Towards a Net Zero Building Using Photovoltaic Panels: A Case Study in an Educational Building

Rabin Dhakal*, Ashish Sedai**, Suman Paneru***, Mohammad Yosofvand* & Hanna Moussa1*‡

*Department of Mechanical Engineering, Texas Tech University, Lubbock TX, USA

**Madan Bhandari Memorial Academy Nepal, Pokhara University, Morang, Nepal

***M.E. Rinker, Sr. School of Construction Management, University of Florida, Gainesville, FL, USA

‡ Corresponding Author; Last Author, Department of Mechanical Engineering, Texas Tech University, Lubbock, TX 79409, USA. Email: hanna.moussa@ttu.edu, Ph# +1-806-632-8141

Received: 12.05.2021 Accepted: 02.06.2021

Abstract- Renewable energy production continues to accelerate as the world recognizes the negative impact of fossil fuel consumption on the environment. Among the renewable energy technologies, there has been rapid growth in the use of solar PV systems in the last two decades. This study aims to design and assess the potential of a grid-connected solar PV system on the rooftop of an educational building in Morang, Nepal. The performance of the system, which can satisfy 100 % of the energy needs of the campus, is simulated using PVsyst and the results are analysed. The result of simulations show that a 48 kWp solar PV power plant would fulfill the total annual energy demand of 66.009 MWh of the campus; the solar array can produce 75.9 MWh/year of energy. The economic analysis of the proposed system is carried out using PV*SOL software, while the environmental analysis is performed using PVsyst. The environmental analysis shows that the proposed PV electricity generation can save 76.3 tonnes of carbon dioxide production. Hence, this green campus design will be a novel significant step towards transforming academic campuses in Nepal into energy-efficient and environmentally sustainable communities.

Keywords Photovoltaics, renewable energy, green campus, PVsyst.

1. Introduction

The energy generation from renewable energy sources such as solar, wind, hydro, and geothermal has experienced unprecedented growth in the last decades [1,2]. The solar photovoltaics (PV) installation has a global share of 4 % of installed capacity and shows the highest annual increase among the other renewable energy sources, i.e., 27 % in the period of the last five years [3]. The growth is fuelled by the decreasing overall cost of PV technology. The PV cost is economically competitive with that of conventional forms of electricity generation [4] and is expected to continue its key role in creating sustainable energy in the future [5]. Hence, solar PV technology has been widely used from a single household to educational institutions to provide green energy. Further, institutional policies promoting renewable energy have added to the boom in the use of PV technology [1]. In addition, climate change and global awareness have compelled designers and engineers to consider eco-friendly designs, and PV has been a preferred choice as one of the clean energy sources [3]. According to the United States Energy Information Administration (EIA), the building constitutes 1/3 of the total energy demand, and the rate of consumption is projected to increase by 2% each year [4]. Net Zero Buildings produce enough renewable energy to meet their own annual energy consumption requirement, and thereby reduce the use of non-renewable energy in the building sector; such buildings can reverse the energy need and be a symbol of sustainability. Institutional buildings are establishing new norms to improve their energy use to achieve Net Zero, and PV is their top pick as a renewable energy source. Thus, there is rapid growth in the solar PV system installation on different educational institutes to create sustainable green campuses, which ultimately have less impact on the environment [6-9].

Globally, to adopt the concept of a sustainable green campus, a significant number of universities are planning relevant investments [10], various plans and policies have been formulated in many countries, and governments are providing subsidies to implement solar PV in buildings, which in many cases makes it more profitable to install a solar PV system compared to the conventional energy systems [11, 12]. There are many successful examples of PV installation in educational buildings [13-15]. For example, Kawn and Hoffmann studied the feasibility of using a renewable energy resource in a city campus in Los Angeles, where a solar PV array is proposed to meet the campus total energy demand [16]. Chowdhary et al. presented a detailed feasibility study of a 50 kW PV installation at the rooftop of a Wyoming University campus building [13]. Baitule et al. showed the reduction of a carbon footprint by 73318.0 tonnes in their simulation of solar PV energy generation to meet 100 % of the energy demand of MANIT campus at Bhopal, India [17]. These studies focused on the concept of developing a sustainable green campus.

Jin H Jo et al. presented a feasibility study of a large-scale solar photovoltaic system of 1MWh capacity at an educational institute in Illinois and suggested three different locations for a photovoltaic installation: rooftop, glare land (land not suitable for the specific purposes or unused land), and vehicle parking canopy within the campus. The study shows that a total project investment of $2,100,000 can produce 1,384,000 kWh/year of solar energy [18]. Johngsung Lee et al. made a similar investigation on the economic feasibility of solar PV installations campus-wide at the University of New Haven, New England. The study suggests that the university could save up to $250,000 per year and approximately $6.3 million over the 25-year lifetime of the solar PV plant [9]. A feasibility study by Sujoy et al. of a PV system installed on the rooftop of a Pondicherry University campus building in India found that 30 kWp of a rooftop PV system produces 590 MWh/year of solar energy and the PV installation could help in reducing carbon emissions by 42 tonnes per year [19].

In recent years, the industry has adopted the term “net zero buildings” which refers to the equilibrium between the total power consumed and energy produced by a building [5]. One way to achieve Net Zero buildings is to use building integrated photovoltaics (BIPV) [8]. Net Zero Energy can be realized even in hot and humid climates if a hybrid design of active and passive cooling techniques is introduced in the building [7]. Reducing the conventional energy use in a building with renewable sources such as PV will make the building more environmentally friendly by lowering the emission of carbon dioxide [6][8]. To achieve a Net Zero outcome, it is also important to select devices and equipment that are energy efficient and choose reliable energy sources [9].

2. Nepal and its Perspective

All Nepal has thousands of free-flowing rivers, and it is the second richest country in water resources in the world after Brazil [20]. This tremendous potential of clean energy production is possible because of big, mini, and micro hydropower plants [21-23]. In addition, Nepal has wind resources, geothermal resources, biomass, and receives abundant solar power; these resources are equally distributed all over the country [24]. Undoubtedly, hydropower plants are the most significant long-term source to meet the rising load demand in Nepal; however, there are issues such as difficulty in dam construction, the large capital investment needed, and problems with building electro-mechanical structures in a mountainous landscape that contains fragile and unique ecosystem [25]. Even though hydropower is expected to be the key resource for electricity, conversion of abundant solar energy through solar photovoltaic arrays provides a good opportunity to increase the energy supply. Solar PV systems have become the best energy resource to light homes in the rural off-grid area in Nepal since this country has an average global solar radiation of 3.6-6.2 kWh/m2day. Consequently, solar PV power plants can be installed at almost any site in Nepal and generate distributed power for different consumers [26, 27]. There has been a 200% increase in the number of houses with solar PV installed this decade; there were 300,000 such systems installed in the previous decade [28, 29]. However, the use of solar PV technology in urban regions was limited due to its higher capital cost compared to the conventional electricity obtained from the grid. Nowadays PV is slowly gaining traction even in urban areas due to the reduction in the costs. Although the first PV power plants were built in 1963, their adoption within institutional buildings is low compared to residential ones [30]. PV as a primary power source in educational institutions is a new concept in Nepal. Even though the reliability of grid electricity in Nepal is poor, the use of a green energy source such as PV has been underexplored.

There are about 14 engineering campuses affiliated with Tribhuvan University (TU), one of the largest universities in Nepal, and about the same number of campuses in other large universities such as Pokhara University and Purbanchal University [31]. Kathmandu University and Paschimanchal University have only constituent engineering campuses. Altogether, Nepal currently has almost 50 engineering campuses and PV use can offset the use of grid energy while powering these institutions with a green source of energy. One of the leading engineering campuses, Central Campus Pulchowk of TU, has attempted to implement the concept of a green sustainable campus by constructing a PV-powered building for the energy studies graduate program, but much more needs to be done. Likewise, other campuses have also tried to explore renewable energy sources to offset their grid energy use [32, 33].

3. Methodology

The methodology is developed holistically in this study, which is shown in Figure 1. The monthly electricity consumption of the case study campus from 2018 to 2020 is taken from the electricity bills of the Nepal Electricity Authority, Biratnagar Branch, provided by the administration of the college. The average daily solar irradiation is calculated for the location, and an appropriate site for the solar PV installation is selected on the campus. After getting all the inputs for the simulation, PVsyst and PV*SOL software packages for solar PV system design are used to simulate the proposed solar PV installation. The simulation results and the components of the grid-connected solar PV power plant are discussed, and energy analysis and economic analysis are carried out to assess the technical and economic feasibility of the solar PV installation. Environmental analysis is also performed as this research aims at securing green energy with less environmental pollution.

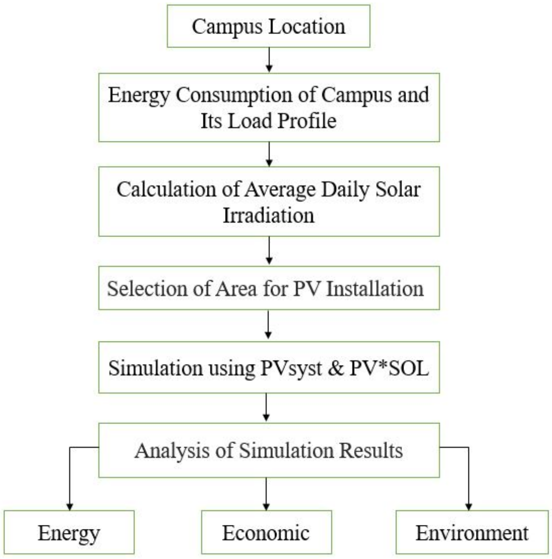

Fig. 1. Methodology of the Study

3.1. Study Location

Madan Bhandari Engineering College, situated in the eastern part of Nepal in Morang district, is a constituent affiliate college of Pokhara University. The geographical coordinates of the campus are 26.6649° N latitude and 87.6137° E longitude, and the altitude is 100 m above sea level. The campus is electrified through the national grid supplied by Nepal Electricity Authority, but the grid supply is frequently interrupted during periods of high electricity demand in the city and the whole nation. Therefore, the campus is looking for an alternative source of energy that will provide uninterrupted electricity. The campus has 20 acres of glare land where a solar PV system can be installed. The newly established campus is thus an ideal site to study the feasibility of solar installation.

Fig. 2. Campus layout on google maps.

The mean annual global horizontal solar insolation for Nepal having over 300 bright sunny days in a year ranges from 3.6 to 6.2 kWh/m2/day and the average solar intensity is 4.7 kWh/day [34]. The project site is in the south-eastern part of Nepal, in the region having more bright sunny days than the country average in a year; the average global horizontal solar radiation for the campus site is 4.7 kWh/m2 at an altitude of 100 m above the sea level. Its climate is closer to tropical and it is extremely hot, up to 40°C, humid in summer, and very cold and foggy in winter (the minimum temperature is about 10 °C). Its total precipitation is about 1300 mm to 2780 mm per year, which varies annually [35]. The monthly average wind speed is 1.1 m/s at 10 m above the ground, and air temperature is 25.8°C at 10 m above the surface of the earth.

Table 1. Global horizontal irradiance and temperature in various months at the site

Months	Global Horizontal Irradiance ($kWhr/m^2$)	Global Horizontal Diffuse ($kWhr/m^2$)	Temperature (°C)
Jan	129.7	34.54	15.13
Feb	126	53.28	19.88
Mar	167.8	69.36	25.77
Apr	177	87.17	30.28
May	177.4	99.41	31.69
Jun	157.4	91.72	30.85
Jul	141.4	87.72	30.06
Aug	147.4	88.82	29.97
Sep	132.1	77.25	28.97
Oct	133.6	70.31	27.18
Nov	128.2	42.61	22.17
Dec	115.4	41.41	17.13
Year	1733.3	843.61	25.78

3.2. Campus Energy Consumption

To determine the total solar energy required to operate the campus, the yearly electrical energy consumption shown in the campus bills for the period from 2018 to 2020 was obtained from Nepal Electricity Authority at Biratnagar Branch. The monthly electricity use is the best and most reliable data for analysis of the electricity consumed. According to the campus administration, due to the construction period and the first year of operation, there was not much consumption of electricity in the year 2018. The campus has plans for the expansion of academic programs and other activities every year; therefore, the electricity consumption will increase every year. To capture these trends and assess the future electricity demand, we analyzed the three years' data and obtained a logarithmic fit for each month to forecast the campus energy needs in the next three years. The log fit gives the coefficient of determination (R2) value of more than 85 % for each month except for November where it is just 28 %. The logarithmic fit is the best fit for the existing data. The 2018-2020 data and the predicted energy consumption for the 2021-2023 period are shown in Table 2.

To make the proposed solar PV power plant sustainable, the maximum consumed energy from each month is chosen for the calculation. According to Table 2, the predicted electricity consumption in each month of the year 2023 is higher than the corresponding consumption in the previous years. Therefore, the predicted energy consumption of 66008 kWh in 2023 is used as the input data for the PVsyst simulation.

Table 2. Electricity consumption in 2018-2020 and forecasted demand till 2023.

Months	Energy Consumption in different years in kWh					
	Actual			Forecasted		
	2018	2019	2020	2021	2022	2023
Jan	1816	3223	3478	4077	4427	4713
Feb	1996	3540	3299	3969	4259	4496
Mar	1717	3945	3865	4825	5292	5673
Apr	2013	4025	4863	5707	6293	6772
May	2123	3965	4746	5518	6057	6498
Jun	2437	4562	5215	6112	6689	7161
July	2508	4489	5198	6032	6588	7042
Aug	2436	4756	4756	5754	6255	6664
Sep	2356	4125	4132	4893	5276	5589
Oct	1988	3312	2796	4893	5276	5589
Nov	1607	2989	2156	2772	2919	3040
Dec	1630	2265	2253	2526	2661	2772
Total Yearly Consumption	24627	45196	46757	57078	61993	66008

Table 2 also shows that the total energy required to operate the campus is 24627 kWh, 45196 kWh, and 46757 kWh in 2018, 2019, and 2020, respectively. Hence, the existing 18 kWp PV plant would not be sufficient to supply green energy for the campus. The proposed PV system is designed to generate more electricity than the total consumption of energy in 2023. i.e., 66008 kWh.

3.3. Components of the Proposed Solar PV Power Plant

The existing solar PV power plant of 18 kWp on the campus is not sufficient to supply green electricity. The components of the existing solar PV power plant are shown in Figure 3. The proposed system consists of similar components with the following specifications:

3.3.1. Area

The total area of the campus rooftops is 1096 m2. The proposed solar PV power plant has the capacity of 48 kWp and consists of 160 PV modules with a total area of 266 m2. Since this area is available at the rooftop of a campus building, the rooftop is selected for the installation of the PV modules.

3.3.2 Tilt and Azimuthal Angle

The tilt angle and azimuthal angle of the proposed solar PV plant are selected based on the latitude of the location and angle at which the maximum absorption of solar radiation is possible. Hence, the PV array is fixed at 30° tilt angle and 0° azimuthal angle to obtain the maximum energy from the sun.

3.3.3 PV Module

The PV module is selected based on its availability, reliability, and the cost as there are various kinds of solar panels available in the market [35]. For a large-scale solar PV power plant, modules of polycrystalline are the most popular, and hence, in the proposed power plant polycrystalline PV module CS3K-300P P4 from Canadian Solar Inc. is considered for the design. The unit normal power of the PV module is 300 Wp and the array global power is 48 kWp at standard test conditions (STC) and 43.6 kWp at operating conditions at 50°C. The array operating characteristics at 50°C are Umpp 595 V (maximum power point voltage (Umpp) is the maximum available voltage that can be extracted from the PV module) and Impp 73 A (maximum power point current (Impp) is the maximum current that can be extracted from the PV module).

3.3.4. Inverters

Two 20 kW rated inverters are used for the proposed solar PV power plant. The inverters are manufactured by SMA Solar Technology AG and the model is Sunny Tripower 2000TLEE-JP. The operating voltage of the inverter is 580-800 V. The unit normal power of each inverter is 20 kWAC and hence the total power capacity for the two inverters is 40 kWAC

3.3.5 Battery Bank

The Pathari city where the campus is located has a grid supplied through 33 kV lines, and the proposed PV power plant would be connected to 11/0.4 kV distribution system. A grid-connected system is proposed in this study because it is easier to export the excess electricity produced to the gird. However, for providing emergency backup for a short time, a small battery bank can be installed. In this study, the battery bank is not considered because of its short life (4-5 years in general and 10 years at most) [37].

3.3.6 Other Components

There are other components, sub-systems, and accessories like mountings for panels, cables, transformers for grid connection, etc. The panels are mounted with the desired tilt and azimuthal angle by means of mountings/frame. Transformers are essential for grid connection and for transforming generation voltage into the voltage required at the supply. DC/AC cables are required for connecting panels, inverters, and to the grid.

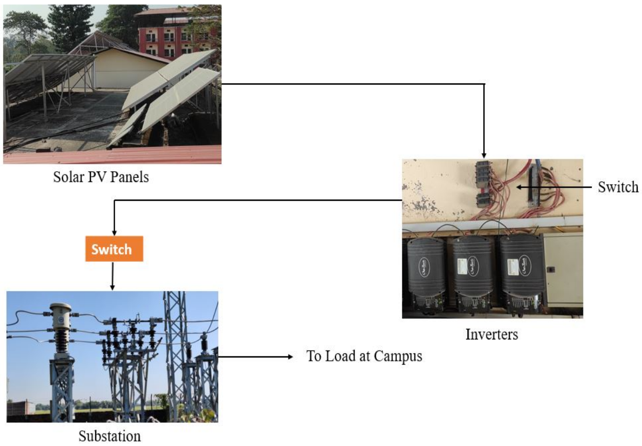

Fig. 3. Block diagram of existing 18 kWp PV plant at the campus

3.4 Calculation of Monthly Average Daily Solar Radiation

To determine the monthly average solar power energy produced by the solar panel with the tilted surface facing towards the equator, the average daily solar radiation is calculated based on the model described by Liu and Jordan[36]. S. A. Klein experimented at solar energy laboratory in the University of Wisconsin-Madison [38, 39] using the following equation:

$$\overline{K}_T = \overline{H}/\overline{H}_0, \tag{1}$$

where $\overline{H}$, $\overline{K}_T$, and $\overline{H}_0$ are the monthly average of daily global radiation (W/m2day), the monthly average of daily clearness index, and the monthly average of daily extraterrestrial radiation (W/m2day), respectively. The daily mean solar radiation is given by

$$\overline{H}_0 = \frac{1}{m_2 - m_1} \sum_{n=m_1}^{m_2} (H_0)_n \ , \tag{2}$$

where m_1 and m_2 are respectively the days of the year at the start and end of the month. $(H_0)_n$ is the extraterrestrial radiation on a horizontal surface on day n of the year, which is given by:

$$(H_0)_n = \frac{24}{n} I_{SC}\left[1 + 0.033 \cos\left(\frac{360\, n}{365}\right)\right]\left[\cos\phi \cos\delta \sin\omega_s + \frac{\omega_s 2\pi c}{360} \sin\phi \sin\delta\right], \tag{3}$$

where I_{SC} is the solar constant, n is the day of the year given for each month, ϕ is the latitude, and δ is the solar declination which can be approximately expressed as

$$\delta = 23.45^0 \sin\left[360 \frac{(284+n)}{365}\right], \tag{4}$$

Here ω_s is the sunset hour angle given by

$$\omega_s = -\tan\phi \tan\delta, \tag{5}$$

The average daily radiation on the tilted surface, $\overline{H}_T$, can be expressed as;

$$\overline{H}_T = \overline{RH} = \overline{R}\,\overline{K}_T\,\overline{H}_0, \tag{6}$$

where $\overline{R}$ is the ratio of the daily average solar power radiation on a tilted surface for each month. Assuming diffuse and reflected beam radiation incidence on the tilted face of the solar PV panel, it is given by.

$$\overline{R} = \left(1 - \frac{\overline{H}_d}{\overline{H}}\right)\overline{R}_b + \frac{\overline{H}_d}{\overline{H}}(1 + \cos s)/2 + \rho(1 - \cos s)/2, \tag{7}$$

where $\overline{H}_d$ is the average monthly daily diffuse radiation, $\overline{R}_b$ is the ratio of the average beam radiation on the tilted surface to that on a horizontal surface for each month, s is the ground reflectance (ρ varies from 0.2 to 0.7). Moreover, $\overline{R}_b$ as the ratio of extraterrestrial radiation on the tilted surface to that on a horizontal surface for a month can be calculated as

$$\overline{R}_b = \frac{\cos(\phi - s) \sin\omega_s' + \pi/180\, \omega_s' \sin(\phi - s) \sin\delta}{\cos\phi \cos\delta \sin\omega_s + \pi/180\, \omega_s \sin\phi \sin\delta}, \tag{8}$$

where, ω is the hour angle and ω_s' is the sunset hour angle for the titled surface, which is given as follows:

$$\omega_s' = \min\left[\omega_s, \arccos[-\tan(\phi - s) \tan\delta]\right]. \tag{9}$$

3.5 Calculation of Performance Parameters

3.5.1 Yield Factor (YF)

It is the ratio of total energy power output to the nameplate direct current power output of the solar PV array. YF represents the total time needed by the PV array to function at its rated power to provide the same energy. The units of yield factor are hours [40-42]. The yield factor also known as specific yield is computed as:

$$\mathrm{YF} = \frac{\text{PV array Energy Output (kWh)}}{\text{The capacity of the installed solar PV plant (kWp)}} \times 100\% \quad (10)$$

3.5.2 Capacity Factor (CF)

The capacity factor (CF) is the ratio of the actual output of energy over a specific period to the maximum possible electrical energy that can be generated over that time. This capacity factor is computed over various time scales such as years and months for seasonal fluctuations. The capacity factor is a dimensionless value given by [41, 43].

$$\mathrm{CF} = \frac{\text{Yield factor}}{\text{Operating time}} \quad (11)$$

3.5.3 Performance ratio (PR)

The performance ratio (PR) is a parameter which is a dimensionless quantity that represents the long-range effect of losses on the solar energy output. PR is also calculated in different period of time such as monthly or yearly depending on the temperature of PV module. PR value varies in different seasons based on the sun irradiation incident on the PV cells. The performance ratio is defined as [41, 43].

$$\mathrm{PR} = \frac{\text{Yield factor}}{\text{Solar irradiation} \times \text{Area of the PV Plant}} \quad (12)$$

3.6 Performance Simulation

In this study two different simulation software packages are used for the comparison of the result obtained from the simulation of the proposed solar PV power plant.

3.6.1 PVsyst

PVsyst V7.1.4 is a PC software package for data analysis and system design for PV power plants. It has different modules for the simulation of grid-connected, stand-alone, pumping, and DC-grid PV systems. It also has extensive meteonorm software, PV system component database, and solar energy tools. It can be used for both preliminary and detailed designs of a PV system. Besides the technical analysis, it has a feature to perform the economic analysis of a project along with environmental analysis. We have selected a grid-connected module of PVsyst and used PVsyst for energy and environmental analyses only.

*3.6.2 PV*SOL*

PV*SOL 2020 (R8) is also a software package to design PV systems. It has various modules for simulations and similar functions as the PVsyst. The energy analysis results by PV*SOL are too descriptive to demonstrate them in this manuscript. However, the economic analysis by PV*SOL is better than that by PVsyst due to the extensive economic database in PV*SOL. To have reliable data, we first searched the price of each component on the market, defined it ourselves, and compared it with the existing database prices.

4. Results and Discussion

4.1 Energy Analysis

The energy analysis of the proposed PV power plant installed on the rooftop of a campus building shows that it can generate 75.9 MWh of electricity annually with a specific output of 581 kWh/kWp/year. The normalized production per installed kWp of the PV power plant and the PR are shown in Figure 4 and Figure 5. The performance ratio of the proposed PV power plant is 82.19 % with a solar fraction (SF) of 41.59 %, which are good values according to several past investigations [44]. The variation of the performance ratio is almost negligible, but the smallest value of performance ratio is seen in April as shown in Figure 5. The daily collection loss in the PV array for each month is provided in Figure 4 and its whole year average is obtained to be 0.86 kWh/kWp/day. The whole system loss per day of each month is also provided in Figure 4 and its whole year average is 0.08 kWh/kWp/day; the annual average energy produced as an output from the inverter is around 4.33 kWh/kWp/day. As shown in Figure 4, the average value of the energy produced is minimum in July and maximum in January, which is closely followed by March and November. The minimum energy production in July is due to the rainy season and cloudy weather of monsoon that occurs from June to August in Nepal; therefore, the minimum production months are from June to September.

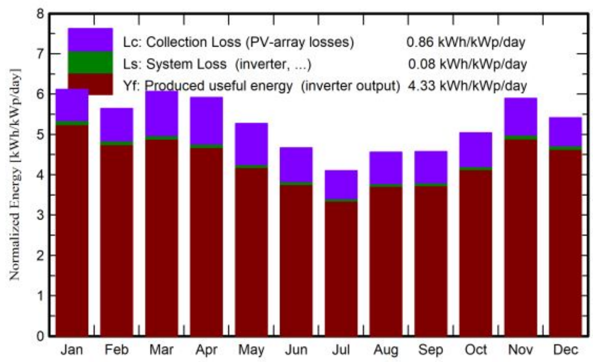

Fig. 4. Normalized energy production of PV power plant

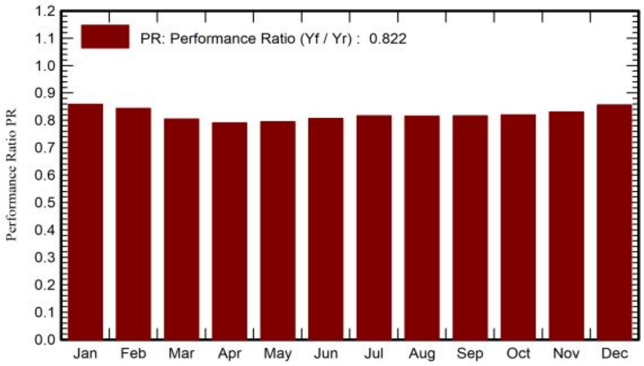

Fig. 5. Performance Ratio of PV power plant

Table 3 shows the main results of the simulation using PVsyst, where 1924 kWh/m2 is the total global irradiance per year available at the proposed campus site and 75.9 MWh of electricity is produced by the array of solar PV panels. Out of the total electricity produced, 38.557 MWh of electricity can be injected into the grid from the proposed solar PV power plant and 48.451 MWh of electricity is supplied to the load at the campus from the grid, while about 27.452 MWh of electricity is directly supplied from the solar PV panels to the load. The solar PV system is designed for two purposes. The first one is to export the energy generated from the panels to the grid and the second one is to inject the energy from the grid for the reliability of higher order as the instant output of the solar PV panels depends upon the irradiance in the system. The variation in the electricity generation from the solar PV power plant cannot be predicted due to the variability of the daily solar irradiation on panels. The input/output of the global irradiance on a daily basis is shown in Figure 6.

Table 3. Main output and results of simulation

Months	Global incident in collinear plane kWh/m²	Effective global irradiation kWh/m²	Effective energy at the output of the array MWh	Energy consumption of campus MWh	Solar to Load MWh	Energy from Grid to User MWh	Energy injected into the grid MWh
January	189.6	187.3	7.963	4.713	1.961	5.851	2.752
February	158.0	155.9	6.514	4.496	1.847	4.547	2.649
March	188.2	185.3	7.409	5.673	2.384	4.889	3.289
April	177.6	174.2	6.863	6.772	2.943	3.799	3.829
May	163.3	159.8	6.343	6.498	2.875	3.357	3.623
June	140.1	136.7	5.520	7.161	2.981	2.443	4.180
July	127.2	124.0	5.077	7.042	2.812	2.176	4.230
August	141.5	138.3	5.635	6.664	2.730	2.808	3.934
September	137.3	134.5	5.480	5.589	2.298	3.086	3.291
October	156.3	153.9	6.265	5.589	2.283	3.871	3.306
November	176.9	174.9	7.190	3.040	1.230	5.827	1.810
December	167.9	165.9	7.036	2.772	1.110	5.796	1.662
Year	1924	1890.6	77.296	66.009	27.452	48.451	38.557

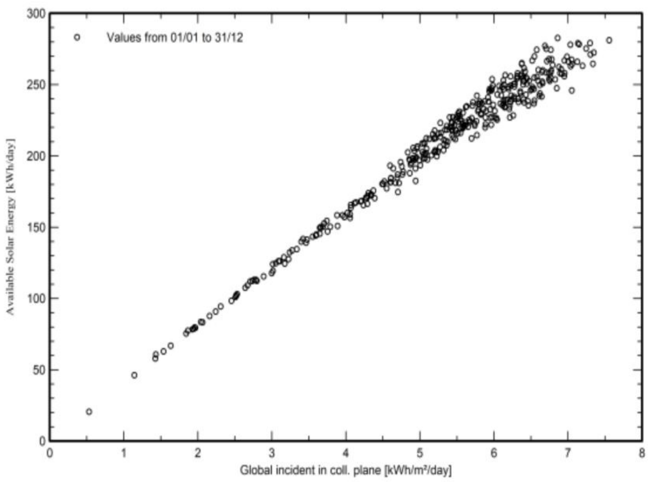

Fig. 6. Daily input and output of global irradiance

The panels used in the proposed solar PV power plant are 18.08 % efficient, which corresponds to the total effective radiation of 1891.6 kWh/m2. The solar PV array of 48 kWp produces 75.9 MWh of electricity annually excluding losses.

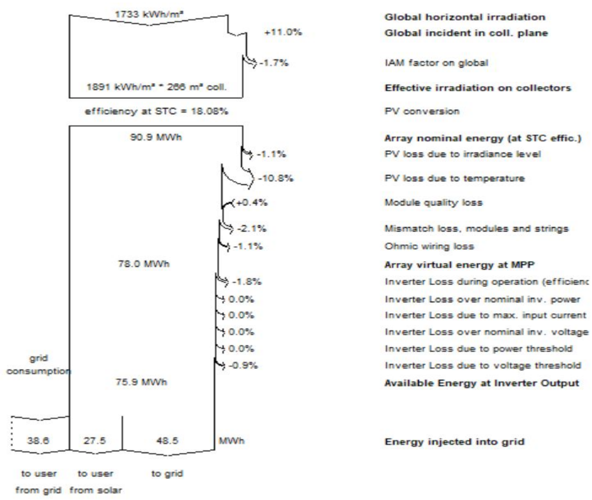

Fig. 7. Loss Diagram

There are different types of energy losses in the proposed solar PV power plant. The total energy loss in a year is about 17.81% of which 1.1% is due to irradiation level, 10.8% is due to temperature, 0.4% is due to module quality, 2.1% is due to mismatch loss, 1.1% is due to Ohmic wiring, 1.8% is due to inverter during operation, and 0.9% is due to voltage threshold in the inverter. The complete loss diagram is shown in Figure 7. Temperature is the biggest loss in the system because of the hot weather conditions on the proposed campus site.

4.2 Economic Analysis

The economic evaluation of the project is based on the cost of system components on the market in Nepal, verified in the existing cost data in the PV*SOL library dataset. The cost of each component of the system is shown in Table 4. The total capital cost for the installation of the proposed solar PV power plant of 48 kWp capacity is 36800 USD; the system will produce 75.9 MWh of electricity annually. The campus will sell 48.5 MWh of electricity to the grid, and the remaining 27.5 MWh of electricity will be consumed by the campus.

Table 4. Cost of each component for economic analysis

Item	Quantity	Cost	Total (USD)
1. PV modules CS3K-300P P4	160	120	19200
2. Supports for Modules	160	15	2400
3. Inverters (Sunny Tripower 20000TLEE-JP)	2	4000	8000
4. Other Components			
Accessories, fasteners	1	1000	1000
Wiring	1	1000	1000
5. Studies and Analysis			
Engineering	1	600	600
Permitting and other admin fees	1	600	600
Economic analysis	1	500	500
Environment Analysis	1	500	500
6. Installation			
Transportation	1	1000	1000
Setting	1	1000	1000
Grid Connection	1	1000	1000
7. Maintenance			
Salaries	1	600	600
Reparation	1	600	600
8. Summary of Cost			
Total Installation Cost			36800 USD
Total Operating and Maintenance Cost			1200 USD/yr

The financial calculation is based on the 20-year economic life of the solar PV power plant and the 0.11 USD/kWh feed-in tariff rate. The levelized cost of energy (LCOE) is 0.016 USD/kWh, which is a reasonable value for a solar PV power plant. The payback period of the power plant is 8.9 years, which is also reasonable since a typical solar PV power plant has a payback period of more than 8 years [45]. The life cycle of the proposed solar PV power plant is twenty years from 2022, and the return on investment (ROI) is 224.4 %. The summary of our financial analysis is shown in Table 5.

Table 5. Summary of Financial Analysis

Project Lifetime	20 years
Feed-in Tariff	0.11 USD/kWh
Unused Energy	27.5 MWh/yr
Energy Sold to Grid	48.5 MWh/yr
Levelized Cost of produced energy (LCOE)	0.016 USD/kWh
Payback Period	8.9 years
Net Present Value	82591.23 USD
Return on Investment (ROI)	224.4 %

4.3 Environmental Analysis

Renewable energy is popular nowadays due to its clean energy production without emissions. However, there are also emissions associated with renewable energy systems such as solar PV power plants. The emissions from the renewable energy system are regarded as indirect emissions; there are no direct emissions [46]. The emissions from the solar PV power plant occur during the manufacturing of solar PV panels and during the manufacturing and disposal of the battery bank if it was installed [47]. The CO2 emissions during the 30-year life of the proposed project are estimated to be 82.25 tonnes, 6.8 tonnes of CO2 emission are replaced, and 76.3 tonnes of the CO2 emissions will be balanced annually, with the degradation of 1.0% of the solar PV plant. The saved CO2 emissions are shown in Figure 8 and the system lifecycle emissions are shown in Table 6.

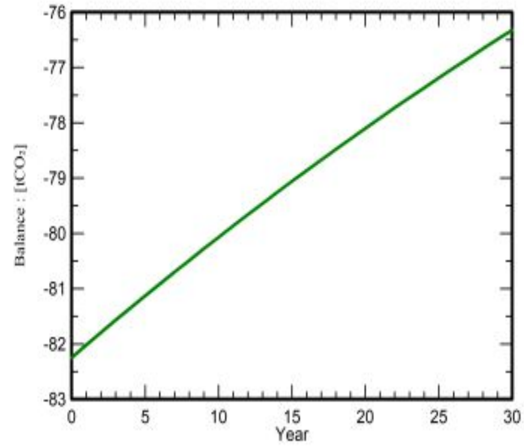

Fig. 8. Saved CO2 emissions vs time.

Table 6. Life Cycle Emissions from different items of solar PV power plant

Item	Life Cycle Emission	Quantity	Subtotal ($kgCO_2$)
Modules	1713 kgCO2/kWp	48 kWp	82211
Supports	0.02 kgCO2/kg	1600 kg	32
Inverters	1.98 $kgCO_2$/unit	2 units	3.96

5. Conclusions

This study presents the feasibility analysis of a rooftop solar PV power plant for a Nepalese educational institution to ensure that it is self-sufficient with respect to its electricity needs. The technical and economic viability of the proposed PV system is assessed by conducting detailed energy, economic, and environmental analyses using PVsyst and PV*SOL software. PVsyst software enables the better presentation of the results than PV*SOL. However, PV*SOL software has a huge data set for the economic analysis of a PV power plant. Hence, our study uses both software packages.

The proposed rooftop solar PV power plant would produce 75.9 MWh of clean energy annually based on the yearly total horizontal irradiation of 1733.3 kWh/m2 of the solar PV panels at Madan Bhandari Engineering College, as shown by PVsyst and PV*SOL simulations. The 48 kWp PV system consists of 160 300 Wp modules tilted at 30° with 0° azimuthal angle. The PV power plant has PR of 82.19 % with a specific production of 581 kWh/kWp/year. Among the different types of losses in the PV power plant, the 10.8% loss due to temperature is the biggest; it can be lowered using passive and active cooling methods. The construction of a rooftop solar PV power plant on the campus is cost effective and also helps in reducing emissions by eliminating 76.3 tonnes of carbon-dioxide production during the project life.

This solar PV power plant can serve as an exemplary project for more than 50 engineering campuses in Nepal and will be an ideal opportunity for the campus to support the mission of Alternative Energy Promotion Center Nepal of promoting grid-connected solar systems in Nepal. It will also follow the sustainable development goals of 2030 of the United Nations.

Acknowledgment

The authors would like to acknowledge the administration of Madan Bhandari Engineering College in Morang, Nepal for providing the campus site details and the electricity consumption data from Nepal Electricity Authority. The authors would also like to acknowledge Mr. Binod Babu Kumal and Mr. Subash Gautam for their technical support in the project.

References

[1] S. R. Sinsel, R. L. Riemke, and V. H. Hoffmann, "Challenges and solution technologies for the integration of variable renewable energy sources—a review," renewable energy, vol. 145, pp. 2271-2285, 2020.

[2] Elsayed, Y., Saad, N. H., & Zekry, A. (2020). Assessing Wind Energy Conversion Systems Based on Newly Developed Wind Turbine Emulator. International Journal of Smart Grid-ijSmartGrid, 4(4), 139-148.

[3] I. E. Agency, "2018 World electricity generation (26,700 TWh) by source," Paris, 2019.

[4] S. Chatzivasileiadis, D. Ernst, and G. Andersson, "The global grid," Renewable Energy, vol. 57, pp. 372-383, 2013.

[5] J. Jean, P. R. Brown, R. L. Jaffe, T. Buonassisi, and V. Bulović, "Pathways for solar photovoltaics," Energy & Environmental Science, vol. 8, no. 4, pp. 1200-1219, 2015.

[6] P. Sharma, H. Bojja, and P. Yemula, "Techno-economic analysis of off-grid rooftop solar PV system," in 2016 IEEE 6th international conference on power systems (ICPS), 2016: IEEE, pp. 1-5.

[7] A. A. Hafez and A. Alblawi, "A feasibility study of PV installation: Case study at Shaqra University," in 2018 9th International Renewable Energy Congress (IREC), 2018: IEEE, pp. 1-5.

[8] Nag, S., Kundu, S., Sinha, D., Chowdhury, S. R., Mukherjee, P., Goswami, U., & Ganguly, "A comparative-techno economic feasibility study between roof-top and building integrated photovoltaic technology for development of green campus," in 2016 IEEE 7th Annual Ubiquitous Computing, Electronics & Mobile Communication Conference (UEMCON), 2016: IEEE, pp. 1-6.

[9] J. Lee, B. Chang, C. Aktas, and R. Gorthala, "Economic feasibility of campus-wide photovoltaic systems in New England," Renewable Energy, vol. 99, pp. 452-464, 2016.

[10] D. Hasapis, N. Savvakis, T. Tsoutsos, K. Kalaitzakis, S. Psychis, and N. P. Nikolaidis, "Design of large scale prosuming in Universities: The solar energy vision of the TUC campus," Energy and Buildings, vol. 141, pp. 39-55, 2017.

[11] R. Poudyal, P. Loskot, R. Nepal, R. Parajuli, and S. K. Khadka, "Mitigating the current energy crisis in Nepal with renewable energy sources," Renewable and Sustainable Energy Reviews, vol. 116, p. 109388, 2019.

[12] K. K. Zander, G. Simpson, S. Mathew, R. Nepal, and S. T. Garnett, "Preferences for and potential impacts of financial incentives to install residential rooftop solar photovoltaic systems in Australia," Journal of Cleaner Production, vol. 230, pp. 328-338, 2019.

[13] B. H. Chowdhury, S. Muknahallipatna, J. Cupal, J. Hamann, T. Dinwoodie, and D. Shugar, "A 50 kilowatt distributed grid-connected photovoltaic generation system for the University of Wyoming," in Conference Record of the Twenty Sixth IEEE Photovoltaic Specialists Conference-1997, 1997: IEEE, pp. 1369-1372.

[14] B. S. Kumar and K. Sudhakar, "Performance evaluation of 10 MW grid connected solar photovoltaic power plant in India," Energy reports, vol. 1, pp. 184-192, 2015.

[15] A. Allouhi, R. Saadani, T. Kousksou, R. Saidur, A. Jamil, and M. Rahmoune, "Grid-connected PV systems installed on institutional buildings: Technology comparison, energy analysis and economic performance," Energy and Buildings, vol. 130, pp. 188-201, 2016.

[16] C. L. Kwan and A. Hoffmann, "The Los Angeles Community College District: Establishing a net-zero energy campus," in Sustainable Communities Design Handbook: Elsevier, 2010, pp. 181-215.

[17] A. S. Baitule and K. Sudhakar, "Solar powered green campus: a simulation study," International Journal of Low-Carbon Technologies, vol. 12, no. 4, pp. 400-410, 2017.

[18] J. H. Jo, K. Ilves, T. Barth, and E. Leszczynski, "Implementation of a large-scale solar photovoltaic system at a higher education institution in Illinois, USA," AIMS Energy, vol. 5, no. 1, pp. 54-62, 2017.

[19] Barua, S., Prasath, R. A., & Boruah, D. (2017). Rooftop solar photovoltaic system design and assessment for the academic campus using PVsyst software. International Journal of Electronics and Electrical Engineering, 5(1), 76-83.

[20]Dhakal, S., Timilsina, A. B., Dhakal, R., Fuyal, D., Bajracharya, T. R., Pandit, H. P., Amatya, N., & Nakarmi, A. M., "Comparison of cylindrical and conical basins with optimum position of runner: Gravitational water vortex power plant," Renewable and Sustainable Energy Reviews, vol. 48, pp. 662-669, 2015.

[21] Koirala, N., Dhakal, R., Lubitz, D., Bhandari, S., Dev, G. P., Dhakal, Y., & Niraula, U., "Review of low head turbines system of Nepal for rural electrification," in 2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA), 2017: IEEE, pp. 861-869.

[22] Dhakal, R., Dhakal, S., Koirala, N., Itani, S. C., Bhandari, S., Amgain, G. B., & Shrestha, R. K. (2018, October). Prospects of Off Grid Energy Generation through Low Head Screw Turbine in Nepal. In 2018 7th International Conference on Renewable Energy Research and Applications (ICRERA) (pp. 537-543). IEEE.

[23] Dhakal, R., Nepal, A., Acharya, A., Kumal, B., Aryal, T., Williamson, S. J., Khanal, K., & Devkota, L. (2016, November). Technical and economic prospects for the site implementation of a gravitational water vortex power plant in Nepal. In 2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA) (pp. 1001-1006). IEEE.

[24] K. C. Surendra, S. K. Khanal, P. Shrestha, and B. Lamsal, "Current status of renewable energy in Nepal: Opportunities and challenges," Renewable and Sustainable Energy Reviews, vol. 15, no. 8, pp. 4107-4117, 2011.

[25] S. Nawaraj, S. Malesh, Z. Alex, and U. Muniraj, "Power Generation Potential and Cost of a Roof Top Solar PV System in Kathmandu, Nepal," in National Conference RETSUD, 2009.

[26] R. Bhandari and I. Stadler, "Electrification using solar photovoltaic systems in Nepal," Applied Energy, vol. 88, no. 2, pp. 458-465, 2011.

[27] U. Joshi, U. Joshi, K. N. Poudyal, I. B. Karki, and I. Koirala, "Estimation of solar energy in Pokhara, Nepal," Himalayan Physics, vol. 8, pp. 93-99, 2019.

[28] B. R. Gautam, F. Li, and G. Ru, "Assessment of urban roof top solar photovoltaic potential to solve power shortage problem in Nepal," Energy and Buildings, vol. 86, pp. 735-744, 2015.

[29] AEPC. "Solar Home System." Alternative Energy Promotion Center, Nepal. https://www.aepc.gov.np/statistic/solar-home-system (accessed 12/30/2020).

[30] AEPC, "Price Analysis of Solar Home System: Assessment of Influences of Subsidy," Alternative Energy Promotion Center, Nepal, Kathmandu, Nepal, 2003.

[31] J. P. Upadhyay, "Higher education in Nepal," Pravaha, vol. 24, no. 1, pp. 96-108, 2018.

[32] A. Shrestha, A. Singh, K. Khanal, and R. Maskey, "Potentiality of off-grid hybrid systems for sustainable power supply at Kathmandu University campus," in 2016 IEEE 6th International Conference on Power Systems (ICPS), 2016: IEEE, pp. 1-6.

[33] B. K. Yadav, P. K. Rauniyar, K. Sudhakar, T. R. Bajracharya, and S. S. Priya, "Sustainable green campus in NEPAL: 3E analysis," International Journal of Low-Carbon Technologies, 2020.

[34] K. N. Poudyal, B. K. Bhattarai, B. Sapkota, B. Kjeldstad, and P. Daponte, "Estimation of the daily global solar radiation; Nepal experience," Measurement, vol. 46, no. 6, pp. 1807-1817, 2013.

[35] D. o. H. a. Meteorology. Rainfall Data of Morang District. (accessed: 4/7/2021).

[36] E. Tzen, K. Perrakis, and P. Baltas, "Design of a standalone PV-desalination system for rural areas," Desalination, vol. 119, no. 1-3, pp. 327-333, 1998.

[37] S. Gautam, D. B. Raut, P. Neupane, D. P. Ghale, and R. Dhakal, "Maximum power point tracker with solar prioritizer in photovoltaic application," in 2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA), 2016: IEEE, pp. 1051-1054.

[38] B. Liu and R. Jordan, "Daily insolation on surfaces tilted towards equator," ASHRAE J.; (United States), p. Medium: X; Size: Pages: 53, 1961.

[39] S. A. Klein, "Calculation of Monthly Average Insolation On Tilted Surfaces," Solar Energy, vol. 19, no. 4, pp. 235-329, Pentagon Press 1977, doi: https://doi.org/10.1016/0038-092X(77)90001-9.

[40] N. Manoj Kumar, K. Sudhakar, and M. Samykano, "Techno-economic analysis of 1 MWp grid connected solar PV plant in Malaysia," International Journal of Ambient Energy, vol. 40, no. 4, pp. 434-443, 2017, doi: 10.1080/01430750.2017.1410226.

[41] M. Malvoni, A. Leggieri, G. Maggiotto, P. M. Congedo, and M. G. De Giorgi, "Long term performance, losses and efficiency analysis of a 960 kW P photovoltaic system in the Mediterranean climate," Energy Conversion and Management, vol. 145, pp. 169-181, 2017, doi: 10.1016/j.enconman.2017.04.075.

[42] Kasim, N. K., Hussain, H. H., & Abed, A. N. (2019). Performance Analysis of Grid-Connected CIGS PV Solar System and Comparison with PVsyst Simulation Program. International Journal of Smart GrÄ±d, 3, 172-179.

[43] R. Sharma and S. Goel, "Performance analysis of a 11.2 kWp roof top grid-connected PV system in Eastern India," Energy Reports, vol. 3, pp. 76-84, 2017, doi: 10.1016/j.egyr.2017.05.001.

[44] N. H. Reich, B. Mueller, A. Armbruster, W. G. Van Sark, K. Kiefer, and C. Reise, "Performance ratio revisited: is PR> 90% realistic?," Progress in Photovoltaics: Research and Applications, vol. 20, no. 6, pp. 717-726, 2012.

[45] A. Sherwani and J. Usmani, "Life cycle assessment of solar PV based electricity generation systems: A review," Renewable and Sustainable Energy Reviews, vol. 14, no. 1, pp. 540-544, 2010.

[46] K. Sudhakar, M. Rajesh, and M. Premalatha, "Carbon mitigation potential of Jatropha Biodiesel in Indian context," Energy Procedia, vol. 14, pp. 1421-1426, 2012.

[47] D. Nugent and B. K. Sovacool, "Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey," Energy Policy, vol. 65, pp. 229-244, 2014.