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THESIS NO: M-168-MSESPM-2012-2023

A comparative performance analysis of four monocrystalline silicon based grid-tied solar photovoltaic systems installed at Nepal Telecom

by

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A THESIS

SUBMITTED TO THE DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTERS OF SCIENCE IN ENERGY SYSTEMS PLANNING AND MANAGEMENT

DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING

LALITPUR, NEPAL

AUGUST, 2023

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The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a thesis entitled "A comparative performance analysis of four monocrystalline silicon based grid-tied solar photovoltaic systems installed at Nepal Telecom" submitted by Jeewan Shrestha, in partial fulfillment of the requirements for the degree of Master of Science in Energy Systems Planning and Management.

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Date: 2080/04/22 BS (2023/08/07 AD)

ABSTRACT

This research evaluates four 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 offices at Chhauni, 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, same technology comparison of the plants at Pokhara, Biratnagar, and Chhauni, and same system comparison of plants at Pokhara and Biratnagar was performed.

Long term analysis (four years) of plant at Sundhara found that the yield decreased from 2.91 kWh per kW_p in 2019 to 2.21 kWh per 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. Same technology analysis showed variation in final yield from 3.04 kWh/kW_p at Chhauni plant to 3.76 kWh per kW_p at Pokhara plant. Similarly, yearly capacity utilization factor varied between 12.7% at Chhauni plant to 15.6% at Pokhara plant, and system efficiency varied between 13.2% at Chhauni plant to 16.0% at Pokhara plant. 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 temperature at Biratnagar caused more reduction in the power output from the solar panels. It was seen that, on average, the 440 W panel worked at 420.6 W at Pokhara and 399.1 W at Biratnagar. The total amount saved by NTC during the observation period from the solar plants is Rs.66,92,999.75 with an average saving of Rs. 12,918.85 per kW per year. Finally, this study provides insights to researchers, PV installers, and panel manufacturers on the actual performance of grid-connected solar PV in Nepal.

ACKNOWLEDGEMENT

I would like to express gratitude to my thesis supervisor Dr. Nawraj Bhattarai for his continuous guidance and monitoring to keep me in track and the entire family of Department of Mechanical and Aerospace Engineering for their continuous encouragement during the research period. I would express my gratitude to Er. Ambish Kaji Shakya of Nepal Telecom (NT) for helping me with the generation data of the solar plants installed at NT offices and my colleague Er. Sajendra Man Bajracharya for connecting with him. I would also like to thank my external examiner Prof. Dr. Jagan Nath Shrestha for his continuous encouragement and suggestions in completion of the research.

Finally, I would like to thank my family, and friends for their encouragement, support, and motivation during the thesis period.

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LIST OF ABBREVIATIONS

AEPC	Alternative Energy Promotion Center
CUF	Capacity Utilization Factor
GHI	Global Horizontal Irradiance
IOE	Institute of Engineering
KUKL	Kathmandu Upatyaka Khanepani Limited
MPPT	Maximum Power Point Tracker
m-Si	monocrystalline Silicon
NEA	Nepal Electricity Authority
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Database
NT	Nepal Telecom
PERC	Passivated Emitter and Rear Contact
PPA	Power Purchase Agreement
PR	Performance Ratio
STC	Standard Test Condition
STP	Standard Temperature and Pressure
TU	Tribhuvan University
WECS	Water and Energy Commission Secretariat

1. INTRODUCTION

1.1. Background

Nepal has depended mostly on traditional sources like fuelwood for its energy needs. However, use of commercial and renewable energy sources are on a rise. The consumption of traditional fuel decreased from nearly 90% to less than 70 % in 15 years while the consumption of commercial fuels, like petroleum, electricity and coal, 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 contribution of modern renewable energy, solar and wind, is currently 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). Using high-resolution data-sets, Neupane et al. (2022) found that Nepal has an abundant resource of solar energy, upto 47,628 MW. And, a large part of Nepal has specific PV electricity output in the range between 3.8 and 4.4 kWh/kWp daily (SOLARGIS, 2017). After 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. Recently, Nepal Electricity Authority had invited proposals for buying up a maximum of 100 MW power from grid-tied solar plants through competitive bidding at 16 locations across the country for the first time (Shrestha, 2022). "Working Procedure on Grid Connected Alternative Electric Energy Development – 2017" formulated on February 2018 fixed the bidding rate at Rs. 7.30 per unit, which was later capped at Rs. 5.94 per unit on March 2022. Bidding would require NEA to sign power purchase agreement (PPA) with developers who pass 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 the plants, it is important to consider their operational performance so that the developers can use the information to design their systems, be it for selling to NEA or other purposes. This thesis takes four monocrystalline Silicon (m-Si) PV plants installed at different locations of Nepal Telecom for comparative analysis.

1.2. Problem Statement

There is just 10 years' history of connecting PV systems to the country's national grid. There have been various studies on performance evaluation of these systems but there is need for long term as well as comparative evaluation of the systems. Developers have been using monocrystalline silicon citing their higher efficiency but it is necessary to know the actual performance of the system on the ground. There will be a lot of factors that affect the output generation of the system as mentioned in the specification sheets. Thus, it is necessary to understand their performance in real climatic conditions so that developers can design optimum systems. This research aims to compare the performance of monocrystalline silicon based grid-tied systems taking the long-term data available, using system yield, performance ratio, capacity utilization factor, and system efficiency as the parameters of comparison.

1.3. Rationale

The purpose of this research is to compare the performance of monocrystalline silicon based grid-tied solar PV systems under real climatic conditions in Nepal by considering four plants installed at NTC offices at various locations. This will help the stakeholders understand the performance of the technology and plan accordingly for optimum benefits.

1.4. Objectives

The main objective of this thesis is to compare the performance of four grid-tied monocrystalline silicon solar systems installed at Nepal Telecom offices. To achieve this objective, following specific objectives are developed:

a. To analyze the long-term performance of the grid-tied system installed at NTC Sundhara.
b. To compare the performance of systems with half-cut solar technology installed at NTC Chhauni, Pokhara, and Biratnagar in monthly, seasonal, and yearly basis.
c. To compare the performance of systems with same components installed at NTC Pokhara and Biratnagar for different climatic condition analysis.
d. To calculate the financial benefit obtained from the systems.

1.5. Scope of the work

Following are the scope of works of this research:

a. Collect generation data of at least three grid-tied PV systems.
b. Determine technical parameters of the systems.
c. Compare parameters among the systems.
d. Compare performance of same systems under different climatic condition.

1.6. Limitations

Following are the limitations of this research:

a) Generation data of the plants have been obtained from the remote monitoring website so dust and shading analysis have not been performed, and mismatched and empty data have been discarded in the calculation process.
b) The solar radiation data for the plants installed at Pokhara and Biratnagar was not available on the website. Thus, radiation data for a typical meteorological year for these locations have been taken from the National Solar Radiation Database of National Renewable Energy Laboratory (NREL).

2. LITERATURE REVIEW

A grid-tied or grid-connected PV system is a solar PV power system that is connected to the utility grid. It comprises of solar panels, grid inverters, power conditioning unit, and grid connection equipment. Parameters such as array yield, final yield, reference system yield, performance ratio, capacity utilization factor, system efficiency are used to analyze the performance of such systems. This thesis compares the performance of monocrystalline silicon PV systems. 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 silicon fragments are melted together to form wafers. Because of this process, monocrystalline solar cells have uniform dark appearance and rounded edges square with small gaps between each cell, while polycrystalline solar cells have bluish hue and no rounded edges. Three of the four solar plants use half-cut solar technology. Half-cut solar cell technology increases the number of solar cells in a panel by cutting the cells in half with a laser (fig. 3). This halves the current within the cells which means that the resistive losses are reduced, which equals better performance (Almerini, 2021). Also, half cut cells are usually made with passivated emitter and rear contact (PERC) technology which offers higher module efficiency by capturing as many extra photons as possible (Zientara, 2021). Traditional monocrystalline panels have 60 to 72 cells, so when they are half cut, the number of cells increase to 120 to 144. As the panel is split in half, more energy is created as each half operates independently of the other and the other half can generate energy when one half is shaded (fig. 4). Literature study revealed that many studies used performance ratio and capacity utilization factor to evaluate the performance of grid-tied solar systems.

Ameur et al. (2022) performed long-term performance and degradation analysis of three silicon-based PV technologies including amorphous silicon, polycrystalline silicon, and monocrystalline silicon in Morocco. They found that crystalline silicon PV system are better than amorphous PV system based on performance ratio analysis with the values of 84.25%, 84.32%, and 79.14% for monocrystalline, polycrystalline, and amorphous silicon.

Aste et al. (2014) analyzed three photovoltaic technologies in real conditions using performance ratio. The performance of the c-Si modules was stable and predictable while the a-Si module presented widely variable seasonal performance.

Ayadi et al. (2022) investigated experimentally the performance of monocrystalline, polycrystalline, and thin-film solar panels under sunny climatic conditions. They found that monocrystalline PV systems performed better than other technologies in terms of specific yield per unit area, performance ratio (80.5%), and efficiency (12.8%), whereas thin-film systems demonstrated somewhat better performance in specific yield per installed capacity compared to monocrystalline due to its low temperature coefficient.

Bahanni et al. (2022) compared two mini grid-connected PV plants based on monocrystalline, polycrystalline, and amorphous technologies located in Beni Mellal and El Jadida, Morocco. They found that ambient temperature has a greater impact on performance ratio of mono-crystalline as for every 8^0C rise in temperature, the PR decreased by 2.5%, 2%, and 1% for monocrystalline, polycrystalline, and amorphous technologies at Beni Mellal and by 5.5%, 5.2%, and 3% at El Jadida.

Bajracharya & Maharjan (2019) conducted the techno-economic analysis of the 64.6 kWp grid-tied solar PV system at Nepal Telecom, Sundhara, and found that the performance ratio and capacity utilization factor were 0.859 and 14.09%, respectively.

Elshazly et al. (2021) studied effect of a dust accumulation and high temperature on solar panels in outdoor conditions at El-Sherouk City, Egypt and found that increase in temperature of monocrystalline panels by 10^0C resulted in a degradation of panel's efficiency by approximately 7% and dust accumulation on the panels' surface could reduce the efficiency by 30%.

Owolabi et al. (2022) compared 5 kWp grid-tied monocrystalline silicon (m-Si) solar PV system and 4.6 kWp grid-tied polycrystalline silicon (p-Si) solar PV system installed on the roof of the Engineering building at Kyungpook National University, Republic of Korea and found that m-Si solar cell technology demonstrated better annual performance than the p-Si solar cell in terms of final energy output, system yield, capacity factor, and system efficiency, except for the performance ratio.

Paudyal et al. (2017) performed an experiment to study the transmittance losses in solar PV modules and the subsequent power degradation. They found that the transmittance reduced by as much as 69.06% over the dry study period and the power of dusty modules reduced by 29.76

% compared to the cleaned modules.

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 maximum in rainy season because of natural cleaning of panels and in winter season because of lower temperatures.

Tiwari et al. (2017) studied the performance of 100 kW_p grid-connected PV system at NEA training center, Kharipati and found that the performance ratio fluctuated between 34% in January to 70% in December with an annual average of 54%. Similarly, the capacity utilization factor fluctuated between 5.9 % (January) to 14.6% (November) with an annual average of 10.1%.

Zain et al. (2013) compared the performance of monocrystalline and polycrystalline PV plants using 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 greater performance ratio just indicated higher energy yield in comparison to expected energy yield under STC and need to be taken as relative data.

3. RESEARCH METHODOLOGY

3.1. Research Method

The thesis is a quantitative study where after identifying the problem and conducting relevant literature study, the performance data from the sites were collected. The data were then analyzed, compared, and then relevant information brought out.

3.1.1. Data Sources and Collection

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 National Renewable Energy Laboratory.

3.1.2. Data Analysis and Interpretation

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 same components were done. Charts were made to visualize the differences in the parameter among the various sites. Conclusion and recommendation were written based on the results obtained. Figure 1 below shows the research methodology flowchart followed for this study.

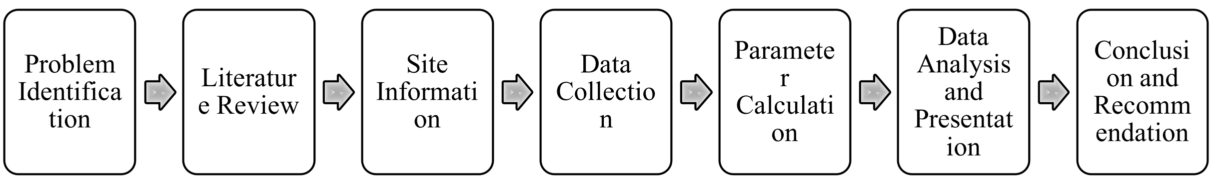

Figure 1Research Methodology Flowchart

3.2. Overview of the grid-tied solar photovoltaic systems

Four grid-tied solar PV systems installed at Nepal Telecom offices at Sundhara, Chhauni, Biratnagar, and Pokhara were considered for this study. The PV systems follow the system archetype (Owolabi et al., 2022) as shown in figure 2, 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 affect the performance of solar panel. The measured solar irradiation gives the reference yield based on which the yield of solar panel 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 final yield, performance ratio, capacity utilization factor, and system efficiency.

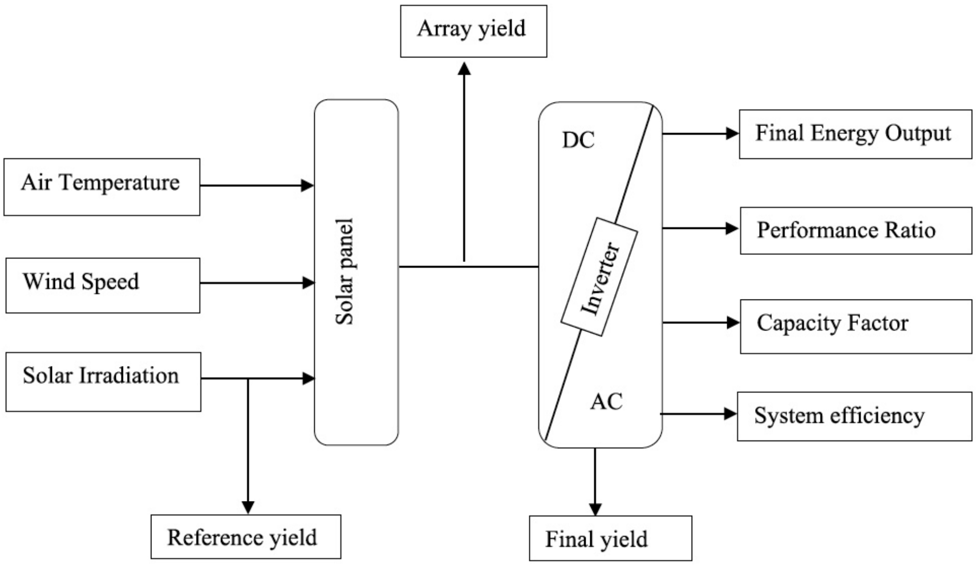

Figure 2 Archetype of solar photovoltaic system

3.2.1. Nepal Telecom, Sundhara

The 64.6 kW_p solar plant at Sundhara is situated at a latitude of 27.70^0 N, a longitude of 85.31^0 E and altitude of 1,305 m in Kathmandu district of Bagmati province in Nepal which was commissioned on 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 data logger.

3.2.1.1. Solar panel. 340 W_p solar panels composed of 72 pieces of mono-crystalline silicon 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 linear power warranty of 27 years with 3% degradation in the 1st year and 0.65% degradation from year 2 to year 27. The electrical parameters of the solar module are as shown in table 1.

Table 1 Electrical specification of Vikram Solar 340 W_p module

Electrical parameter at Standard Test Condition (STC*)	**Value**
Model	VSM.72.AAA.03.04
Maximum power, P_{max} (W_p)	340
Cells	72 monocrystalline solar cells
Voltage at maximum power, V_{mpp} (V)	37.98
Current at maximum power, I_{mpp} (A)	8.98
Open circuit voltage, V_{oc} (V)	47.10
Short circuit current, I_{sc} (A)	9.42
Module efficiency, η (%)	17.52

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

3.2.1.2. Inverter. A single 80 kW Delta grid-tied transformerless solar inverter has been used in the system. It connects 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 the 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.

Table 2 Technical data of Delta 80 kW inverter

Technical parameter	**Value**
Recommended DC power (kW_p)	95
Maximum input voltage (V)	1100
MPPT voltage range (V)	200 – 1000
Total input current (A)	140
Rated / Maximum output power (kVA)	69 / 76
Rated / Maximum output current (A)	96 / 106
Reactive power (Adjustable)	0.8 lagging ~ 0.8 leading
Harmonics	< 3% at rated power
Nominal AC voltage (V)	3-ϕ, 400 / 415
Maximum efficiency (%)	98.8
Self-consumption at night (W)	< 3

3.2.2. Nepal Telecom, Chhauni

The 102 kW_p solar plant at Chhauni is situated at a latitude of 27.71^0 N, a longitude of 85.29^0 E and altitude of 1,318 m in Kathmandu district of Bagmati province in Nepal which was commissioned on February 7, 2021. The system consists of 16 strings of solar panels (each string consisting of 17 solar panels in series), two grid-tied inverters, protection and measuring devices, and data logger.

3.2.2.1. Solar panel. Seraphim's Blade™ series 375 W_p solar module composed of monocrystalline silicon solar cells are used in the system with single module dimension of 1,996 x 992 x 40 mm. The electrical parameters of the solar module are as shown in table 3. The solar module has two identical parts with cells that are half the size of ordinary solar cells. Half-cells (fig. 3) will reduce cell-to-module loss, increasing the output. Instead of 6 internal strings of cells, this has 2 x 6 shorter ones which helps reduce mismatch loss, internal power loss and shadow effect. When a module has slight shading, current of one half portion will be impacted, while the other half portion will still be producing power (fig. 4).

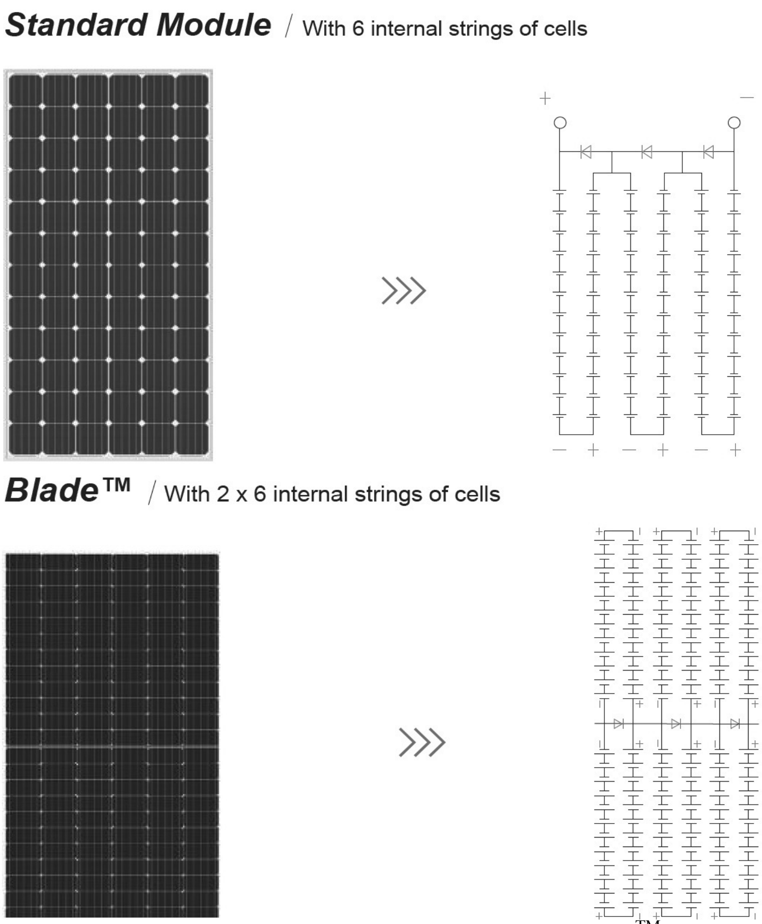

Figure 3 Internal cell arrangement in standard and Blade™ module

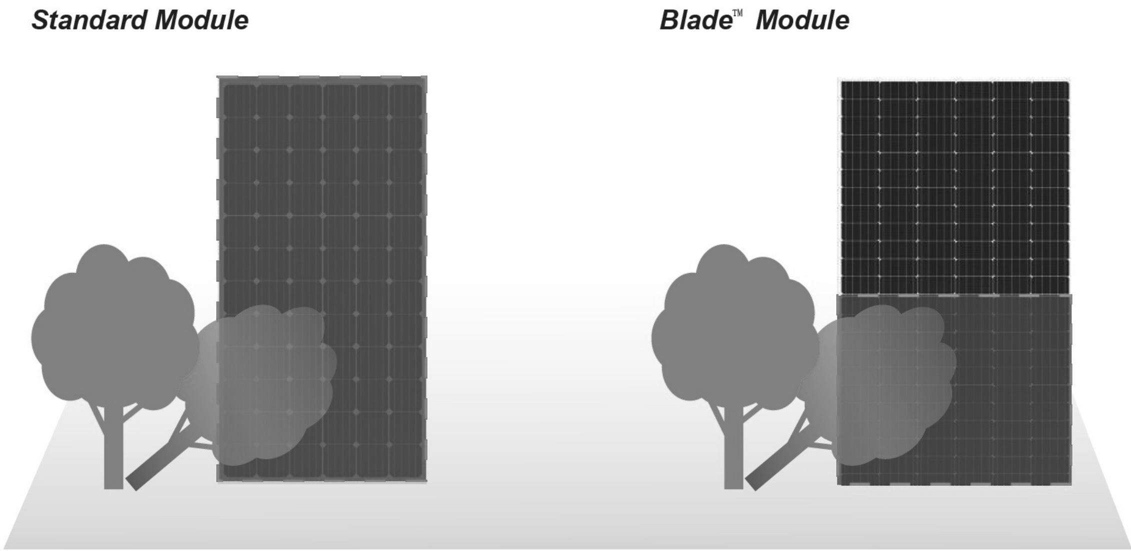

Figure 4 Blade™ module functioning in shaded condition

Table 3 Electrical specification of Seraphim 's Blade 375 W_p module

Electrical parameter at STC	Value
Model	SRP-375-BMA
Maximum power, P_{max} (W_p)	375
Solar cells	PERC monocrystalline (144 pcs)
Voltage at maximum power, V_{mpp} (V)	40.5
Current at maximum power, I_{mpp} (A)	9.26
Open circuit voltage, V_{oc} (V)	48.1
Short circuit current, I_{sc} (A)	9.7
Module efficiency, η (%)	18.94

3.2.2.2. Inverter. Two Sunny Tripower Core1 50 kW inverter (Model: STP 50-40) have been used in the system. It is the world's first free-standing string inverter (SMA, 2020) for decentralized rooftop and ground-based PV systems. It has yield upto 150% DC:AC ratio due to integrated shade management. The maximum DC input it can handle is 75 kW at STC. It operates at a nominal voltage of 670 V with the maximum input current of 120 A. The technical data of the inverter is shown in table 4.

Table 4 Technical data of Sunny Tripower Core1 50 kW inverter

Technical parameter	Value
Recommended DC power (kW_p)	75
Maximum input voltage (V)	1000
MPPT voltage range (V)	500 – 800
Maximum operating input current (A)	120
Rated output power (kW)	50
Rated output current (A)	72.5
Power factor at rated power / Adjustable displacement power factor	1 / 0.0 leading to 0.0 lagging
Total harmonic distortion	< 3%
Nominal AC voltage (V)	3-ϕ, 400 / 415
Maximum efficiency (%)	98.1
Self-consumption at night (W)	4.8

3.2.3. Nepal Telecom, Pokhara

The 45.32 kW_p solar plant at Pokhara is situated at a latitude of 28.22^0 N, a 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 data logger.

3.2.3.1. 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 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 module are as shown in table 5.

3.2.3.2. 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) design with precise algorithm that reduces string mismatch and has over 98.8% maximum efficiency. It can handle maximum input power of 33 kW and 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 dual MPPT design with 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 6.

Table 5 Electrical specification of Longi 440 W_p module

Electrical parameter at STC	**Value**
Model	LR4-72HPH-440M
Maximum power, P_{max} (W_p)	440
Cells	PERC monocrystalline (144 pcs)
Voltage at maximum power, V_{mpp} (V)	41.1
Current at maximum power, I_{mpp} (A)	10.71
Open circuit voltage, V_{oc} (V)	48.9
Short circuit current, I_{sc} (A)	11.46
Module efficiency, η (%)	20.2

Table 6 Technical data of Solis inverters

Technical parameter	**Solis-3P20K-4G**	**Solis-25K-5G**
Maximum DC power (kW_p)	24	33
Maximum DC input voltage (V)	1000	1100
MPPT voltage range (V)	160 - 850	200 – 1000
Maximum operating input current (A)	44	52
Rated/Maximum output power (kW)	20 / 22	25 / 27.5
Rated/Maximum output current (A)	28.9 / 31.8	36 / 41.8
Power factor (at rated output power)	0.8 leading to 0.8 lagging	
THD (at rated output power)	< 1.5%	< 3%
Nominal AC voltage (V)	3-ø, 400	3-ø, 400
Maximum efficiency (%)	98.7	98.8
Self-consumption at night (W)	< 1	< 1

3.2.4. Nepal Telecom, Biratnagar

The 45.32 kW_p solar plant at Biratnagar is situated at a latitude of 26.46^0 N, a 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.

3.3. Performance assessment parameters

The assessment of grid-tied solar PV systems is necessary to evaluate their performance in various climatic regions and to identify issues associated with their operation. Parameters such as array yield, final yield, performance ratio, capacity utilization factor, and system efficiency were calculated to help in the assessment.

3.3.1. 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,

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

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

3.3.2. Final yield

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

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

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 of the 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).

3.3.3. Reference yield

The 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

$$Y_r = \frac{H_T}{G_{STC}} \text{ (kWh/kW}_p\text{)}. \text{ --------------------------- (iii)}$$

It represents an equivalent number of hours that the system need to operate at the reference irradiance (Roumpakias & Stamatelos, 2017) and defines the amount of solar radiation for the PV system (Marion et al., 2005).

3.3.4. Performance ratio

The performance ratio (PR) measures the quality of a solar photovoltaic and is independent of location (Verma & Singhal, 2015). It indicates how close a PV system is to its ideal performance during actual operation and allows PV systems comparison independent of location, tilt angle, orientation, and nominal power capacity (Sharma & Goel, 2017). It is given by,

$$\text{PR} = \frac{Y_f}{Y_r}\ x\ 100\%. \text{ ----------------------------- (iv)}$$

By normalizing with irradiance, it quantifies the overall effect of losses on the rated output due to inefficiency of inverter, wiring losses, PV module temperature, dust accumulation, system down-time, and component failures (Marion et al., 2005). It does not represent the amount of energy produced, as a system with low PR in high solar resource location can produce more energy than a system with high PR in low solar resource location. Gopi et al. (2021) compared normal and weather-corrected PR of PV solar plants in hot and cold climates and found that weather-corrected PR is important for colder areas than warmer areas. The weather-corrected PR of Montana (annual average temperature of 1.58 ^{0}C) PV plant had maximum variation of 7.64% during summer and -8.61% during winter, whereas the weather-corrected PR of Kuzhalmannam (annual average temperature of 27.28 ^{0}C), PV plant had maximum variation of 1.16% during summer and -0.91% during rainy.

3.3.5. 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 energy output that would have been generated if the system were operated at full capacity for the entire period" (Adaramola & Vagnes, 2015, p.461). It is given by,

$$CUF = \frac{E_{AC}}{P_{STC}\ x\ 8760}\ x\ 100\%. \text{ -------------------------- (v)}$$

3.3.6. System efficiency

The system efficiency is the ratio of AC output energy generated to the total possible energy that can be generated from the surface area of the solar panel. It is given by,

$$\eta_{sys} = \frac{E_{AC}}{H_T \; x \; A_m} \; x \; 100\%, \text{ ---------------------------- (vi)}$$

where A_m is the module area in m^2.

3.3.7. PV Cell Temperature

It is the temperature of the solar cell. 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 & Beckman (1991), the PV cell temperature is calculated by HOMER ENERGY (n.d.) as:

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

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

α_p = temperature coefficient of power

τ = solar transmittance of any cover over the PV array

α = solar absorptance of the PV array

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

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

where,

P_{rated} = rated power of the solar panel

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

4. RESULTS AND DISCUSSIONS

This section presents the result obtained from the data analysis. This is divided into four sections;

a) Long term comparison (NTC Sundhara),

b) Comparison of systems with half-cut solar technology (NTC Chhauni, Pokhara, and Biratnagar),

c) Comparison of systems with same components (NTC Pokhara and Biratnagar), and

d) Financial benefit from the systems.

4.1. Long term comparison

The 64.6 kW_p solar plant installed at NTC Sundhara has been generating data from March 2019. The four years of operation gave opportunity to analyze the long-term performance of a monocrystalline silicon solar plant. For yearly comparison, the data of the individual years have been averaged out.

4.1.1. Final yield

The per kW_p energy generation has been constantly decreasing since 2019. The value of 2.91 kWh per kW_p in 2019 has decreased by 24% in 2022 to 2.21 kWh per kW_p (fig. 5). Besides,

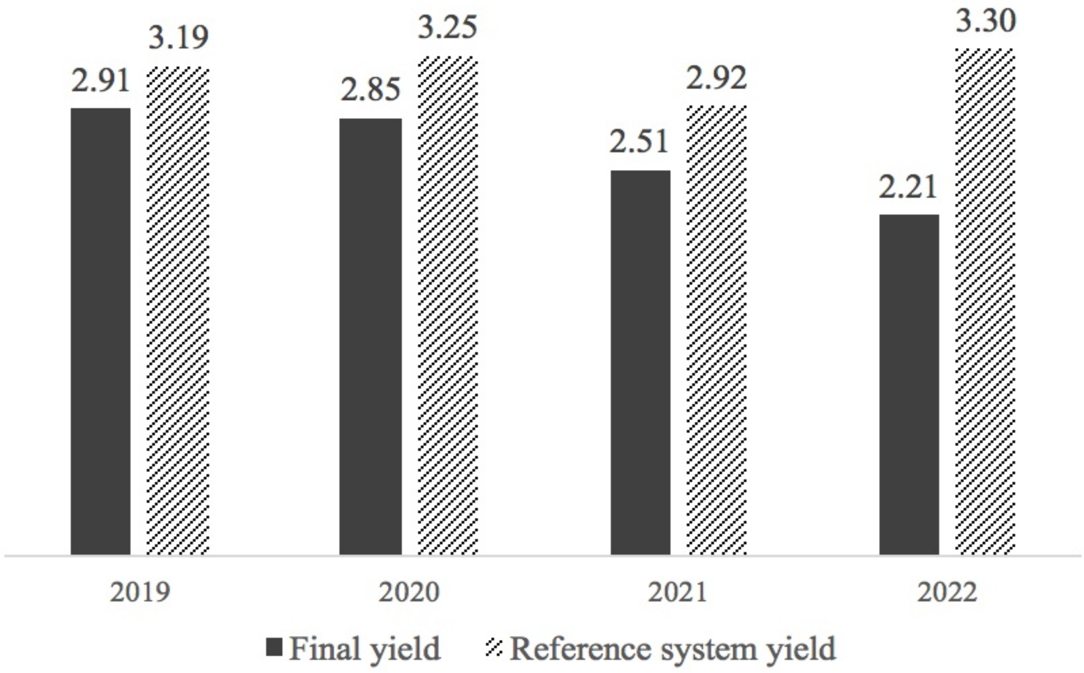

Figure 5 Yearly average final yield and reference system yield (kWh/kWp) at NTC, Sundhara

the per square meter energy generation also has decreased from 0.54 kWh/m^2 in 2019 to 0.41 kWh/m^2, i.e. 24% reduction. This decrease is relatively high compared to the data claimed by the manufacturer (see Section 3.2.1.1). Kazem et al. (2022) found that in just 35 days, the accumulation of dust decreased power from monocrystalline panels by 20%, Salimi et al. (2019) found that the output power of panel with dust covering was approximately 8 – 12% less per month compared to the clean panel and Paudyal et al. (2017) found that the power of panel in Kathmandu Valley with dust covering decreased by 29.76% compared to the module cleaned on daily basis. This shows that dust accumulation might be a major reason for this huge decrease. As a new tower is being built nearby alongside the fallen Dharahara, the dust from the construction works coat 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 that the panels can get for electricity production.

Besides, there are some strings in the system which 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 (see fig.6), whereas there was some shading in the summer

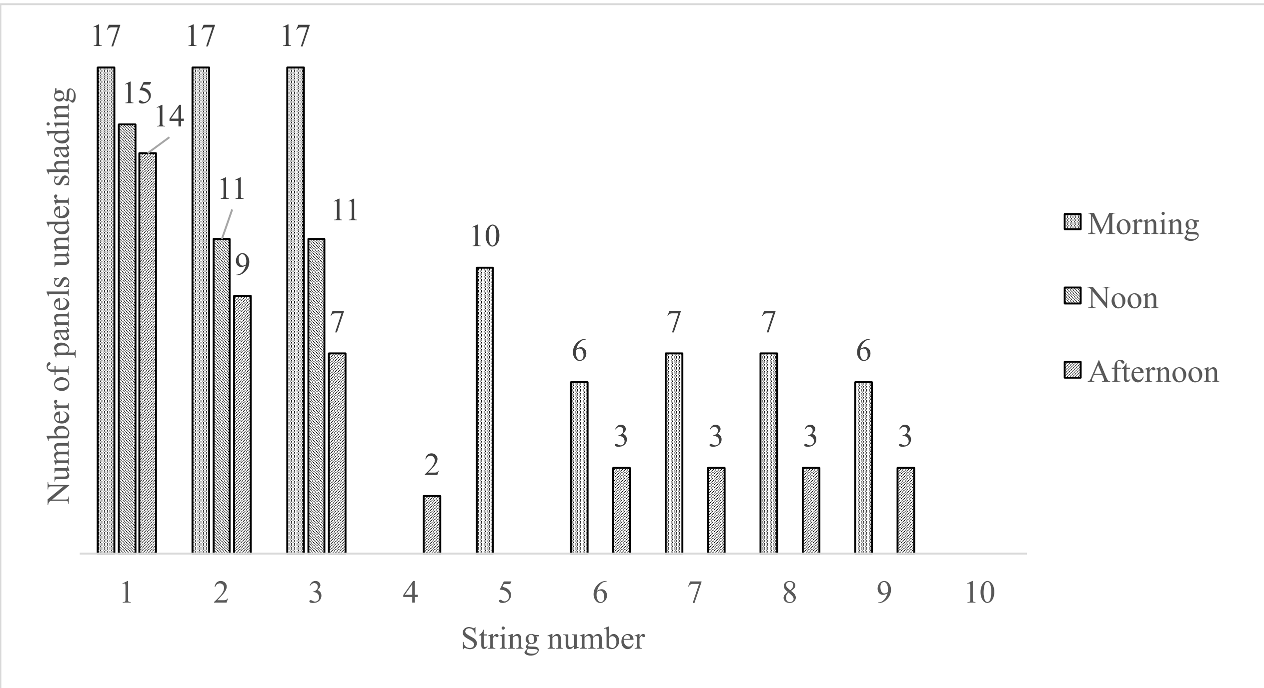

Figure 6 Number of panels under shade in winter in the solar plant at NTC Sundhara

morning in one of the strings (fig. 7). 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 (fig. 8).

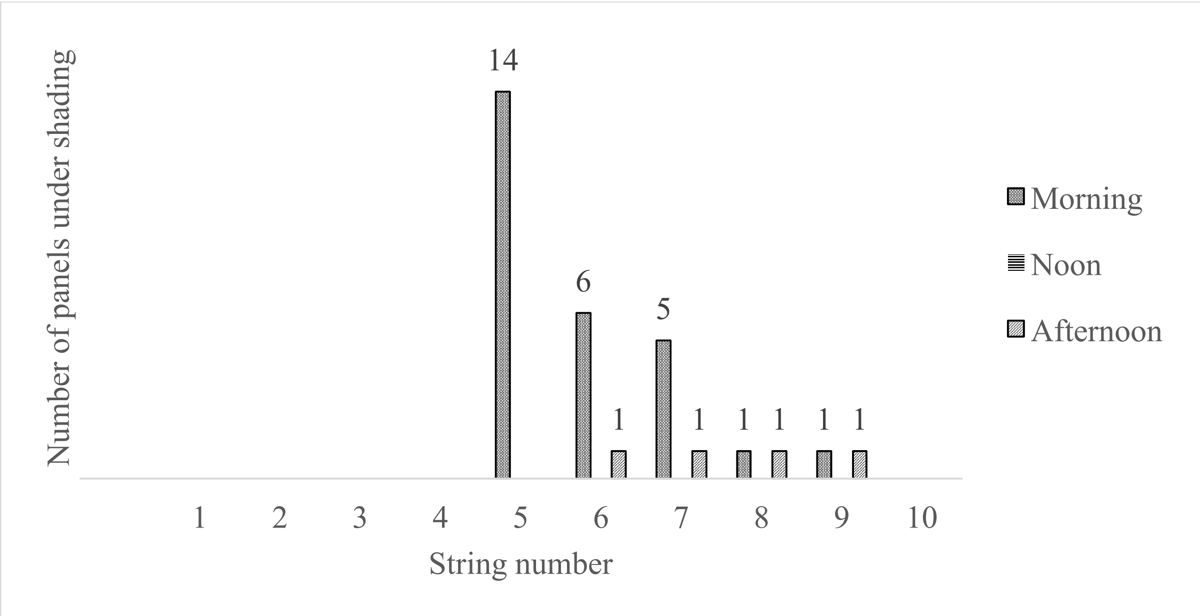

Figure 7 Number of panels under shade in summer in the solar plant at NTC Sundhara

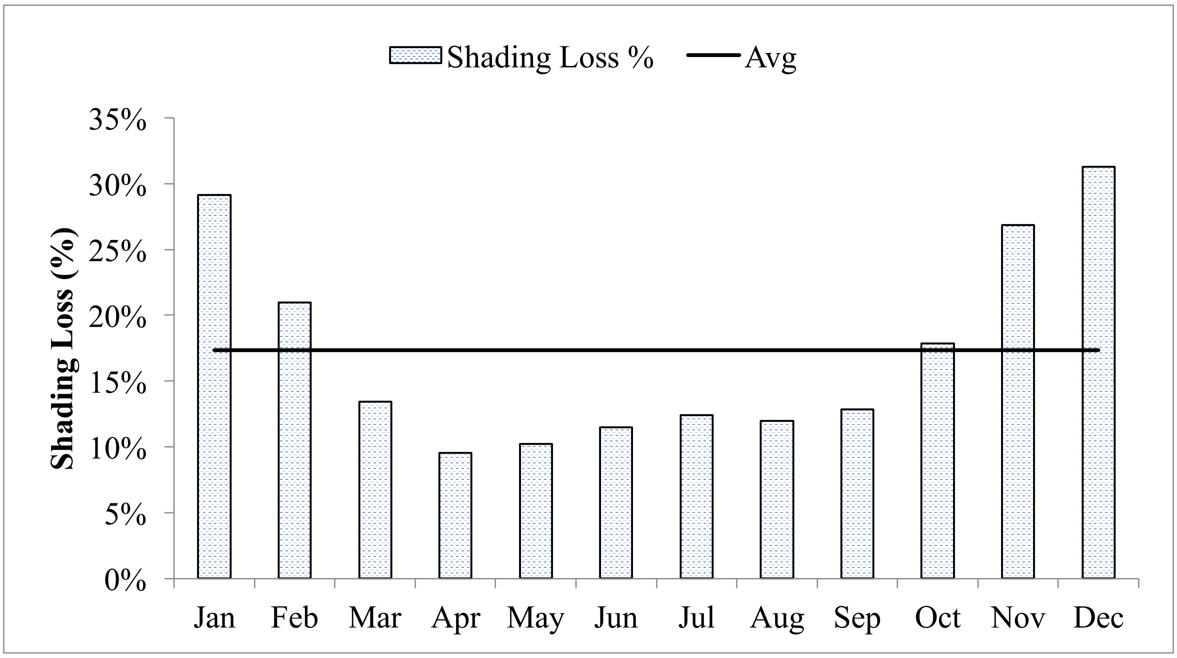

Figure 8 Shading losses (simulated) in the solar plant at NTC Sundhara

4.1.2. Performance ratio

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. 9). Looking at figure 4, the final yield continuously decreased as expected but the reference yield dipped significantly in the year 2021 compared to other years. This was due to the lesser value of solar radiation in the spring (March – May) of that year. This dip resulted in the higher value of performance ratio in the year 2021 causing the drastic decrease from 2021 to 2022. Bajracharya (2020) calculated the average performance ratio of the plant at 84.9% using the data from March to October 2019 while the value changed slightly to 82.97% using the data from March 2019 to December 2022.

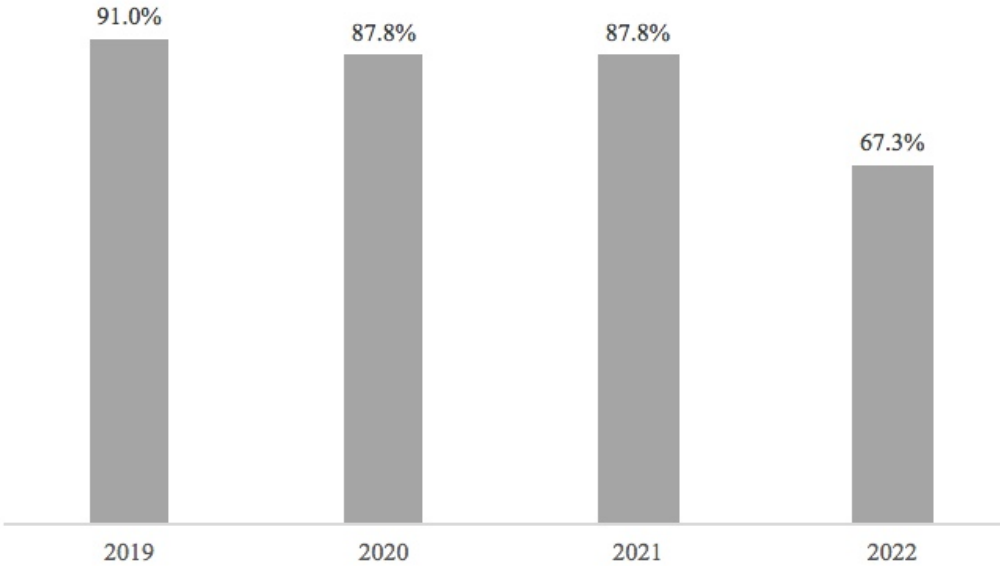

Figure 9 Yearly performance ratio of the solar plant at NTC Sundhara

4.1.3. Capacity utilization factor

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 (fig. 10). Bajracharya (2020) calculated the average capacity utilization factor of the plant at 16.62% using the data from March to October 2019 while the value changed to 10.83% using the data from March 2019 to December 2022.

4.1.4. System efficiency

As the system efficiency is dependent on the solar irradiance, like performance ratio, the efficiency dropped drastically from 16.3% in 2021 to 12.5% in 2022, due to lesser value of solar irradiance in spring 2021 (fig. 11). Bajracharya (2020) calculated the average system efficiency of the plant at 15.02% using the data from March to October 2019 while the value changed to 15.37% using the data from March 2019 to December 2022.

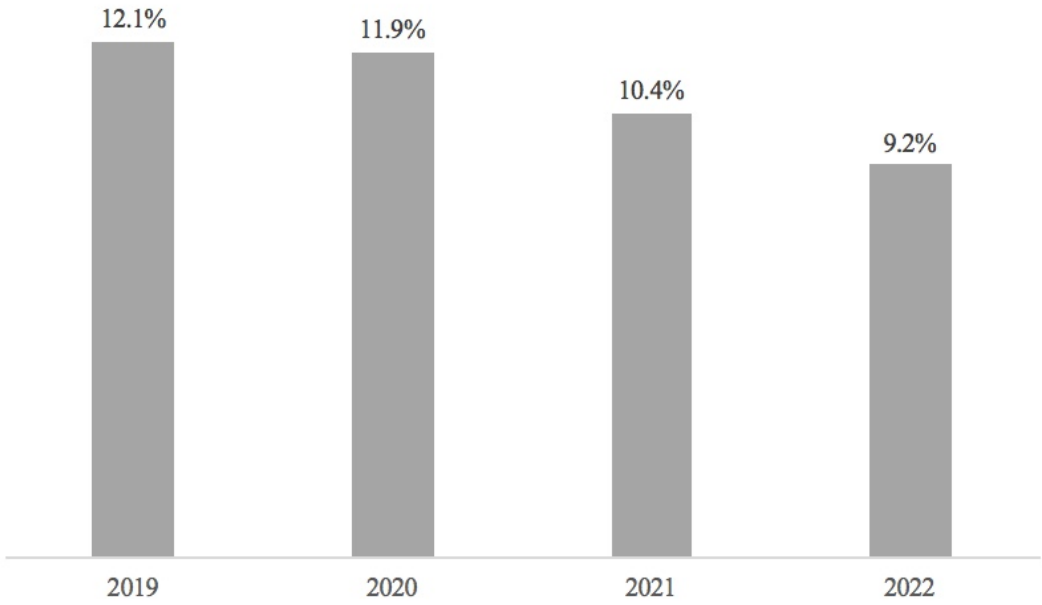

Figure 10 Yearly capacity utilization factor of the solar plant at NTC Sundhara

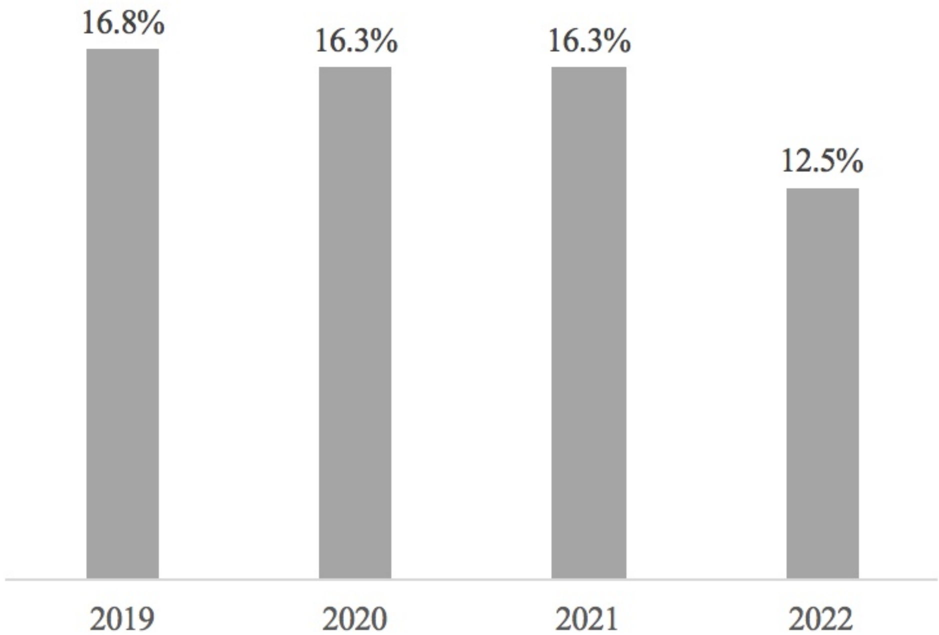

Figure 11 Yearly system efficiency of the solar plant at NTC Sundhara

4.2. Comparison of systems with half-cut solar technology

4.2.1. Final yield

4.2.1.1. Yearly comparison. The plant at Pokhara generated the maximum yearly final yield of 3.76 kWh/kW$_p$ followed by the plant at Biratnagar with a value of 3.46 kWh/kW$_p$, although the average horizontal irradiance at both the places (4.83 kWh/m^2/day[1] at Pokhara and 5.01 kWh/m^2/day at Biratnagar) are lower than that of Chhauni (5.04 kWh/m^2/day) (fig. 12). Also, per square meter wise, the plant at Pokhara produced the highest value of 0.76 kWh per square meter (fig. 13).

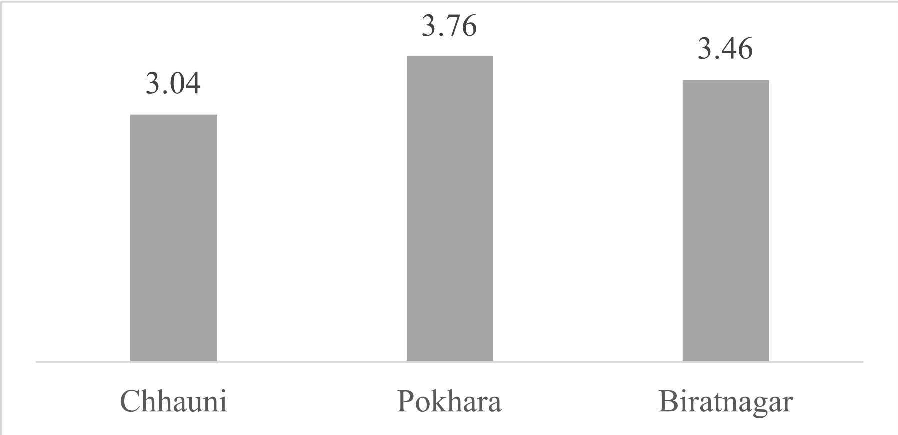

Figure 12 Yearly average final yield (kWh/kWp) of the plants

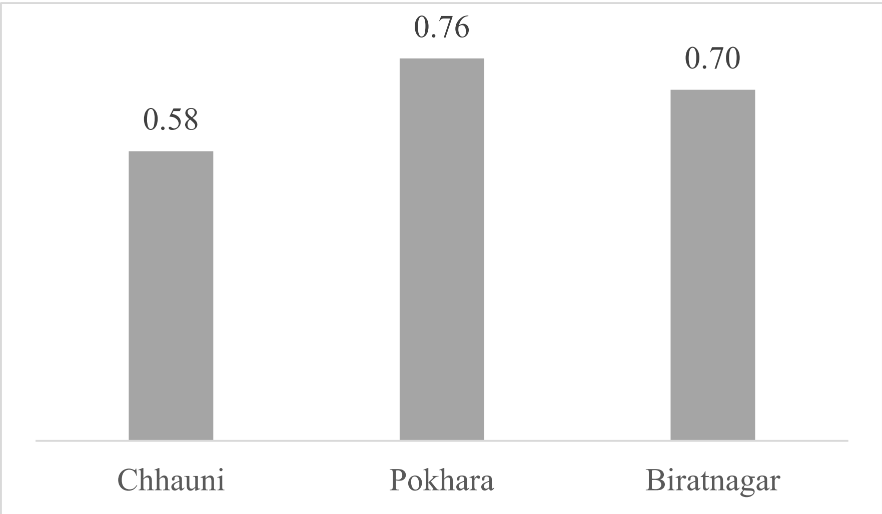

Figure 13 Yearly average final yield (kWh/m^2) of the plants

[1] These yearly average data are taken from the values of GHI generated for the location for a typical meteorological year from the NSRD at NREL. The data can be accessed at https://nsrdb.nrel.gov/data-viewer.

4.2.1.2. Seasonal comparison. The yield per kWp is the highest in the spring season for all the plants (fig. 14). It is because the months of March, April, and May have relatively clearer sky and higher value of solar irradiance. The plant at Pokhara has the highest value of yield per kWp for all the seasons. It is because of half – cut solar cells (less loss), higher efficiency of solar cells, and less average temperature. Similarly, the yield per square meter is the highest in the spring season and in the plant at Pokhara (fig. 15).

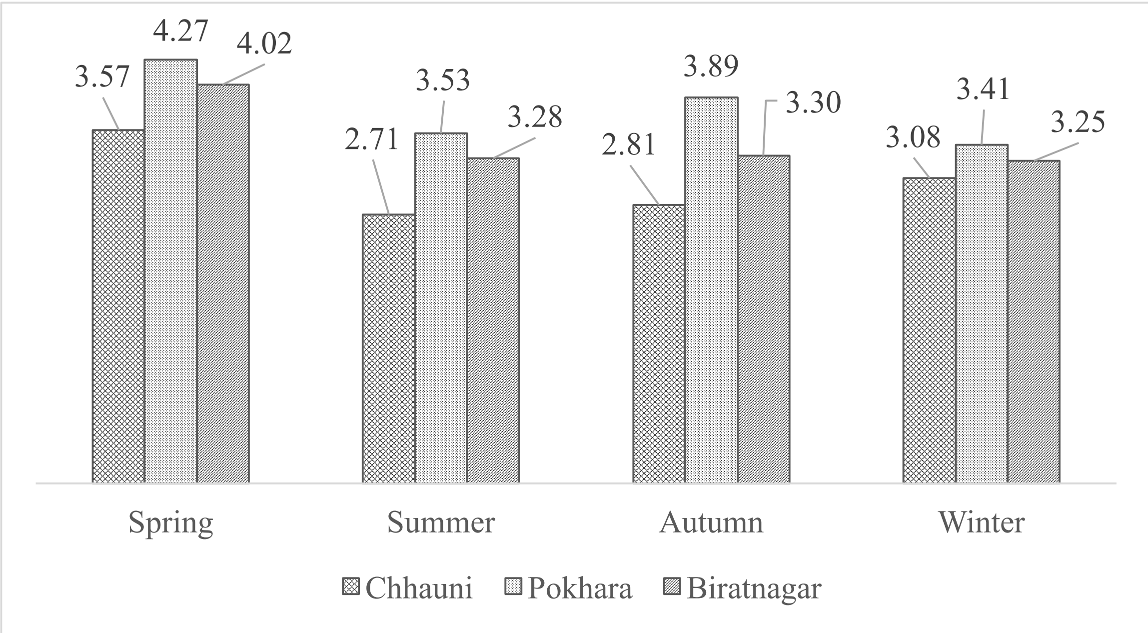

Figure 14 Seasonal average final yield (kWh/kWp) of the plants

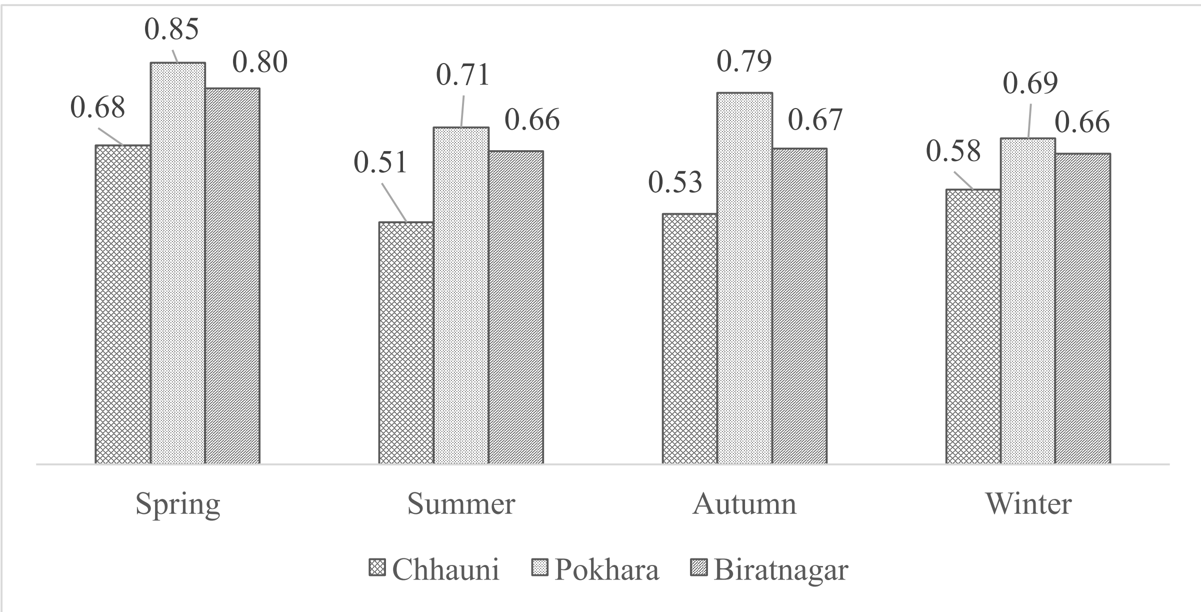

Figure 15 Seasonal average final yield (kWh/ m^2) of the plants

4.2.1.3. Monthly comparison. Almost all the months, the solar plant at Pokhara generated the maximum amount of energy per kW_p among the four plants (fig. 16). As seen in seasonal comparison, the maximum values are seen in the spring months of March to May. The Pokhara plant (4.90 kWh/kW_p) produced the highest yield in March. Similarly, the highest yield of Biratnagar plant (4.06 kWh/kW_p) came in May and the highest yield of Chhauni plant (3.76 kWh/kW_p) came in April. The lowest value observed was 2.26 kWh/kWp in September at Chhauni plant. Similarly, the yield in terms of area of the solar panel also follow similar trend with the highest value of 0.99 kWh/m^2 in March at Pokhara and the lowest value of 0.43 kWh/m^2 in September at Chhauni (fig. 17).

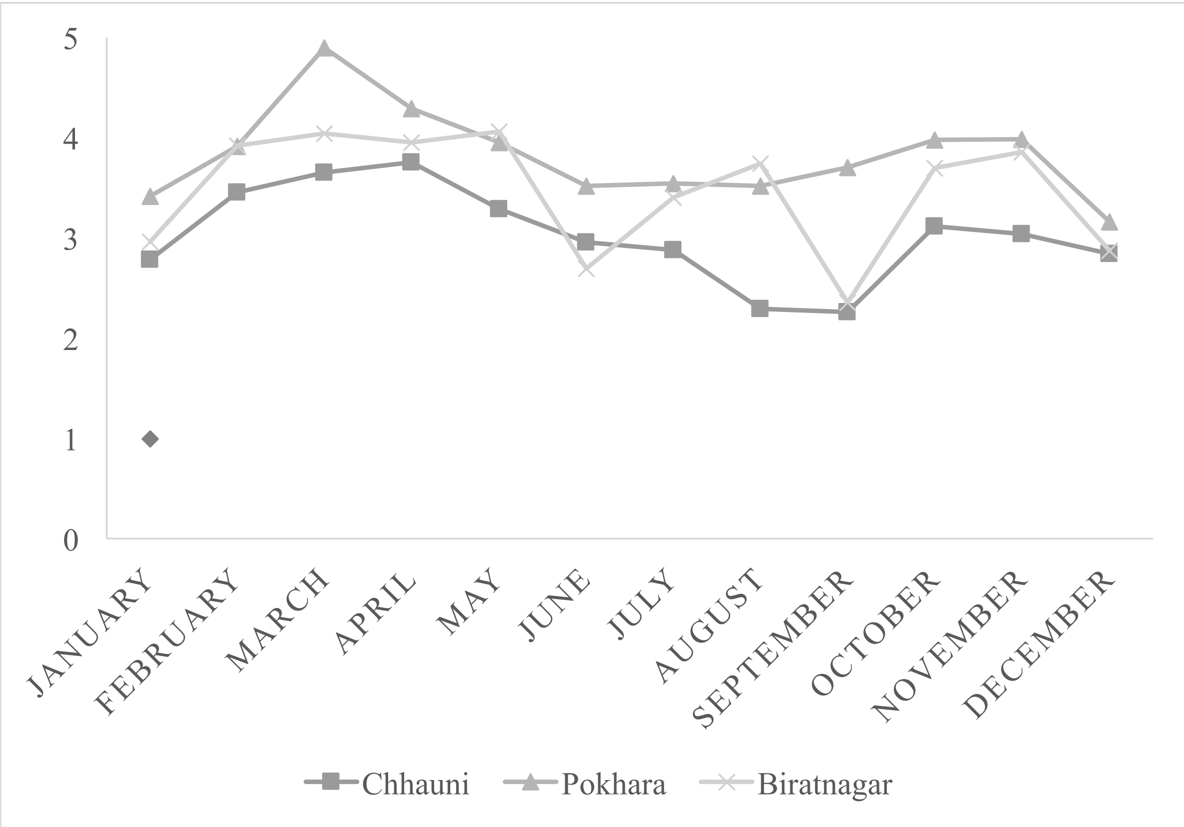

Figure 16 Monthly average final yield (kWh/kWp) of the plants

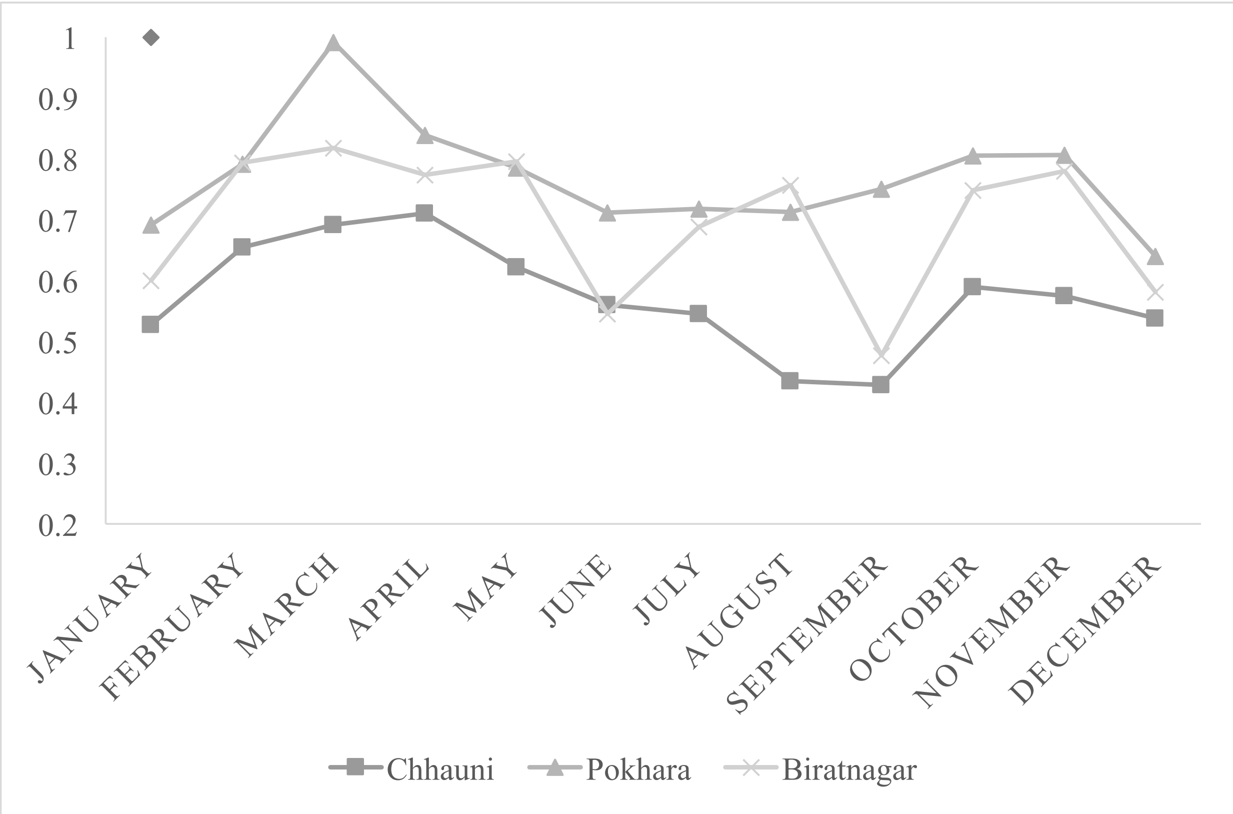

Figure 17 Monthly average final yield (kWh/m^2) of the plants

4.2.2. Capacity utilization factor

4.2.2.1. Yearly comparison. The plant at Pokhara had the highest yearly capacity utilization factor of 15.6%, i.e., the plant would produce the generated amount of electricity upon continuously operating 15.6% of the time, or 3.74 hours daily (fig. 18). The capacity factor was lowest for the plant at Chhauni (12.7%, or continuous operation of 3.05 hours daily).

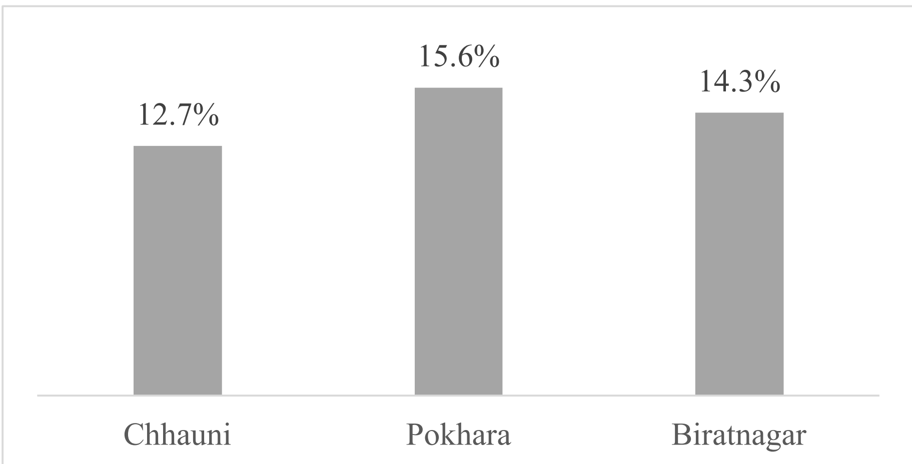

Figure 18 Yearly average capacity utilization factor of the plants

4.2.2.2. Seasonal comparison. Spring season had the highest capacity utilization factor due to its higher energy generation (fig. 19). The value reached a maximum of 17.5% for the plant at Pokhara. Overall, the plant at Pokhara had the highest numbers for all the seasons, while the plant at Chhauni had the lowest numbers. The lowest value (11.3%) was observed in the summer season at Chhauni plant.

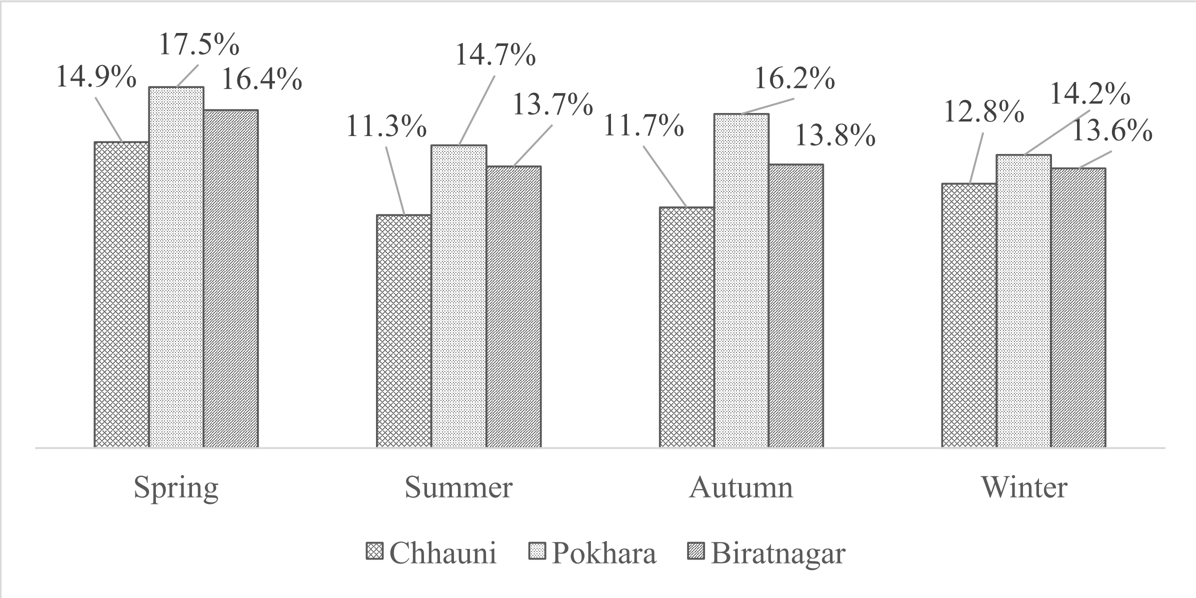

Figure 19 Seasonal average capacity utilization factor of the plants

4.2.2.3. Monthly comparison. Pokhara (20.4%) and Biratnagar (16.8%) had the highest capacity utilization factor in March, whereas Chhauni (15.6%) had the highest value in

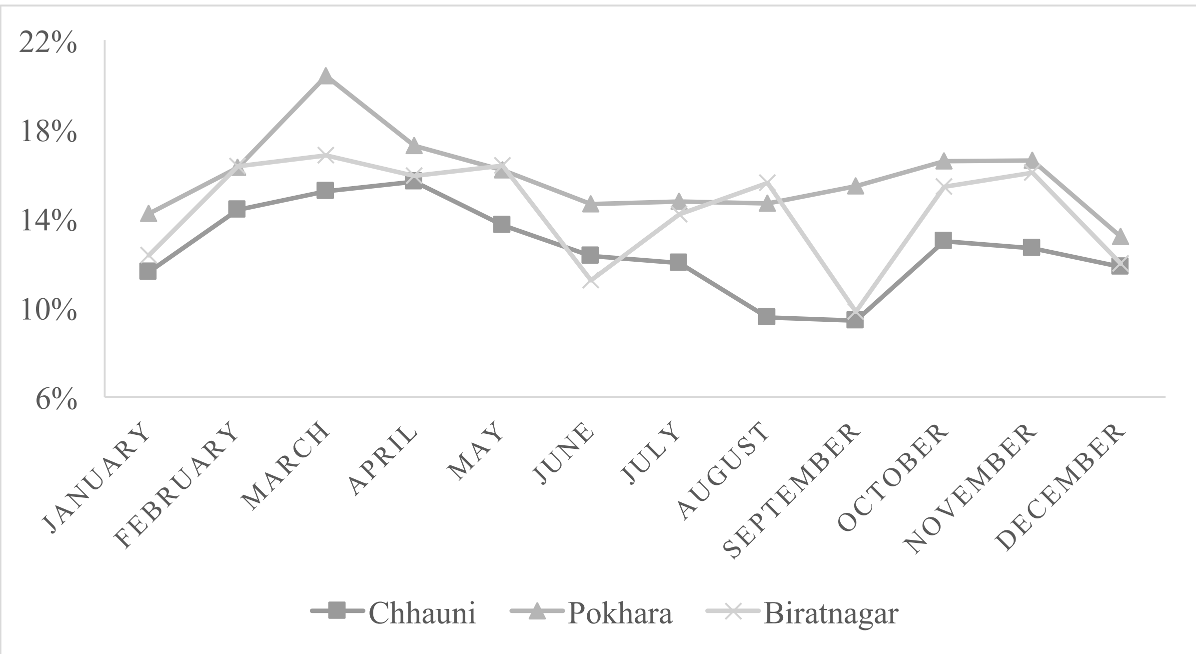

Figure 20 Monthly average capacity utilization factor of the plants

April (fig. 20). The lowest values were seen in December for Pokhara (13.2%), and in September for Biratnagar (9.8%) and Chhauni (9.4%).

4.2.3. System efficiency

4.2.3.1. Yearly comparison. The system efficiency of the Pokhara plant was the highest with the value of 16.0% while the Chhauni plant had the lowest with the value of 13.2% (fig. 21).

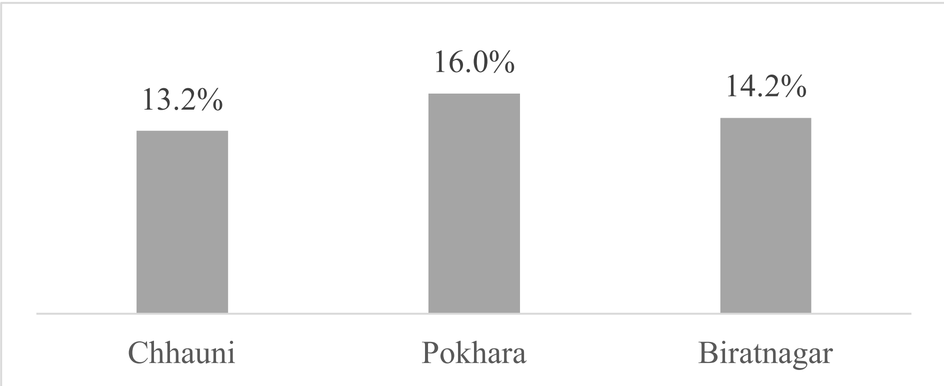

Figure 21 Yearly average system efficiency of the plants

4.2.3.2. Seasonal comparison. The system efficiency of the plants is higher in winter season because of lower solar irradiance. The plant at Pokhara had higher efficiencies in almost all the seasons. The lowest system efficiency of 10.5% was observed in summer season at Chhauni because of low energy generation due to high temperature and rainfall (fig. 22).

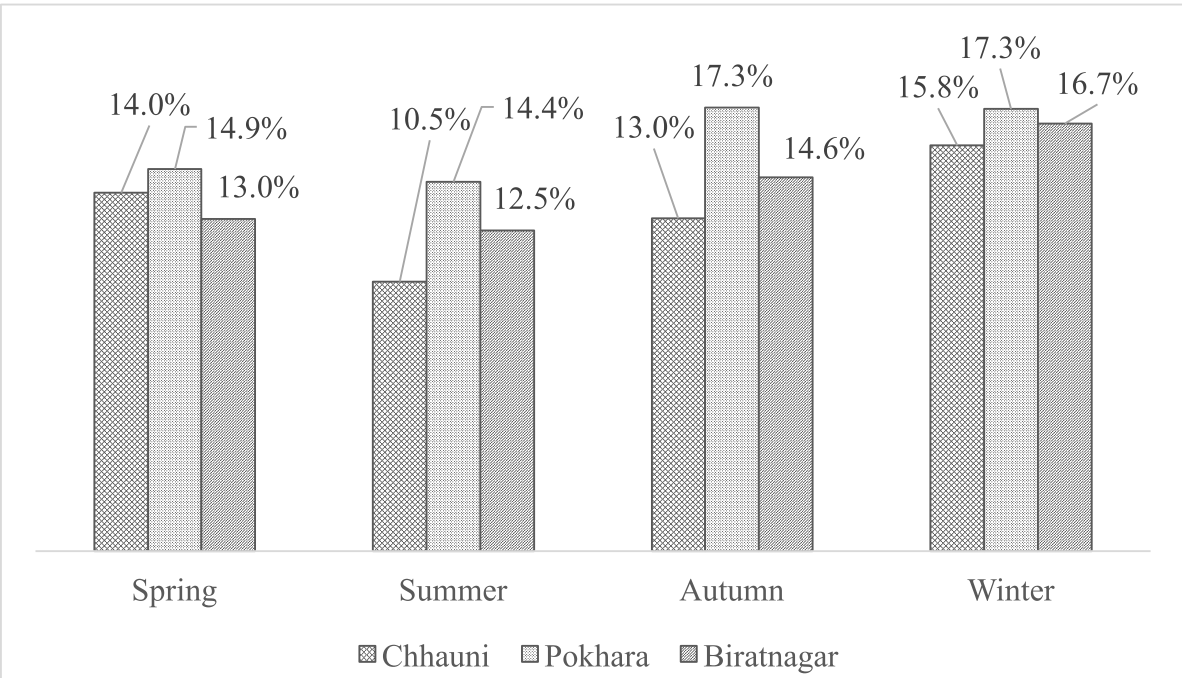

Figure 22 Seasonal average system efficiency of the plants

4.2.3.3. Monthly comparison. The system efficiency of the plants was above 15% during the months between October to February, i.e. autumn and winter season, reaching to a maximum value of 19.5% in the month of November at Pokhara plant (fig. 23). However, the value fell below that value in the months between March to September, i.e. spring and summer season, reaching to a value as low as 8.9% in the month of August at Chhauni plant. System efficiency of Pokhara plant had less variability (standard deviation = 2.1%) than the other plants.

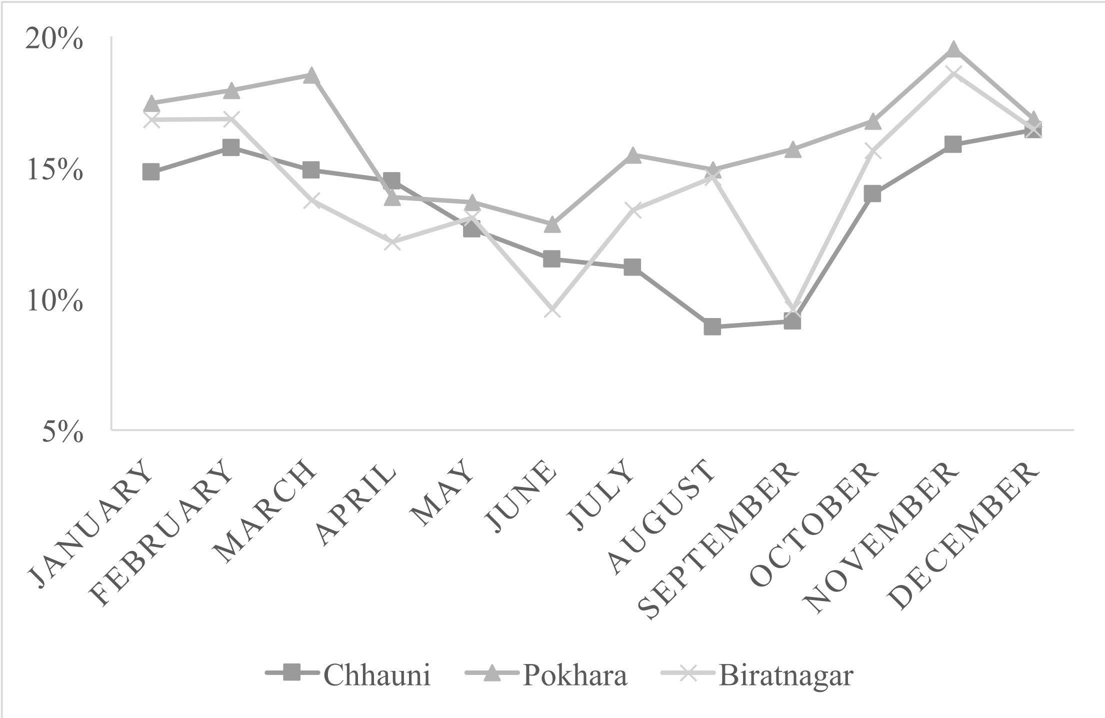

Figure 23 Monthly average system efficiency of the plants

4.3. Comparison of systems with same components

The system 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 hilly region of Nepal while Biratnagar lies in the Terai region (fig. 24). The impact of temperature and radiation on the various parameters was being conducted.

4.3.1. Weather data

Temperature and radiation data were obtained from NREL for a typical meteorological year. The air temperature at Pokhara ranged from 5.7^0C in January to 18.3^0C in June with an average

	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

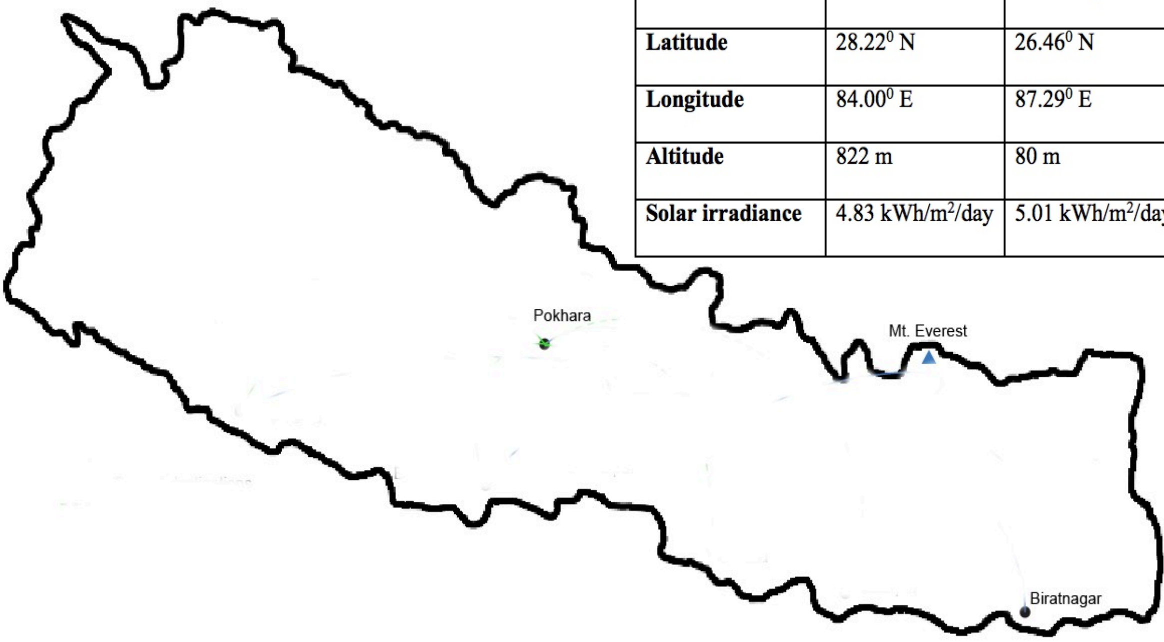

Figure 24 Location of Pokhara and Biratnagar in Nepal

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 (fig. 25). This showed that the average temperature at Biratnagar is double than that of Pokhara.

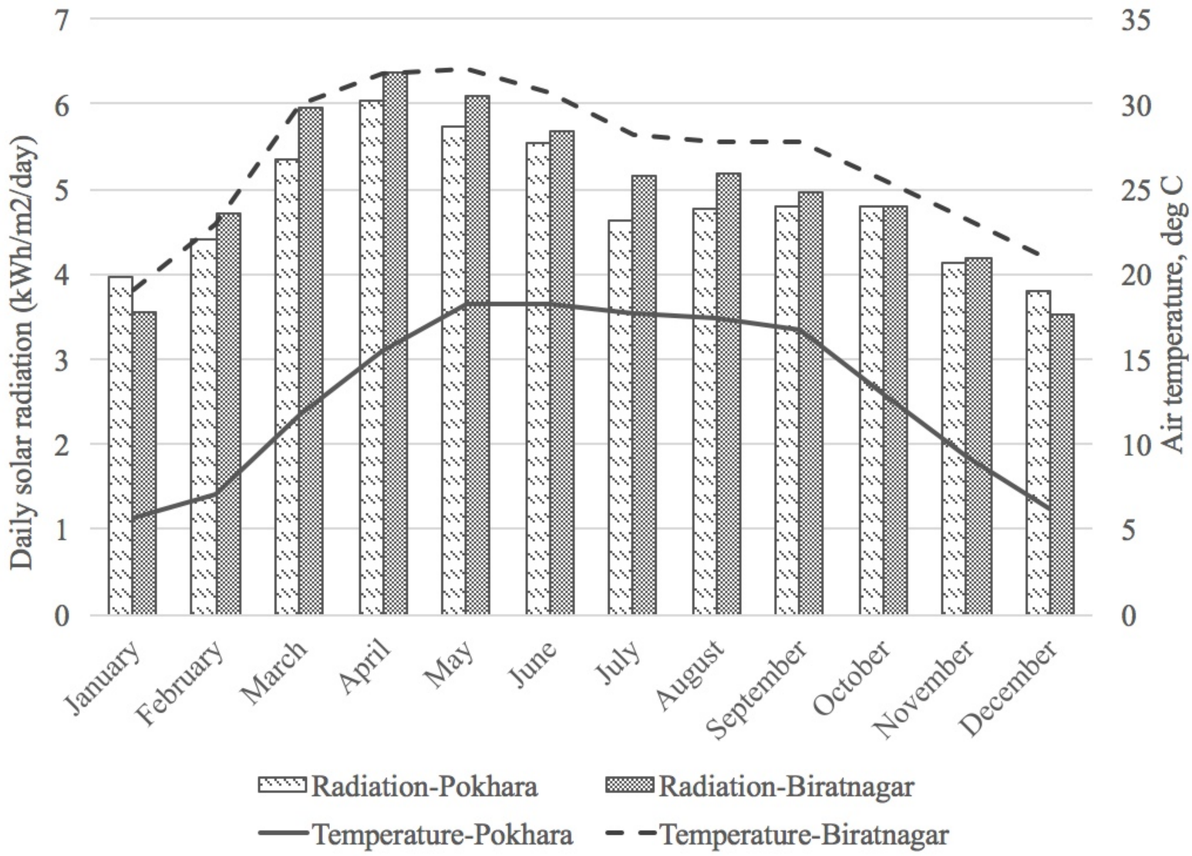

Figure 25 Temperature and radiation data of plants at Pokhara and Biratnagar

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. This showed that the solar radiation at Biratnagar is higher by 4% on average. Only, in the months of 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), that means, higher air temperature was related with higher radiance.

4.3.2. Final yield vs Temperature

While average temperature at Biratnagar (26.7^{0}C) was higher than at Pokhara (13.1^{0}C), the final yield (in kW_p) at Biratnagar was found to be lower than at Pokhara by an average value of 9%. Only the final yield in the months of May and August were higher at Biratnagar by 3% and 6%, respectively, than at Pokhara (fig. 26).

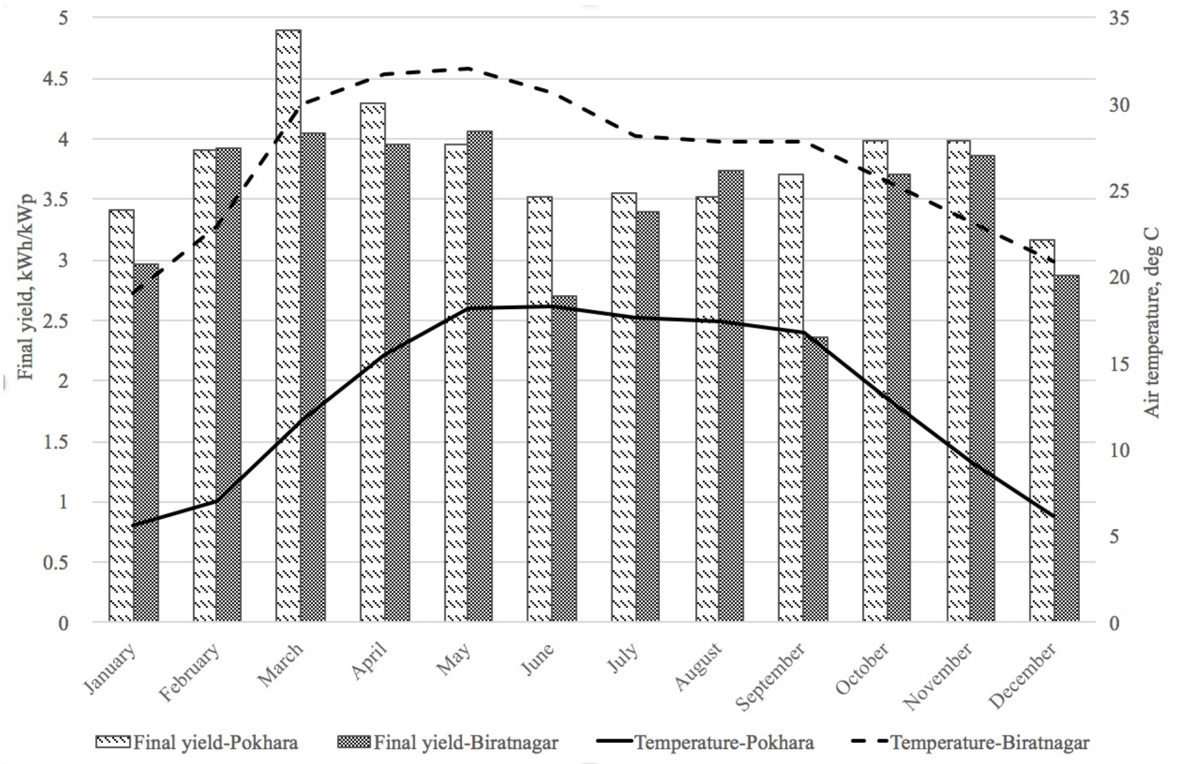

Figure 26 Final yield (kWh / kWp) vs temperature data of plants at Pokhara and Biratnagar

The reason behind lower final yield with higher temperature can be found by understanding the relation between temperature and power generated by the solar panel. The cell temperature was calculated with the formula used by HOMER software in its calculations with the values shown in table 7 and the subsequent power generation was calculated.

Table 7 Value of parameters used for cell temperature calculation

Parameter	**Value**	**Remarks**
$T_{c,\,NOCT}$	45^0C	from Longi solar panel datasheet
$T_{c,\,STC}$	25^0C	Standard test condition
$T_{a,\,NOCT}$	20^0C	Nominal Operating Cell Temperature
G_T	1000 W/m^2	Standard value taken for reference
$G_{T,\,NOCT}$	800 W/m^2	Nominal Operating Cell Temperature
$\eta_{mp,\,STC}$	20.2%	from Longi solar panel datasheet
α_p	-0.35 %/^{0}C	from Longi solar panel datasheet
$\tau\alpha$	0.9	As suggested by Duffie and Beckman in HOMER ENERGY (n.d.)

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 27. Although winter months had higher

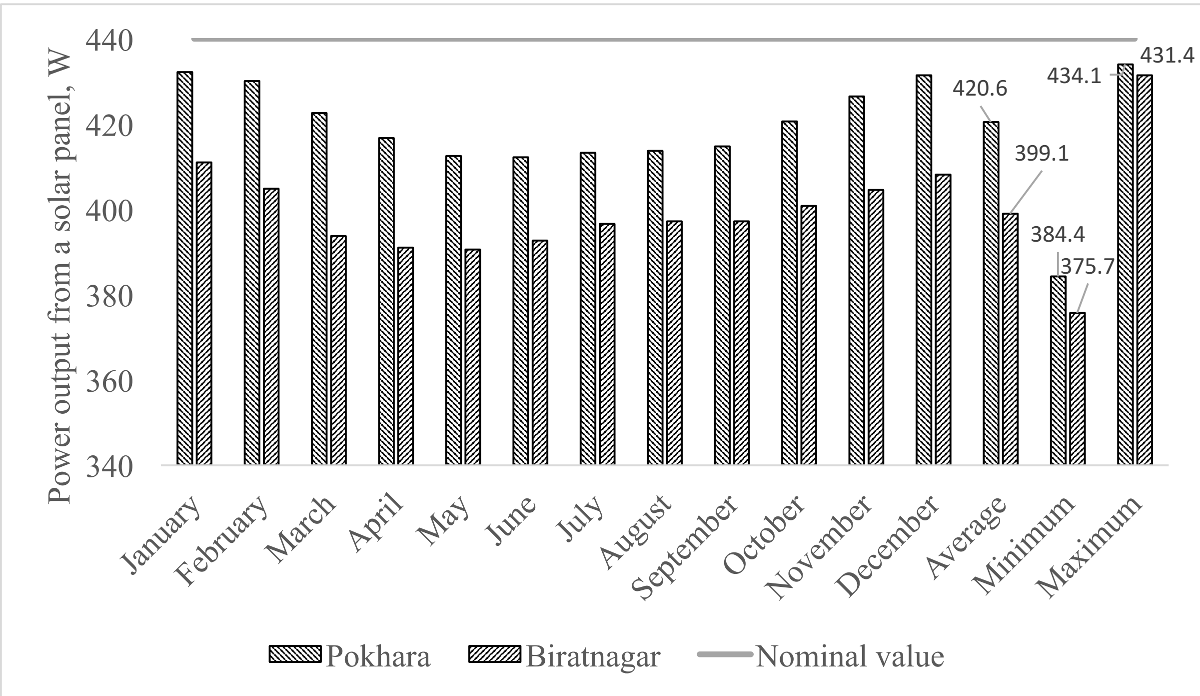

Figure 27 Monthly variation of power of a 440 W_p solar module at Pokhara and Biratnagar

power generation due to lower cell temperature, the final yield was lesser because of lesser solar irradiance. The maximum and minimum power generated from the panel based on the maximum and minimum temperatures recorded at the location (data taken from Meteorological forecasting division) are shown in table 8.

Table 8 Actual power generation from 440 Wp module

Location	Pokhara			Biratnagar		
	Average	**Maximum**	**Minimum**	**Average**	**Maximum**	**Minimum**
Ambient temperature	13.1^{0}C	36.0^{0}C (Jun 10, 2023)	4.5^{0}C (Jan 7, 2023)	26.7^{0}C	41.5^{0}C (Jun 9, 2023)	6.2^{0}C (Jan 19, 2023)
Cell temperature	37.6^{0}C	61.1 ^{0}C	28.8 ^{0}C	51.6^{0}C	66.8 ^{0}C	30.6 ^{0}C
Actual power	420.6 W (95.6%)	384.4 W (87.4%)	434.1 W (98.7%)	399.1 W (90.7%)	375.7 W (85.4%)	431.4 W (98.0%)

The values seen in fig. 27 and table 8 are in accordance to the panel specifications which mentioned that the temperature coefficient of maximum power is -0.35%/^{0}C, i.e. for every ^{0}C increase above 25^{0}C, the power generated decreases by 0.35%. Thus, higher temperature was related to less power and subsequently less energy generation. Revati and Natarajan (2016) also found that the performance of solar cell increased with a decrease in temperature. Higher temperature month was usually associated with lesser energy generation or final yield and this was more pronounced for the plant at Pokhara than at Biratnagar (fig. 28 and 29).

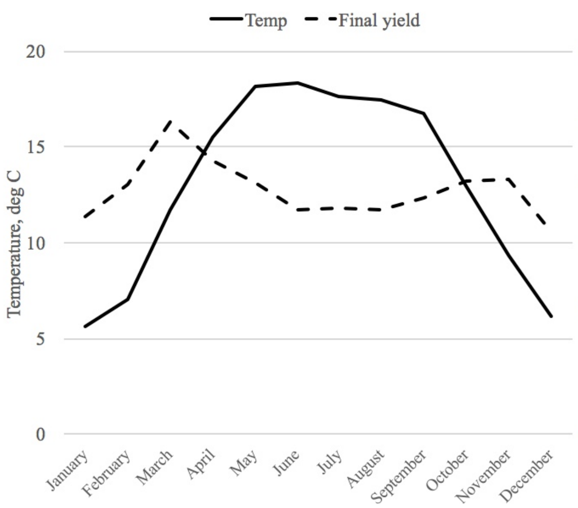

Figure 28 Final yield vs temperature for Pokhara plant

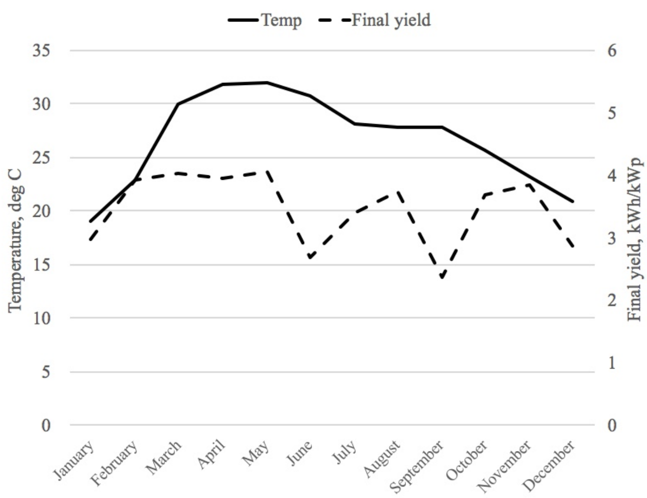

Figure 29 Final yield vs temperature for Biratnagar plant

Same pattern can be observed when the final yield (in per square meter) is compared with the temperature at the locations (fig. 30).

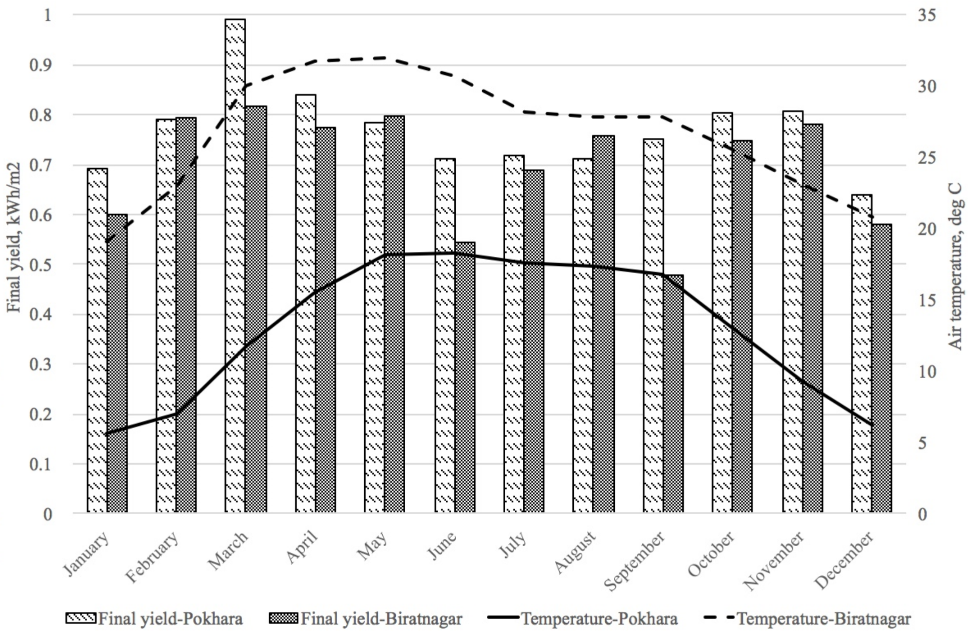

Figure 30 Final yield (kWh / m^2) vs temperature data of plants at Pokhara and Biratnagar

4.3.3. Performance ratio vs Temperature

For each location, the higher temperature month was usually associated with lesser performance ratio. A pronounced difference was observed in November and December (fig. 31 and 32). While the temperature dropped from November to December, the PR also dropped. This can be attributed to larger drop in the final yield than the reference yield. While the reference yield at Pokhara dropped by 7.9%, the final yield dropped by 20.6%. Similarly, the final yield at Biratnagar dropped by 25.4% while the reference yield dropped by 15.9%. The

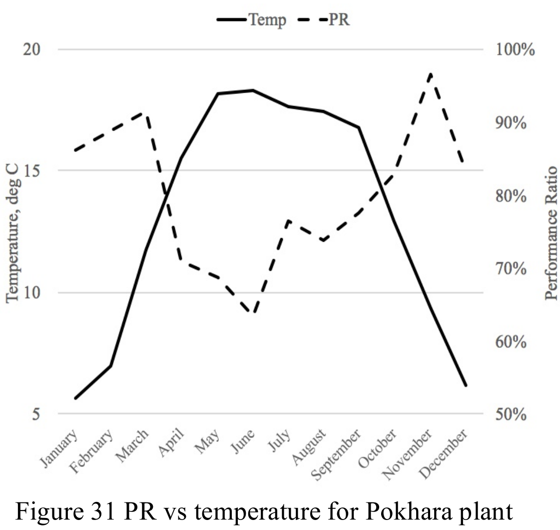

Figure 31 PR vs temperature for Pokhara plant

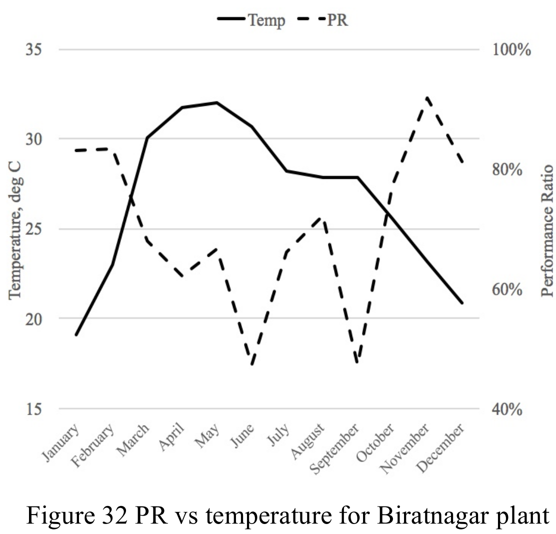

Figure 32 PR vs temperature for Biratnagar plant

PR for the month of June and September at Biratnagar showed drastic drop because of less value of final yield as recorded in the portal.

4.3.4. Capacity utilization factor vs Temperature

The capacity utilization factor of plant at Pokhara was usually higher than at Biratnagar, except for the months of February, May, and August. The yearly average value was 15.9% at Pokhara and 14.3% at Biratnagar (fig. 33). 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.

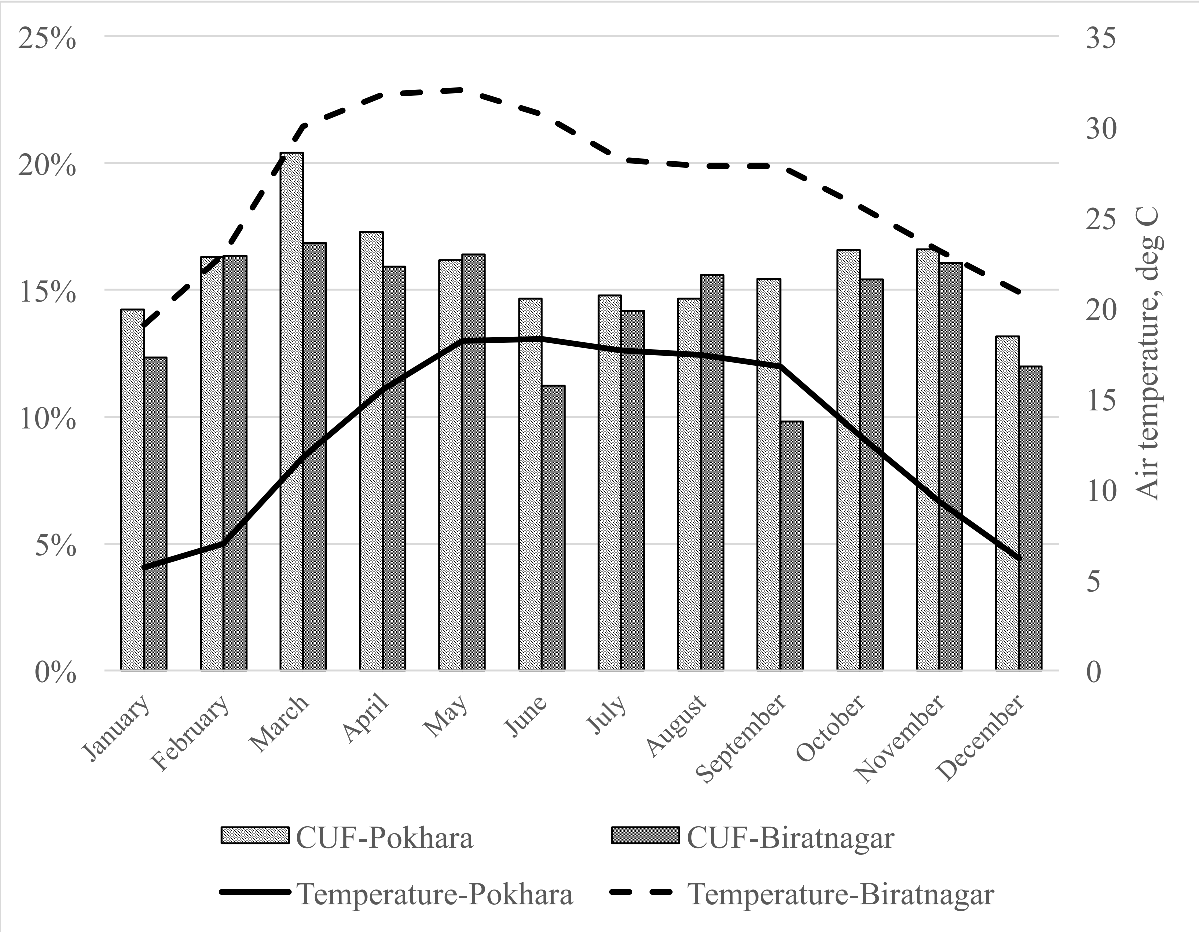

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Figure 33 CUF vs temperature for Pokhara and Biratnagar plants

4.3.5. System efficiency vs Temperature

The system efficiency of the plant at Pokhara was always higher than the plant at Biratnagar (fig. 34). The average system efficiency of Pokhara and Biratnagar plants were 16.1% and

14.2% respectively. For each location, the higher temperature month was usually associated with lower system efficiency. Farahmand et al. (2021) also found that the panel efficiency during winter was higher than summer due to decrease in air temperature. Also, it was calculated that for every 10^0C 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).

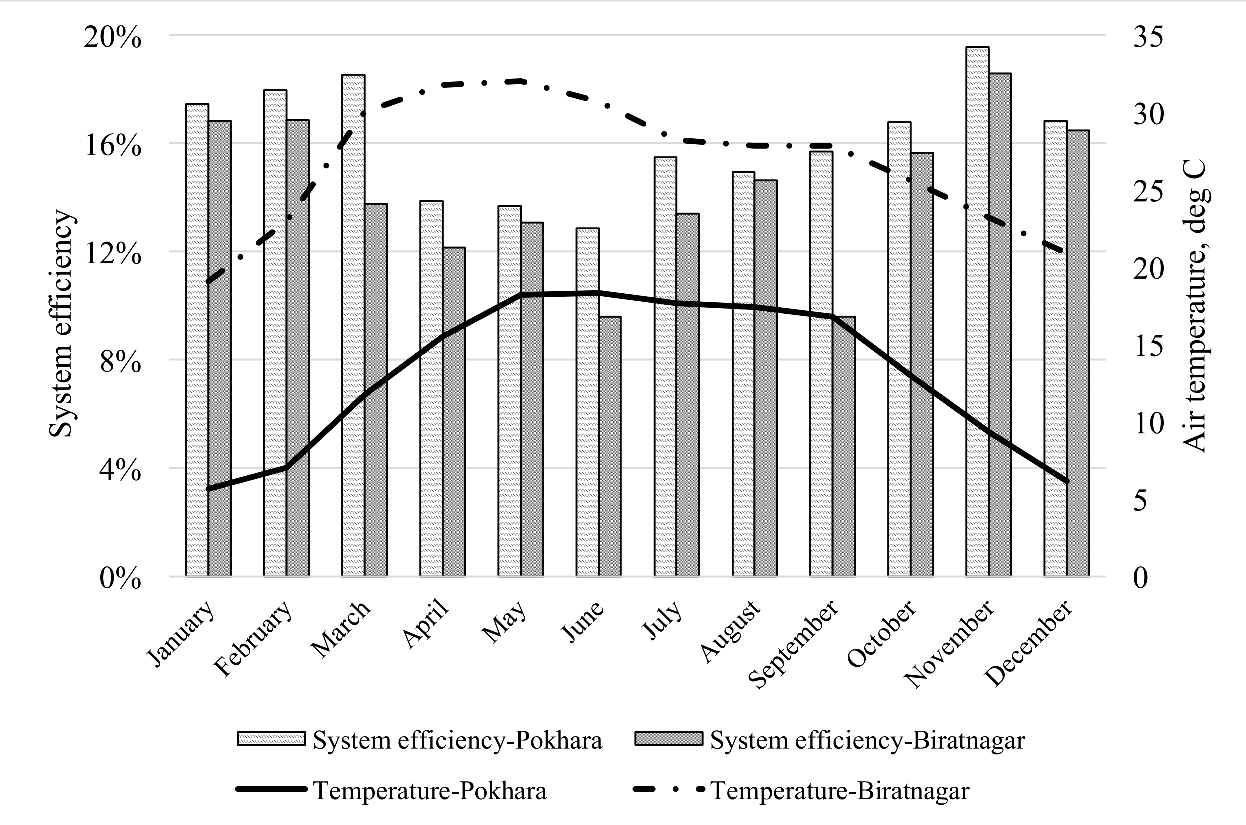

Figure 34 System efficiency vs temperature for Pokhara and Biratnagar plants

4.4. Financial benefit from the systems

The tariff rate for NTC is as set for commercial consumer category of 11 kV range, which is Rs. 11.10 for normal time of operation, i.e. 05.00 AM to 05.00 PM. This is the time when the solar plant operates. The energy generated from the solar plants at the locations studied are consumed within the office and is not exported to the national grid (A. K. Shakya, personal communication, August 10, 2023). So, the energy generated from the plants saves money for the NTC because the energy used from solar plants had to be generated from other sources like NEA, diesel. Table 10 shows the calculation for amount saved during the operation of solar plant till the time of this study.

Table 9 Financial benefit generated by NTC from the solar plants

Plant	**Capacity in kW_p**	**Observation period**	**Total AC energy produced in kWh**	**Total amount saved**	**Amount saved per year per kW**
Sundhara	64.6	Mar 2019 – Dec 2022	228,766.20	Rs. 25,39,304.82	Rs. 10,482.17
Chhauni	102.0	Feb 2021 – Dec 2022	214,085.75	Rs. 23,76,351.83	Rs. 12,155.25
Pokhara	45.32	May 2021 – Dec 2022	103,595.90	Rs. 11,49,914.49	Rs. 15,193.55
Biratnagar	45.32	Sep 2021 – Aug 2022	56,525.10	Rs. 6,27,428.61	Rs. 13,844.41
Total			6,02,972.95	Rs. 66,92,999.75	Rs. 12,918.85 (average)

The total amount saved by installing solar plants at the locations during the observation period is Rs. 66.93 lakhs with an average of Rs. 12,920 saved per year per kW. Bajracharya (2020) calculated the yearly saving from the plant at Sundhara at Rs. 16.08 lakhs using eight months of operational data (Mar ’19 – Oct ’19). However, the current study found the saving at a lesser value of Rs. 6.77 lakhs per year. This is because of the lesser yield from the system owing to the shading, dust accumulation, and power degradation. This shows that financial analysis requires consideration of these factors to show a better picture of the financial gains that can be achieved from a solar project. Besides, the amount saved per year per kW is higher for half cut solar cells with the plant at Pokhara saving the most. However, these plants have been in operation for a lesser period than the plant at Sundhara, so it is important to see their performance in long term to understand whether they save more money than the normal solar cells.

4.5. Summary of technical performance parameters

Summary of technical parameters for the studied plants are presented below:

Table 10 Summary of technical performance parameters of all the plants

S. No.	Technical parameters	NTC Sundhara	NTC Chhauni	NTC Pokhara	NTC Biratnagar
1	Reference yield (Y_r) (kWh/kW_p)	3.16	4.42	4.81	5.01
2	Final yield (Y_f) (kWh/kW_p)	2.60	3.04	3.76	3.46
3	Final yield (Y_f) (kWh/m^2)	0.48	0.58	0.76	0.70
4	Performance Ratio (PR)	83.0%	69.9%	79.1%	70.6%
5	Capacity Utilization Factor (CUF)	10.8%	12.7%	15.6%	14.3%
6	System Efficiency (η)	15.4%	13.2%	16.0%	14.2%

CONCLUSION AND RECOMMENDATION

5.1. Conclusion

This study was conducted to evaluate the performance of four mono-crystalline silicon based grid-tied solar PV plants installed at Nepal Telecom offices of Sundhara, Chhauni, Pokhara, and Biratnagar. The conclusions of the study are as:

a. Since its operation from March 2019, the solar plant at Sundhara has been generating less energy from the installed solar modules. While the plant produced 2.91 kWh/kW$_p$ in 2019, it had dropped to 2.21 kWh/kW$_p$ 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% to 67.3%, capacity utilization factor decreased from 12.1% to 9.2%, and system efficiency decreased from 16.8% to 12.5%.
b. The yearly **final yield** varied between 3.04 kWh/kW$_p$ at Chhauni plant to 3.76 kWh/kW$_p$ at Pokhara plant. All plants had the highest yield in the spring season. The highest and lowest values observed were 4.90 kWh/kW$_p$ in March at Pokhara plant and 2.26 kWh/kW$_p$ in September at Chhauni plant. The yearly **capacity utilization factor** varied between 12.7% at Chhauni plant to 15.6% at Pokhara plant. All plants had the highest value in the spring season. The highest and lowest values observed were 20.4% in March at Pokhara plant and 9.4% in September at Chhauni plant. The yearly **system efficiency** varied between 13.2% at Chhauni plant to 16.0 % at Pokhara plant. The system efficiency was comparatively higher in winter season owing to the lower values of solar irradiance. The highest and lowest values observed were 19.5% in November at Pokhara plant and 8.9% in August at Chhauni plant. For all the parameters, the plant at Pokhara had the highest value in all the seasons and almost all the months.
c. 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 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 temperature, especially the spring and summer seasons.

d. The total amount saved by NTC during the observation period from the solar plants is Rs. 66,92,999.75 with an average saving of Rs. 12,918.85 per kW per year. The plant at Sundhara showed that as the panel aged, the amount saved gradually decreased due to lesser yield.

5.2. Recommendation

This study has been conducted under limited resources and information. Data from the developers and clients were not available as much as required due to copyright issues and out-of-order data logger. 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 Alternative Energy Promotion Center (AEPC).
- Proper technical research to identify the efficacy of half-cut solar cells in comparison to the 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.
- Financial analysis of any PV system should incorporate power degradation losses and shading/dust losses to show true picture of the financial gains from the system.

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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 11 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, ^0C	GHI, $kWh/m^2/day$	Average temp, ^0C	GHI, $kWh/m^2/day$	Average temp, ^0C	GHI, $kWh/m^2/day$	Average temp, ^0C	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 12 Monthly average parameters of all the plants

Location	Month / 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, 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 13 Seasonal average parameters of all the plants

Location	Season / Category	Final yield, Y_f (kWh/kWp)	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 (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%

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