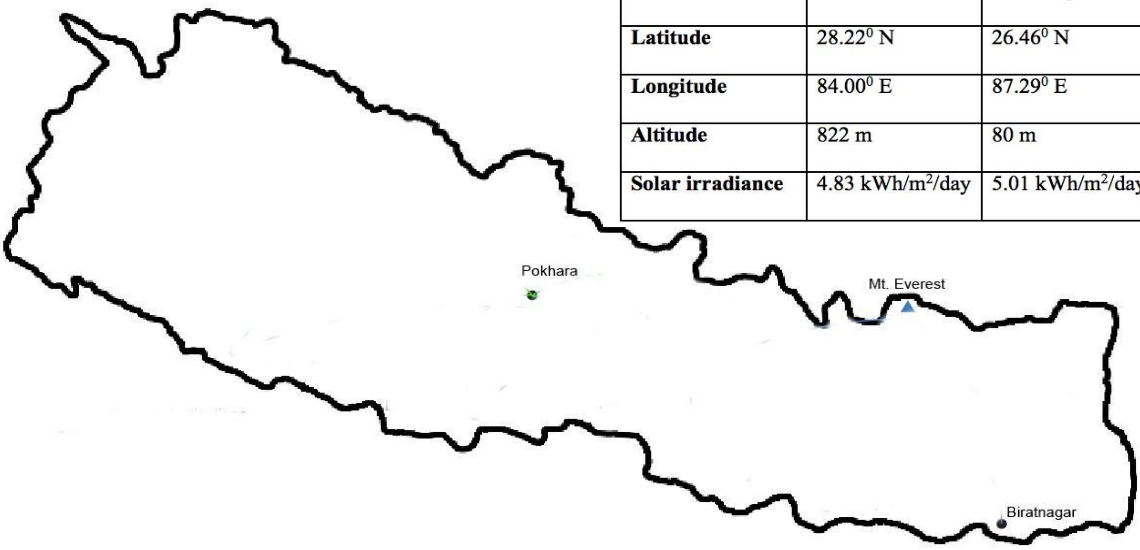


Figure 6 Location of Pokhara and Biratnagar in Nepal

#### *4.2.1. Weather data*

Temperature and radiation data were obtained from NREL for a typical meteorological year for both locations. The air temperature at Pokhara ranged from $5.7^0$C in January to $18.3^0$C in June with an average of $13.1^0$C while the air temperature at Biratnagar ranged from $19.1^0$C in January to $32.0^0$C in May with an average of $26.7^0$C. This showed that the average temperature at Biratnagar is double than that of Pokhara. Similarly, the solar radiation at Pokhara ranged from 3.80 kWh/$m^2$/day in December to 6.05 kWh/$m^2$/day in April, with an average of 4.83 kWh/$m^2$/day, and the solar radiation at Biratnagar ranged from 3.53 kWh/$m^2$/day in December to 6.36 kWh/$m^2$/day in April, with an average of 5.01 kWh/$m^2$/day (fig. 7). This showed that the solar radiation at Biratnagar is higher by 4% on average. Only, during December and January, the radiation at Pokhara was significantly higher than at Biratnagar by 11.1% and 7.6%, respectively. The temperature and radiation data of Pokhara and Biratnagar were highly correlated (correlation for Pokhara = 0.72 and correlation for Biratnagar = 0.97), which means, higher air temperature was related to higher radiance.

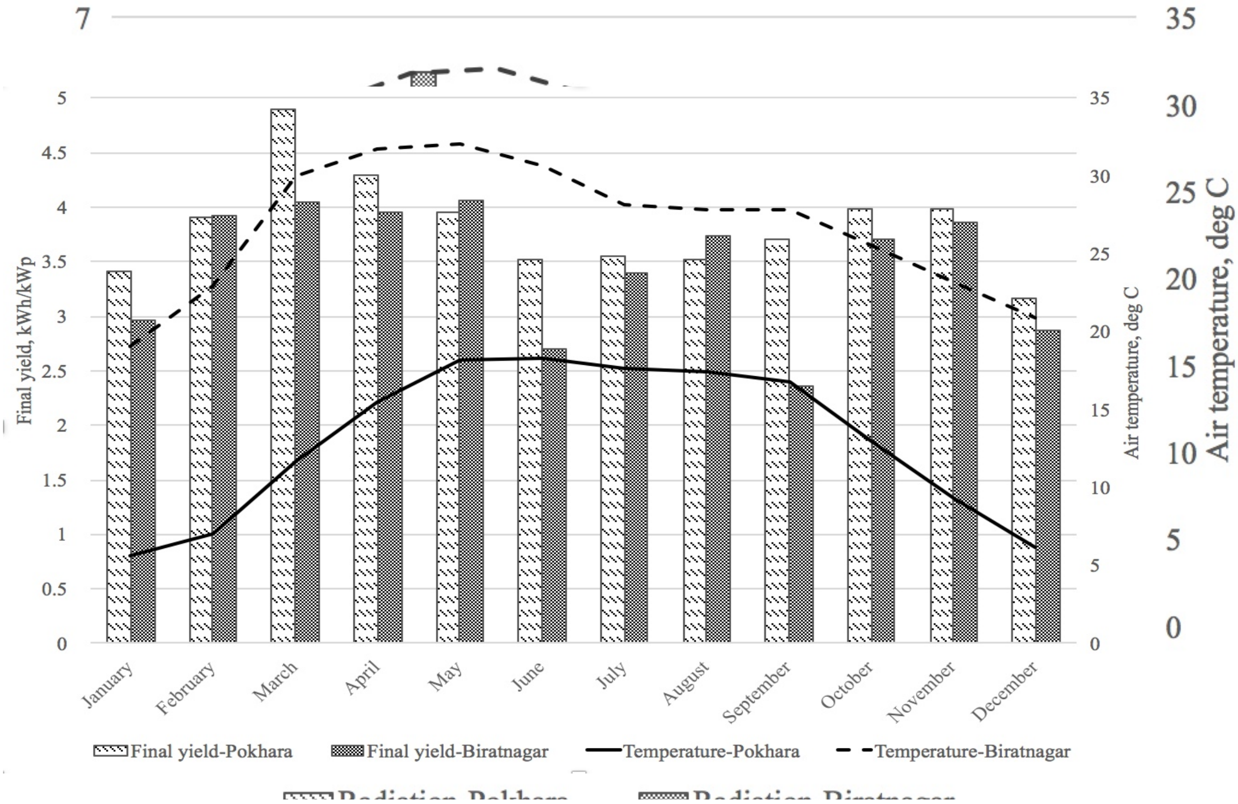


Figure 8 Final yield (kWh / $kW_{p}$) vs temperature data of plants at Pokhara and Biratnagar

Figure 7 Temperature and radiation data of plants at Pokhara and Biratnagar

***Final Yield vs Temperature***

While the average air temperature at Biratnagar (26.7$^{0}$C) was higher than at Pokhara (13.1$^{0}$C), the final yield (kWh/ $kW_p$) was found to be lower by an average value of 9% (fig. 8). Only the final yield in the months of May and August was higher at Biratnagar by 3% and 6%, respectively, than at Pokhara. This kind of higher temperature's relation to less energy generation was confirmed by determining the relation between temperature and power generated by the solar panel. Using weather data for a typical meteorological year, it was found that the 440 $W_p$ solar panel operated normally in the range between 412.3 $W_p$ (in June) and 432.3 $W_p$ (in January) at Pokhara (i.e. 93.7% - 98.2% of the system capacity) and, 390.6 $W_p$ (in May) and 411.1 $W_p$ (in January) at Biratnagar (i.e. 88.8% - 93.4% of the system capacity). The monthly variation of power produced at the locations is shown in Figure 9. Although winter months had higher power generation due to lower cell temperature, the final yield was lesser because of less solar radiation.

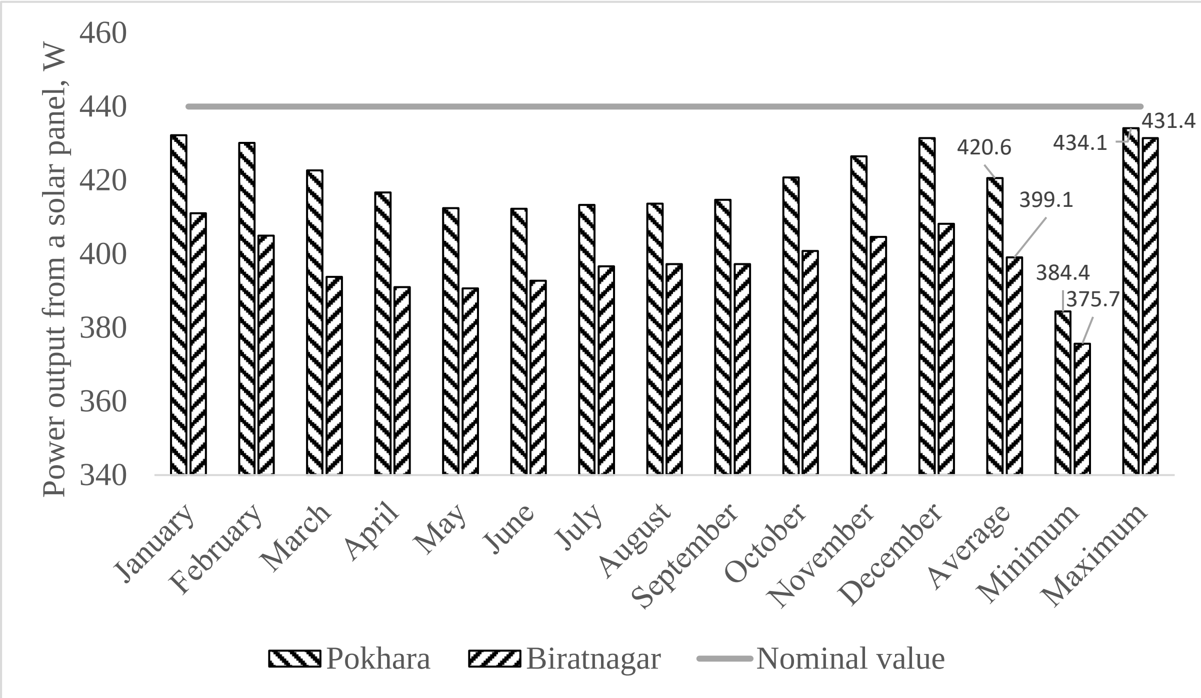


Figure 9 Average monthly power produced from 440 W solar panel at Pokhara and Biratnagar

The values seen in fig 9 is in accordance to the panel specifications which mentioned that the temperature coefficient of maximum power is -0.35%/$^0$C, which means that for every temperature above 25$^0$C, the power generated decreases by 0.35%. Revati and Natarajan (2016) found that the performance of solar cells increased with a decrease in temperature. Besides, for each location, the higher temperature month was usually associated with lesser energy generation or final yield. This was more pronounced for the plant at Pokhara than at Biratnagar (Fig. 10a and 10b).

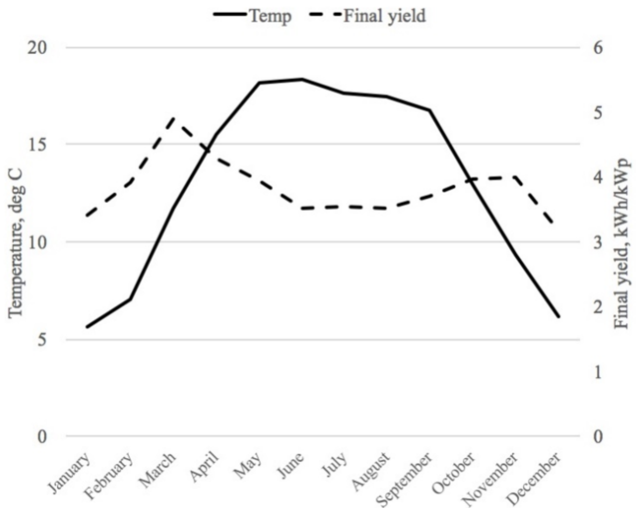


Figure 10a Final yield vs temperature for Pokhara plant

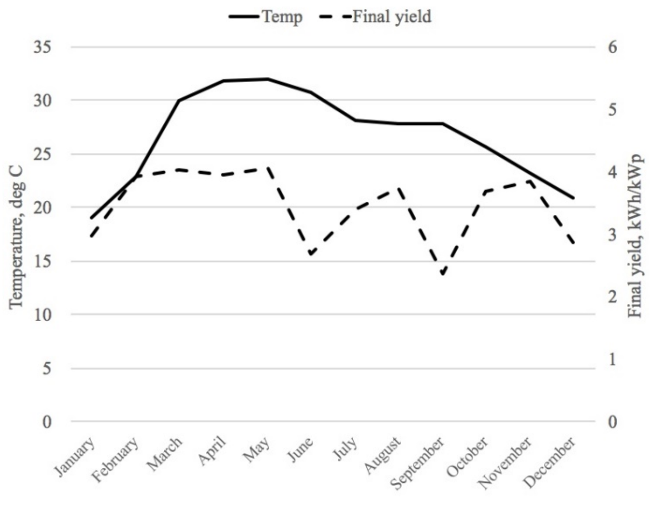


Figure 10b Final yield vs temperature for Biratnagar plant

Capacity utilization factor vs Temperature

The capacity utilization factor of a plant at Pokhara was usually higher than at Biratnagar, except for the months of February, May, and August (fig. 11). The yearly average value was 15.9% at Pokhara and 14.3% at Biratnagar. The value was the highest for both plants in the month of March. For each location, the higher temperature month was usually associated with lesser energy generation or final yield. This was more pronounced for the plant at Pokhara than at Biratnagar just as seen in the final yield.

***System Efficiency vs Temperature***

The system efficiency of the plant at Pokhara was always higher than the plant at Biratnagar (fig. 12). The average system efficiency of Pokhara and Biratnagar plants was 16.1% and 14.2% respectively. For each location, the higher temperature month was usually associated with lesser system efficiency. Farahmand et al. (2021) also found that the panel efficiency during winter was higher than summer due to air temperature decrease. Also, it was calculated that for every $10^0$C rise in cell temperature, the efficiency decreased by 11.5%. This was somewhat close to the value of 7% determined experimentally by Elshazly et al. (2021).

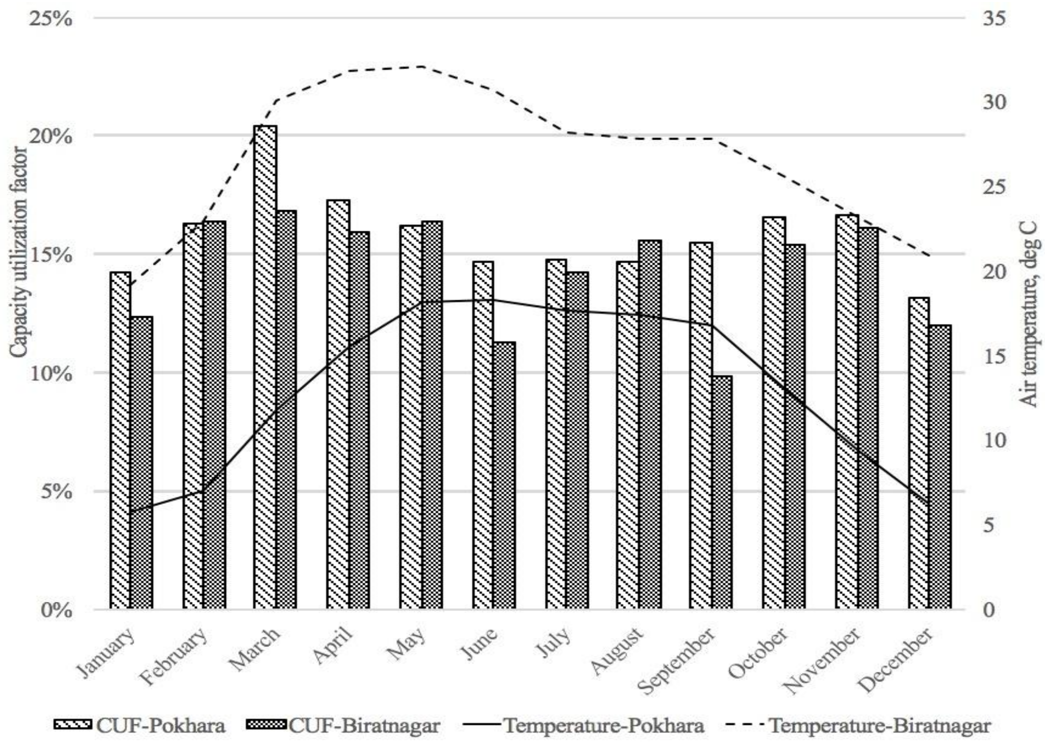


Figure 11 Capacity utilization factor vs temperature for Pokhara and Biratnagar plants

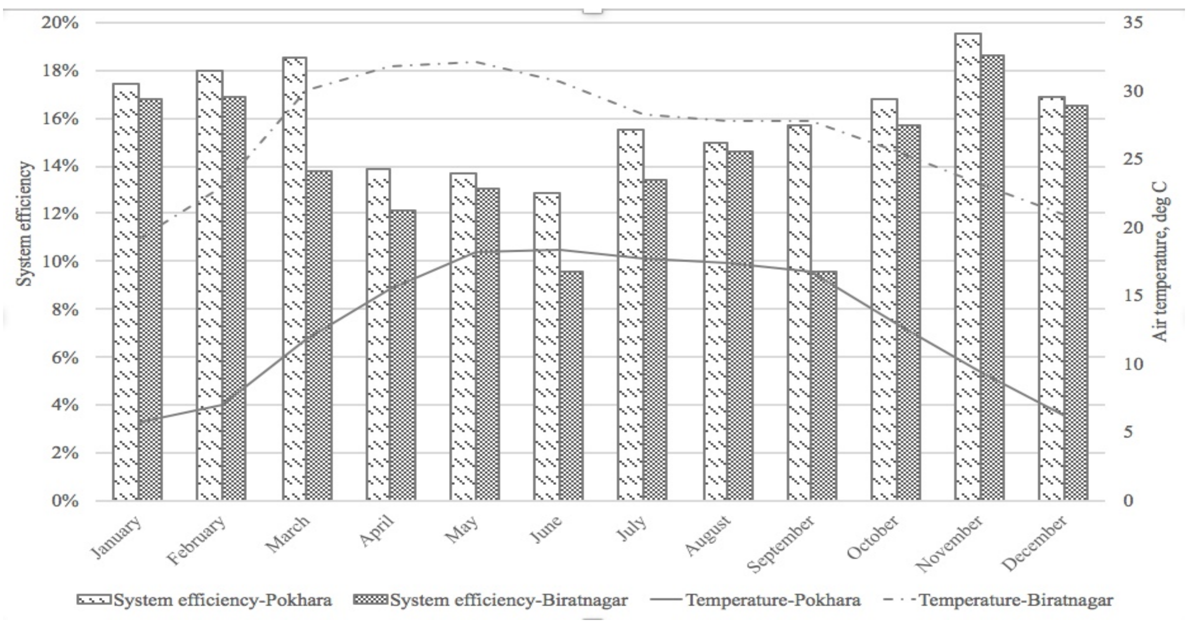


Figure 12 System efficiency vs temperature for Pokhara and Biratnagar plants

### 4.3. Summary

Table 3 Summary of technical performance parameters of all the plants

| S. No. | Technical parameters | NTC Sundhara | NTC Pokhara | NTC Biratnagar |
|---|---|---|---|---|
| 1 | Reference yield ($Y_r$) (kWh/k$W_p$) | 3.16 | 4.81 | 5.01 |
| 2 | Final yield ($Y_f$) (kWh/k$W_p$) | 2.60 | 3.76 | 3.46 |
| 3 | Final yield ($Y_f$) (kWh/$m^2$) | 0.48 | 0.76 | 0.70 |
| 4 | Performance Ratio (PR) | 83.0% | 79.1% | 70.6% |
| 5 | Capacity Utilization Factor (CUF) | 10.8% | 15.6% | 14.3% |
| 6 | System Efficiency ($\eta$) | 15.4% | 16.0% | 14.2% |

**Conclusion**

This study was conducted to evaluate the performance of grid-connected mono-crystalline silicon-based solar plants in Nepal by using the data from solar plants installed at Nepal Telecom offices of Sundhara, Pokhara, and Biratnagar. The following conclusions can be derived from the study:

- Since its operation in March 2019, the solar plant at Sundhara has been generating less energy from the installed solar modules. While the plant produced 2.91 kWh/k$W_p$ in 2019, it dropped to 2.21 kWh/k$W_p$ in 2022. Dust accumulation in the panels due to its location might be a major reason for this decrease. Similarly, the performance ratio decreased from 91.0% in 2019 to 67.3% in 2022, capacity utilization factor decreased from 12.1% in 2019 to 9.2% in 2022, and system efficiency decreased from 16.8% in 2019 to 12.5% in 2022.

- Biratnagar had slightly higher (by 4%) solar radiation than Pokhara but the final yield was 9% lower because the average temperature at Biratnagar (26.7$^0$C) was higher than at Pokhara (13.1$^0$C). The 440 $W_p$ module worked at 431.1 $W_p$ (2% reduction) at Pokhara and 409.6 $W_p$ (6.9% reduction) at Biratnagar in the average temperature. Similarly, the performance ratio of Pokhara (80.0%) was better than that of Biratnagar (70.6%), the capacity utilization factor of Pokhara (15.9%) was better than that of Biratnagar (14.3%), and the system efficiency of Pokhara (16.1%) was also better than that of Biratnagar (14.2%). All the parameters were found to be lower in the months with higher temperatures, especially the spring and summer seasons.

**Recommendation**

This study has been conducted with limited resources and information. Data from the developers and clients were not available as much as required. The 680 k$W_p$ plant at KUKL Sundarighat used heterojunction with an intrinsic thin layer (HIT) solar cell but the data logger was out of order. A few private developers were reluctant to provide data citing copyright issues. So, to truly understand the performance of solar cells under our climatic condition for technical as well as economic feasibility, the following recommendations are provided:

- Data from solar plants using various solar cell technologies need to be available for research purposes. This can be coordinated by the solar technology division at the Alternative Energy Promotion Center (AEPC).

- Proper technical research to identify the efficacy of half-cut solar cells in comparison to normal solar cells, under our climatic conditions, should be done.

- Provision of installing weather systems, at a clear location, at the solar plants should be made compulsory to have accurate meteorological data so that research does not depend only on satellite data.

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# Supporting information

ANNEX A: METEOROLOGICAL DATA

The air temperature and global horizontal irradiance (GHI) data taken from the National Solar Radiation Database of National Renewable Energy Laboratory (NREL) for a typical meteorological year:

Table 4 Average temperature and global horizontal irradiance of Pokhara and Biratnagar taken from NREL

| **Location** | **Pokhara** | | **Biratnagar** | | **Chhauni** | | **Sundhara** | |
|---|---|---|---|---|---|---|---|---|
| Lat (N) /Long (E) | $28.22^0$ | $84.00^0$ | $26.46^0$ | $87.29^0$ | $27.71^0$ | $85.29^0$ | $27.70^0$ | $85.31^0$ |
| Month | Average temp, $^0$C | GHI, kWh/m$^2$/day | Average temp, $^0$C | GHI, kWh/m$^2$/day | Average temp, $^0$C | GHI, kWh/m$^2$/day | Average temp, $^0$C | GHI, kWh/m$^2$/day |
| January | 5.7 | 3.96 | 19.1 | 3.56 | 8.4 | 4.24 | 7.4 | 4.13 |
| February | 7.0 | 4.41 | 23.0 | 4.71 | 11.1 | 4.72 | 9.0 | 4.86 |
| March | 11.8 | 5.35 | 30.0 | 5.95 | 14.7 | 6.04 | 13.4 | 5.80 |
| April | 15.5 | 6.05 | 31.8 | 6.36 | 20.4 | 6.41 | 18.4 | 6.24 |
| May | 18.2 | 5.74 | 32.0 | 6.09 | 22.3 | 6.07 | 20.7 | 6.09 |
| June | 18.3 | 5.54 | 30.7 | 5.69 | 20.9 | 5.65 | 19.6 | 5.51 |
| July | 17.7 | 4.64 | 28.2 | 5.14 | 20.4 | 4.79 | 19.5 | 4.97 |
| August | 17.4 | 4.77 | 27.8 | 5.17 | 20.3 | 4.83 | 19.5 | 5.06 |
| September | 16.8 | 4.78 | 27.8 | 4.97 | 19.5 | 4.72 | 18.0 | 4.88 |
| October | 13.0 | 4.80 | 25.6 | 4.79 | 16.8 | 5.03 | 15.1 | 4.98 |
| November | 9.3 | 4.13 | 23.2 | 4.20 | 13.0 | 4.17 | 11.3 | 4.41 |
| December | 6.2 | 3.80 | 20.9 | 3.53 | 9.5 | 3.87 | 8.5 | 3.88 |
| Average | 13.06 | 4.83 | 26.68 | 5.01 | 16.44 | 5.04 | 15.02 | 5.07 |

ANNEX B: MONTHLY DATA

Table 5 Monthly average parameters of all the plants

| **Location** | **Month / Category** | **Final yield, $Y_f$ ($kWh/kW_p$)** | **Final yield, $Y_f$ ($kWh/m^2$)** | **Reference system yield, $Y_r$ (kWh/kWp)** | **Performance ratio, PR = $Y_f/Y_r$** | **Capacity utilization factor, CUF = $E_{ac}$ / (P * 24)** | **System efficiency, η (E / ($H_t$ * $A_m$))** |
|---|---|---|---|---|---|---|---|
| Sundhara | January | 1.89 | 0.35 | 2.56 | 76.8% | 7.9% | 14.2% |
| | February | 2.41 | 0.45 | 2.97 | 84.8% | 10.0% | 15.7% |
| | March | 3.14 | 0.58 | 3.47 | 93.0% | 13.1% | 17.2% |
| | April | 3.38 | 0.63 | 3.50 | 98.0% | 14.1% | 18.2% |
| | May | 3.11 | 0.58 | 3.43 | 91.1% | 13.0% | 16.9% |
| | June | 2.97 | 0.55 | 3.32 | 89.8% | 12.4% | 16.6% |
| | July | 2.55 | 0.47 | 2.86 | 89.4% | 10.6% | 16.6% |
| | August | 2.87 | 0.53 | 3.18 | 90.8% | 11.9% | 16.8% |
| | September | 2.55 | 0.47 | 2.90 | 89.5% | 10.6% | 16.6% |
| | October | 2.84 | 0.53 | 3.65 | 78.4% | 11.8% | 14.5% |
| | November | 1.87 | 0.35 | 3.18 | 59.4% | 7.8% | 11.0% |
| | December | 1.54 | 0.29 | 2.82 | 5k6.2% | 6.4% | 10.4% |
| Pokhara | January | 3.42 | 0.69 | 3.96 | 86.2% | 14.2% | 17.5% |
| | February | 3.91 | 0.79 | 4.41 | 88.7% | 16.3% | 18.0% |
| | March | 4.90 | 0.99 | 5.35 | 91.6% | 20.4% | 18.5% |
| | April | 4.29 | 0.84 | 6.05 | 70.9% | 17.3% | 13.9% |
| | May | 3.95 | 0.79 | 5.74 | 68.8% | 16.2% | 13.7% |
| | June | 3.52 | 0.71 | 5.54 | 63.5% | 14.7% | 12.9% |
| | July | 3.55 | 0.72 | 4.64 | 76.5% | 14.8% | 15.5% |
| | August | 3.52 | 0.71 | 4.77 | 73.8% | 14.7% | 14.9% |
| | September | 3.71 | 0.75 | 4.78 | 77.5% | 15.4% | 15.7% |
| | October | 3.98 | 0.81 | 4.80 | 82.9% | 16.6% | 16.8% |
| | November | 3.99 | 0.81 | 4.13 | 96.6% | 16.6% | 19.5% |
| | December | 3.16 | 0.64 | 3.80 | 83.2% | 13.2% | 16.8% |
| Biratnagar | January | 2.96 | 0.60 | 3.56 | 83.2% | 12.3% | 16.8% |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | February | 3.92 | 0.79 | 4.71 | 83.2% | 16.4% | 16.8% |
| | March | 4.04 | 0.82 | 5.95 | 67.9% | 16.8% | 13.7% |
| | April | 3.95 | 0.77 | 6.36 | 62.1% | 15.9% | 12.2% |
| | May | 4.06 | 0.80 | 6.09 | 66.8% | 16.4% | 13.1% |
| | June | 2.69 | 0.55 | 5.69 | 47.4% | 11.2% | 9.6% |
| | July | 3.40 | 0.69 | 5.14 | 66.2% | 14.2% | 13.4% |
| | August | 3.74 | 0.76 | 5.17 | 72.3% | 15.6% | 14.6% |
| | September | 2.36 | 0.48 | 4.97 | 47.4% | 9.8% | 9.6% |
| | October | 3.70 | 0.75 | 4.79 | 77.3% | 15.4% | 15.6% |
| | November | 3.85 | 0.78 | 4.20 | 91.8% | 16.1% | 18.6% |
| | December | 2.87 | 0.58 | 3.53 | 81.4% | 12.0% | 16.5% |
| Chhauni | January | 2.79 | 0.53 | 3.56 | 78.3% | 11.6% | 14.8% |
| | February | 3.46 | 0.65 | 4.15 | 83.2% | 14.4% | 15.8% |
| | March | 3.65 | 0.69 | 4.64 | 78.7% | 15.2% | 14.9% |
| | April | 3.76 | 0.71 | 4.91 | 76.5% | 15.6% | 14.5% |
| | May | 3.29 | 0.62 | 4.92 | 66.9% | 13.7% | 12.7% |
| | June | 2.96 | 0.56 | 4.87 | 60.7% | 12.3% | 11.5% |
| | July | 2.88 | 0.55 | 4.88 | 59.1% | 12.0% | 11.2% |
| | August | 2.30 | 0.43 | 4.88 | 47.1% | 9.6% | 8.9% |
| | September | 2.26 | 0.43 | 4.69 | 48.3% | 9.4% | 9.1% |
| | October | 3.12 | 0.59 | 4.21 | 74.0% | 13.0% | 14.0% |
| | November | 3.04 | 0.58 | 3.62 | 83.9% | 12.7% | 15.9% |
| | December | 2.84 | 0.54 | 3.27 | 86.8% | 11.8% | 16.4% |

ANNEX C: SEASONAL DATA

Table 6 Seasonal average parameters of all the plants

| **Location** | **Season / Category** | **Final yield, $Y_f$ (kWh/kWp)** | **Final yield, $Y_f$ (kWh/m²)** | **Reference system yield, $Y_r$ (kWh/kWp)** | **Performance ratio, PR = $Y_f/Y_r$** | **Capacity utilization factor, CUF = $E_{ac}$ / ( P * 24)** | **System efficiency (E / ($H_t$ * $A_m$))** |
|---|---|---|---|---|---|---|---|
| Sundhara | Spring | 3.22 | 0.60 | 3.47 | 94.2% | 13.4% | 17.4% |
| | Summer | 2.79 | 0.52 | 3.12 | 90.0% | 11.6% | 16.7% |
| | Autumn | 2.42 | 0.45 | 3.25 | 75.7% | 10.1% | 14.0% |
| | Winter | 1.89 | 0.35 | 2.78 | 70.6% | 7.9% | 13.1% |
| Pokhara | Spring | 4.27 | 0.85 | 5.72 | 75.0% | 17.5% | 14.9% |
| | Summer | 3.53 | 0.71 | 4.98 | 71.2% | 14.7% | 14.4% |
| | Autumn | 3.89 | 0.79 | 4.57 | 85.7% | 16.2% | 17.3% |
| | Winter | 3.41 | 0.69 | 3.99 | 85.3% | 14.2% | 17.3% |
| Biratnagar | Spring | 4.02 | 0.80 | 6.13 | 65.6% | 16.4% | 13.0% |
| | Summer | 3.28 | 0.66 | 5.33 | 62.0% | 13.7% | 12.5% |
| | Autumn | 3.30 | 0.67 | 4.65 | 72.2% | 13.8% | 14.6% |
| | Winter | 3.25 | 0.66 | 3.94 | 82.6% | 13.6% | 16.7% |
| Chhauni | Spring | 3.57 | 0.68 | 4.82 | 74.0% | 14.9% | 14.0% |
| | Summer | 2.71 | 0.51 | 4.87 | 55.6% | 11.3% | 10.5% |
| | Autumn | 2.81 | 0.53 | 4.17 | 68.7% | 11.7% | 13.0% |
| | Winter | 3.08 | 0.58 | 3.68 | 83.7% | 12.8% | 15.8% |