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Renewables: Wind, Water, and Solar

CASE STUDY

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Techno-economic feasibility analysis of a 3-kW PV system installation in Nepal

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Abstract

This study investigates the techno-economic feasibility of installing a 3-kilowatt-peak (kWp) photovoltaic (PV) system in Kathmandu, Nepal. The study also analyses the importance of scaling up the share of solar energy to contribute to the country's overall energy generation mix. The technical viability of the designed PV system is assessed using PVsyst and Meteonorm simulation software. The performance indicators adopted in our study are the electric energy output, performance ratio, and the economic returns including the levelised cost and the net present value of energy production. The key parameters used in simulations are site-specific meteorological data, solar irradiance, PV capacity factor, and the price of electricity. The achieved PV system efficiency and the performance ratio are 17% and 84%, respectively. The demand–supply gap has been estimated assuming the load profile of a typical household in Kathmandu under the enhanced use of electric appliances. Our results show that the 3-kWp PV system can generate 100% of electricity consumed by a typical residential household in Kathmandu. The calculated levelised cost of energy for the PV system considered is 0.06 $/kWh, and the corresponding rate of investment is 87%. The payback period is estimated to be 8.6 years. The installation of the designed solar PV system could save 10.33 tons of CO_2 emission over its lifetime. Overall, the PV systems with 3 kWp capacity appear to be a viable solution to secure a sufficient amount of electricity for most households in Kathmandu city.

Highlights

The proposed PV system achieves the levelised cost of energy by 0.06 $/kWh, and its investment rate is 87%.

The efficiency of the proposed PV system is 17%, and its performance ratio is 84%.

The payback period for the deployment of the proposed PV system is 8.6 years.

Deployment of the proposed PV system can save 10.33 tons of CO_2 emission over its lifetime.

Introduction

The total primary energy consumption (TPEC) of Nepal in the year 2018 was 0.17 quadrillion Btu. It is increased from 0.05 quadrillion BTU in 1999 to 0.17 quadrillion BTU in 2018, growing at the average annual rate of 7.3% (World Data Atlas, 2018). On the TPEC, the share of biomass energy sources was 74%, followed by fossil fuel 17.32%, coal 5.96%, hydropower 3%, and less than 1% was from other renewable sources (USEI Administration, 2019). The current status of energy consumption reveals that the residential sector has the highest share (80%), followed by the industrial sector (8%) and the transportation sector (7%), respectively (Ministry of Finance, 2017).

By the end of the fiscal year (FY) 2018/2019, the hydroelectricity's installed capacity was 1129 MW (IHA, 2020). In the year 2020, the peak demand for electricity was around 1320 MW (Nepal Electricity Authority, 2020). Hence, to maintain the demand, additional power is imported from India. Moreover, hydroelectricity is

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in short supply compared to the electricity market that prevailed in recent years. In FY 2017/2018, about 33% of the total imports were accounted for petroleum products (Nepal Rastra Bank, 2018). Since there exists a massive dependency on fossil fuels, the country is spending nearly 300 billion Nepalese Rupees (1 US$ = 117.47 NRs, January 10, 2021) on petroleum products and electricity. Nepal's total trade deficit amounted to around 11.24 billion US$ (Statista, 2019).

The per capita electricity consumption of Nepal in FY 2018/19 was 245 kWh. The Government of Nepal has set a target to achieve per capita electricity consumption of 700 kWh by 2021/22 and 1500 kWh by 2026/27 (Nepal Electricity Authority, 2020). The higher per capita electricity consumption is assumed to follow the Government's ambition to have an 8.5% economic growth rate, making the country in the list of middle-income countries by 2030 (NRB, 2019). To deliver such a higher economic growth rate, Nepal needs to increase its electricity consumption (Parajuli et al., 2014). Due to the insufficient supply of electricity and low income, most households who even have access to electricity often consumed for lighting purposes only. Nepal's power sector is bearing an acute shortage of energy, which is primarily exacerbated by energy losses between the prime mover and the consumers' doorsteps. Integration of Renewable Energy Technologies (RETs) at the household level, e.g., through the installation of a rooftop solar photovoltaic (SPV) system, can allow the homeowners to meet their energy need independently (Poudyal et al., 2020). It can also help in the management of energy flows in the national grid and can support to reduce carbon dioxide (CO_2) emissions. The role of RETs is also argued for enhancing economic activities in developing countries like Nepal. The importance of the decentralised form of energy enterprise, such as Solar Power Company (SPC), is also inherited to cope with the country's inability to transfer electricity in poorly established distribution systems.

Nepal's transmission network is limited, outdated, and there is no position to accommodate large power generation that the Government intends to accomplish in the next 10 years (Bajracharya, 2019). Inefficient infrastructure creates substantial electricity losses due to leakage and lack of adequate transmission infrastructure (Basnett, 2014). Therefore, the stand-alone PV generation systems in the country can lessen pressure on the transmission and distribution system and reduce power losses (Bajracharya, 2019). The Government of Nepal (GoN) has set a goal to increase the share of renewable energy from less than 1% to 10% and further improve access to electricity from alternative sources, from 10 to 30% within the next 20 years. According to the energy progress report 2019, 1.3 million people have no access to electricity, and Nepal has targeted to achieve 100% electricity for all by the year 2023 (Nepal Electricity Authority, 2020. Hence the PV system would be the game-changer and help to achieve such targets (see Fig. 1).

In Nepal, a grid-connected solar system is in its emerging phase. The history of solar power has begun with the 1-MW design at Singha Durbar, 680 kW system at Sundharighat, 100 kW system at Kharipati, 65 kW at Nepal Telecom, a 1 KW test project at the Institute of Engineering, Pulchowk, Campus. However, the PV system is yet to gain momentum at a business scale (Bajracharya, 2019). Recently, a 7-MW Grid-connected PV system was added to the national grid of Nepal. Similarly, other initiatives include installing solar power in one of Nepal's regional airports (Bhairahawa airport). The estimated cost for installing the PV system in the airport mentioned above was $10 million (i.e. 1 mil. $ per megawatts) (Kathmandu Post, 2020). In 2018, the GoN initiated to formulate the required policies for net metering and feed-in tariff (FIT) (with NRs 7.30 per unit), however, reluctance to implement such policies is causing a delay in large-scale adoption (Bajracharya, 2019). Nepal Electricity Authority (NEA) has issued licenses to various PV installers to produce more than 500 megawatts of solar energy. NEA plans to have an energy mix, constituting 85% from hydropower and 15% from solar power. Nepal has abundant availability of solar energy throughout the year (Fig. 2). With the average solar radiation varies 3.6–6.2 kWh/m^2/day and 300 days of sunny weather, Nepal is an ideal country for harnessing solar energy (Awasthi & Poudyal, 2018). Even so, the country's power system is mostly dominated by large hydropower. Given the nature of hydropower, mostly dominant by run-off the river types and the connected unreliable power supply during the dry season, it is imperative to upscale other renewable energy technologies, such as solar PV in the country's energy mix (Poudyal, 2019, 2020; Poudyal et al., 2019a, b, 2020).

A PV system's technological feasibility analysis is studied for different countries (Astriani et al., 2019; Al Garni & Awasthi, 2017; Bhattacharjee & Dey, 2014; Bhattacharyya, 2013; Cassard et al., 2011; Ghasemi et al., 2013; Haghighat Mamaghani et al., 2016; Jäger-Waldau, 2020; Jäger-Waldau et al., 2011; Kazem et al., 2017; Llamas & Adana, 2019; Parajuli et al., 2012; Pillai et al., 2016; Shahzad et al., 2017). Regarding the use of PV energy simulation tools, a stand-alone PV system installed in Malaysia (Irwan et al., 2015) evaluated the techno-economic performance using the "PVsyst" software

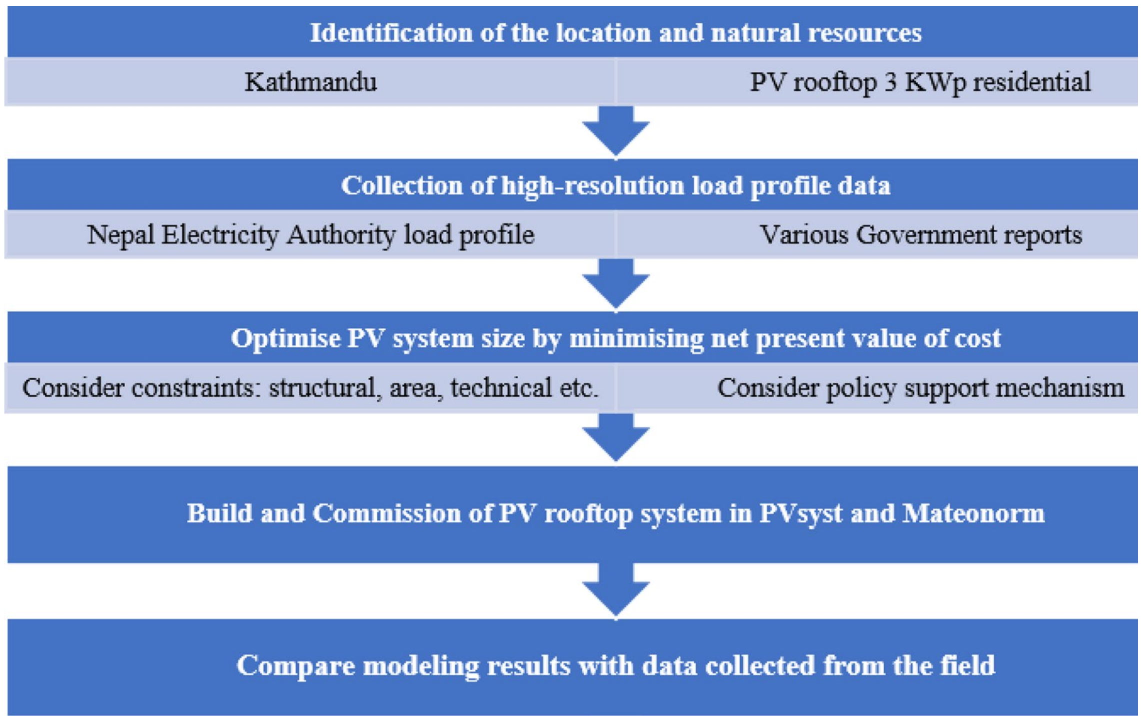

Fig. 1 A flowchart summarising our techno-economic evaluation methodology

simulation tool. PVsyst is generally used for predicting energy output instead of evaluating real-time operating data. Likewise, the performance of a stand-alone PV system is also found for Saudi Arabia (Rehman & El-Amin, 2012). A comparative study of the grid-tied PV system in Kathmandu and Berlin are also available (Karki et al., 2012), which suggested that the solar radiation and sunshine hours of Kathmandu is better than Berlin's.

The increasing global energy demand is mostly driven by consumption in emerging economies, such as China and India. These two countries already account for half of the world's demand increases, and their consumption is expected to double by 2030. China announced that it would spend USD 363 billion on expanding its renewable energy capacity by 2020 (Poudyal, 2019). The subsidies for the new solar PV panels in China are predicted to drop by 75% in 2025, while solar projects in India will be competitive without any financial support well before 2030. Furthermore, the Paris Agreement provides key opportunities for countries to report their fossil fuel production and their plans and strategies to align future production with climate goals, including through the global stocktake, nationally determined contributions (NDCs), long-term low greenhouse gas emission development strategies and financing (UNEP, 2019). Nepal is also one of the signatory countries of this global agreement, and it has prepared to go carbon neutral by 2050. Under such circumstances, it is relevant that large-scale renewable energy interventions, including solar, are deployed. For an upscaled solar PV installations scenario, detailed techno-economic and policy instruments are essential. However, yet to the best of the author's knowledge, the feasibility study of photovoltaic systems in Nepalese context is very limitedly captured. Besides, analytical work and empirical evidence on solar PV system topics' socio-economic benefits remain relatively limited (IRENA, 2014). Most importantly, the application of the available solar energy simulation models is minimal, and most of the models are site-specific and did not apply the techno-economic viability assessments in detail. Therefore, this study aims to fill the research gaps by providing a techno-economic appraisal of a stand-alone and grid-connected system to supply electricity for a residential home in Kathmandu, Nepal. As a case study, the location considered for the analysis is Bishalnagar, located in Kathmandu valley. This study will fill the gaps in the current literature by analysing up-to-date data in the form of clearness index, tilting angle, meteo data, relative sunshine period, effects of temperatures, and irradiations, which are critical parameters for solar PV output.

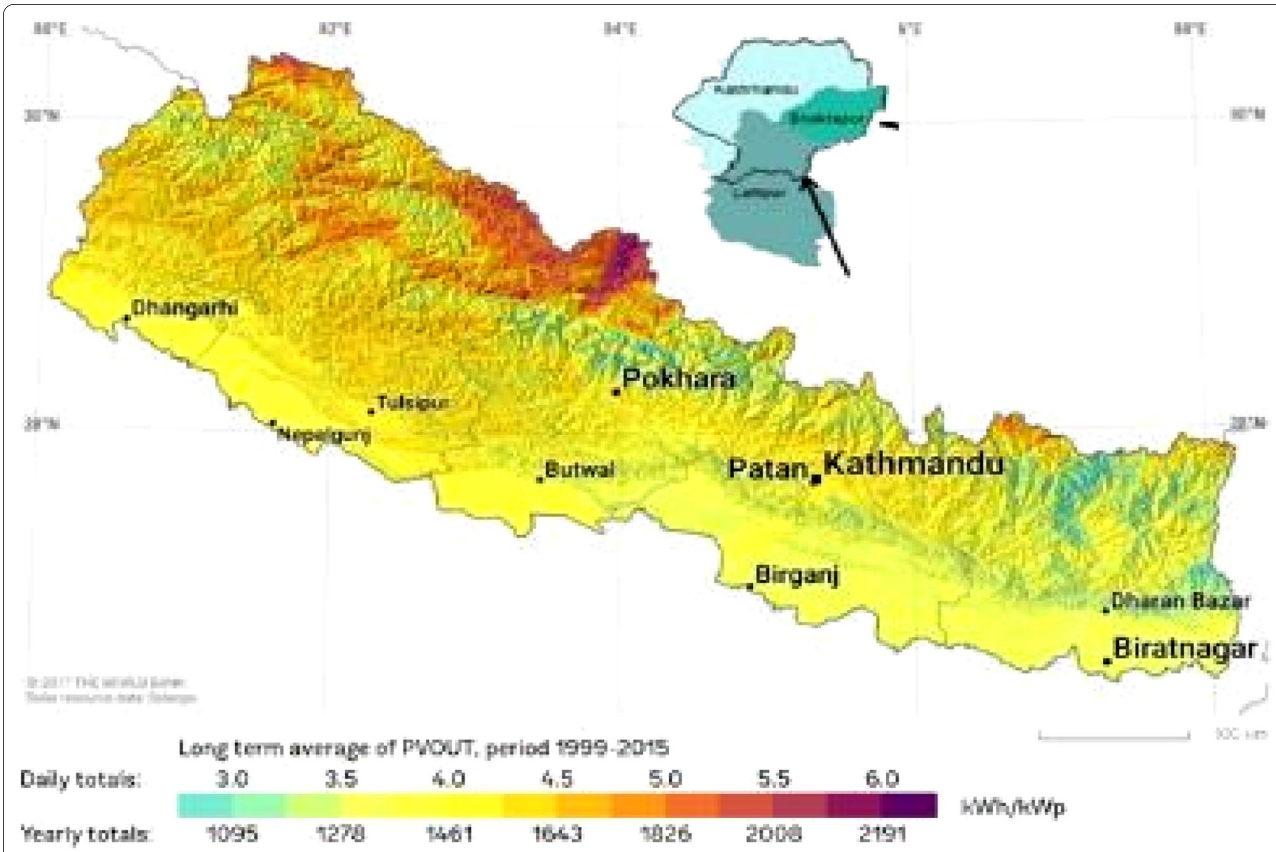

Fig. 2 The solar map of Nepal (World Bank Group, 2017)

Materials and methods

Simulation and optimisation software

The simulation constituted to design a 3-kWp PV system, calculated based on the load profile of the selected study area (Table 3). For this, a PVsyst was used to analyse technical and economic analysis. PVsyst software (Ashok et al., 2020) is a tool that lets its user to analyse different configurations accurately and to evaluate the results while identifying the best feasible solution. PVsyst allows for importing files provided by the Meteonorm software so that well-measured interpolated values can be taken graphically. PVsyst deals only with grid-connected, stand-alone, pumping, and DC-grid (public transportation) PV systems (Irwan et al., 2015). The modelling details are discussed in Sect. "Model inputs and assumptions".

Model inputs and assumptions

Various inputs have been used to operationalise the Solar PV model received from an SPC supplier for a stand-alone PV system and grid-connected PV system (Tables 1, 2). For both systems, a 330-W monocrystalline panel was assumed.

Table 1 Description of a stand-alone solar power supply system SP 3 kW

Product	Quantity	Unit price	Total price
330w monocrystalline panel	10 pcs	$92.4	$924
H4T PV combiner	1 pc	$117	$117
48 V 60A charge controller	1 pc	$98	$98
NW3000W solar inverter	1 pc	$207	$207
200AH gel battery	4 pcs	$200	$800
Solar panel bracket	1 set	$450	$450
PV cable + battery cable	1 set	$185	$185
Total			$2841

Table 2 Description of an on-grid solar power supply system SPB 3KW

Product	Quantity	Unit price	Total price
330 w monocrystalline panel	10 pcs	$92.4	$924
HBF 3 kW on-grid inverter	1 pc	$340	$340
PV cable + battery cable	1 set	$125	$125
Total			$1789

Table 3 The load profile of a typical household in Kathmandu

Appliance/loads	Power (watts) (A)	Hours used in a day (B)	Days per week (C)	Watt-hours per week (A) x (B) x (C)
Lamp LED	15	7	7	735
TV	80	5	7	2800
Laptop	50	5	7	17,500
Computer	80	5	7	2800
Fridge	58	24	7	9744
Fan	150	2	7	2100
Rice cooker	1000	1	7	7000
Washing M/C	1000	1	2	2000
Microwave	1000	1	7	7000
Iron	1000	0.5	5	2500
Dryer	1000	1	5	5000
Kettle	1200	0.75	7	6300
Well pump	750	1	4	3000
Smartphone Recharge	6	3	7	126
Vacuum	1000	1	2	2000
Other	120	1	7	840
	Highest power used at one time		Total power per week	55,695 Wh/w

Table 4 The module specification of the proposed PV system for Kathmandu

Model	Talesun—TP672M –330
Manufacturer	
Electrical characteristics	
Maximum power (Pmax)	330 W
Maximum power voltage (Vmp)	37.3 V
Maximum power current (Imp)	8.85A
Short-circuit current (Isc)	9.19A
Open-circuit voltage (Voc)	46.1 V
Module efficiency	17%
Cell size and series	Monocrystalline 156 × 156–72 pcs (6 × 12)
Temperature coefficient of Pmax	− 0.41%/ °C
Temperature coefficient of Voc	− 0.31%/ °C
Temperature coefficient of Isc	+ 0.055%/ °C
Mechanical characteristics	
Model dimension	1960 × 992 × 35 mm
Frame	Anodized aluminium alloy
Glass	3.2 mm, High transmission, tempered glass
Junction box and cable	IP65/IP67
Weight	24.0 Kgs

A value-added tax (VAT) rate of 15% is added to the original quotation, and shipping cost of $405 for a total volume of 1.2 m^3 and 360 kg is added to the grid-connected system and shipping cost of $479 for the total volume of 1.96 m^3 and 537 kg is added to the stand-alone system. The operation and maintenance (O&M) cost was assumed at 3% of the capital cost. The O&M cost is assumed to increase by 5% per year. The annual rate for the cost of insurance for the plant was set at 1% of the capital cost. The output is assumed to de-rate 1% per year, and the lifetime is taken as 25 years. The technical and commercial loss in the system is 15%, and the saleable output is obtained after deducting the energy lost in the system. Any available capital grant is applied first ($173), and the grant amount reduces the capital investment requirement. The balance of capital is assumed to be funded through loan and equity at an 80:20 ratio. Further, an inflation rate of 9.9%, the interest bank rate of 2.25% for 15 years, 0.35% administration charge of the bank, and a discount rate of 0.06 (6%) are considered to calculate the real rate of interest. The fixed feed-in tariff rate of $0.063/kWh is taken from various sources (Government of Nepal, 2013; Mainali & Silveira, 2012; Mathew, 2007; Nepal Investment Bank Limited, 2020). The load profile calculated to estimate the number and size of panels required for a project is shown in Table 3.

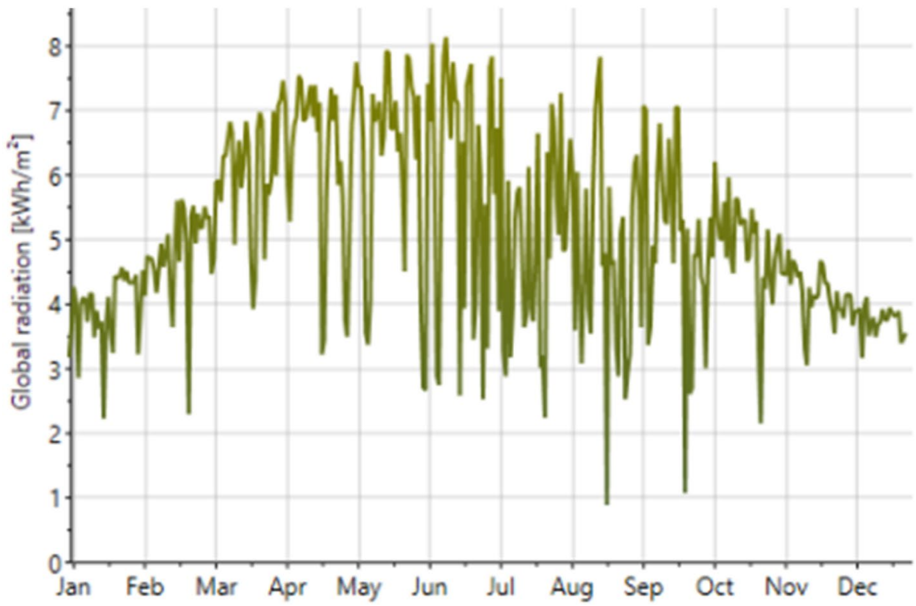

Fig. 3 Daily global radiation at the selected location in Kathmandu

Solar panel specification

The specification of the module used for analysis is listed in Table 4.

Evaluation of site meteorological data

A Meteonorm 7.3 software is used to obtain the relevant solar radiation data for the selected study area.

Global irradiation

The potential for PV power generation, as reported by Solargis, is illustrated in the solar map of Nepal (Fig. 2). The solar irradiance figure on a month-by-month basis is shown in Fig. 3, which illustrates the average daily irradiance based on mounting the solar array (see Table 5) flat on the ground.

The solar path suggests the sun's position relative to the tilt and Azimuth angle view (Fig. 4). Nepal has abundant solar energy available throughout the year (Fig. 2), with the average solar radiation varying from 3.6 to 6.2 kWh/m^2/day with 300 days of sunny weather (Awasthi & Poudyal, 2018; World Bank Group, 2017). Therefore, it is an ideal place for solar energy. Solar radiation in different seasons is enumerated in Table 6. Summer has the highest radiation with 24.76 MJ/m^2, whereas winter has the lowest with 1300 MJ/m^2, as listed in Table 6.

Sunshine duration of Kathmandu appears encouraging for the rooftop PV module, as presented in Fig. 5. April, May, October, and November have the highest sunshine duration for more than 8 h, which means more electricity can be generated during these months. It should be noted that Nepal's hydropower system generates half of its capacity in April and May because of their seasonal flow of the river. In the long run, Nepal can balance its energy system by utilising the Solar PV technologies during this period rather than importing electricity from India (Bajracharya, 2019**).**

Table 5 The areas under different annual normal radiations in Nepal (El Gayar & Anthony, 2010)

S no.	Solar radiation class (kWh/m^2/day)	Average annual (kWh/m^2/day)	Area (km^2)
1	3.5–4.5	4.16	2174.49
2	4.5–5.5	5.22	32,587.00
3	5.5–5.75	5.561	2729.53
	Total	14.941	37,491.02

Temperature

The temperature of Kathmandu, all round the year, ranges from 2.5 to 30 °C. Figure 6 illustrates the temperature of Kathmandu all round the year. In general, high temperature decreases the PV system's efficiency, and low temperature makes power conversion in PV modules more efficient.

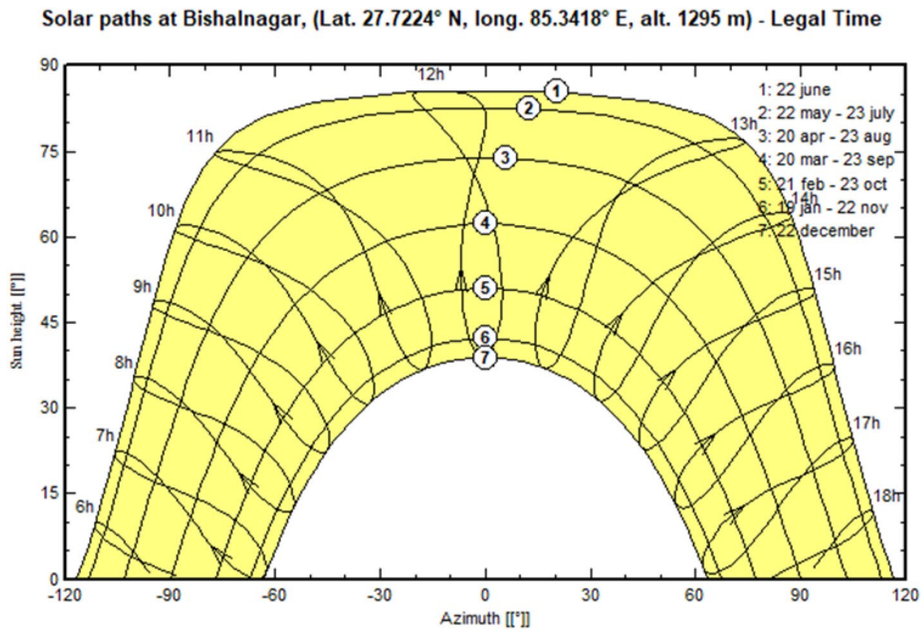

Fig. 4 The solar path of Kathmandu

Humidity and wind

The results of the effect of wind velocity on the performance of the solar system by (Fath, 1995) observed that increasing the wind speed from 0 to 8 m/s decreases the total production by less than 10% (Blanco & Malato, 2009). Low- and medium-speed winds, close to the ground, have cooling effects on the PV modules, increasing their conversion efficiency and increasing energy generation. However, the occurrence of stronger winds poses a risk of damaging the modules and construction components. Although Kathmandu has a constant wind speed, March has the highest wind speed of 2.3 m/s, but this speed does not affect the solar generation, in any case.

Table 6 Climatic solar radiation in Kathmandu, Nepal (Poudyal et al., 1970)

S. no.	Season	Solar radiation MJ/m^2
1	Winter	13.00
2	Spring	20.86
3	Summer	24.76
4	Autumn	15.48

Precipitations

The average yearly rainfall is about 55 inches, most of which falls from June to September.

January to May and October to December have low precipitation, where June to September have high rainfall (Fig. 7). Although July has the highest rainfall, it still has 5 h of sunshine. The amount and periodicity of rain determine the cleaning efficiency of the surface of the PV modules. Manual cleaning of PV modules requires special attention in a dry and dusty climate. Average relative humidity in Kathmandu shows that humidity remains 80% throughout the year except for March to May, when it drops to 60–70%.

Results

In PVsyst, the simulation is carried out for a 3-kW off-grid (stand-alone) and on-grid system. The techno-economic parameters for simulation are described in Sect. "Materials and Methods".

Modelling using PVsyst software

The PV system's feasibility analysis has been conducted with the PVsyst software for two scenarios: case 1—standalone (off-grid) system and case 2—grid-connected system. The simulation results are presented below.

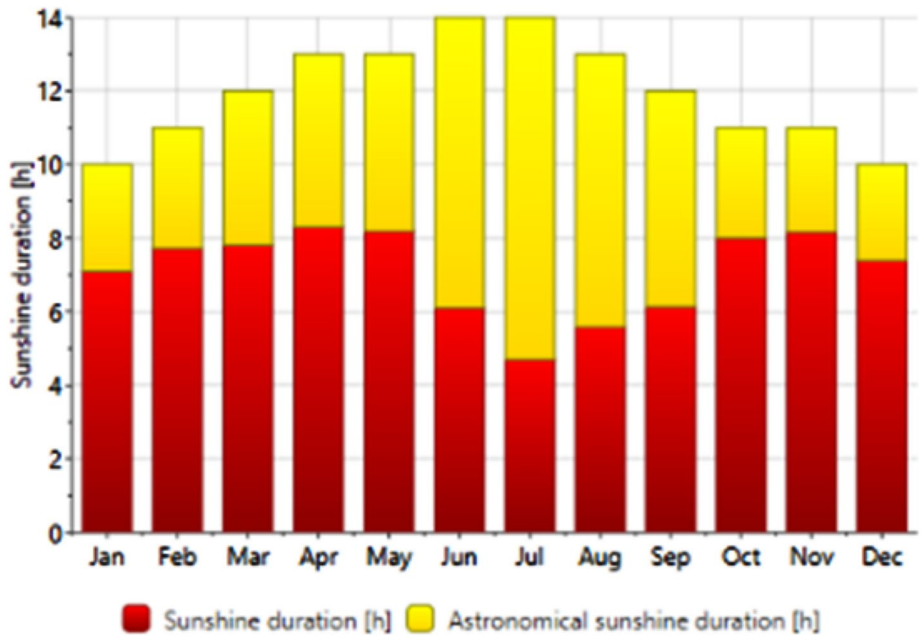

Fig. 5 The sunshine duration in Kathmandu

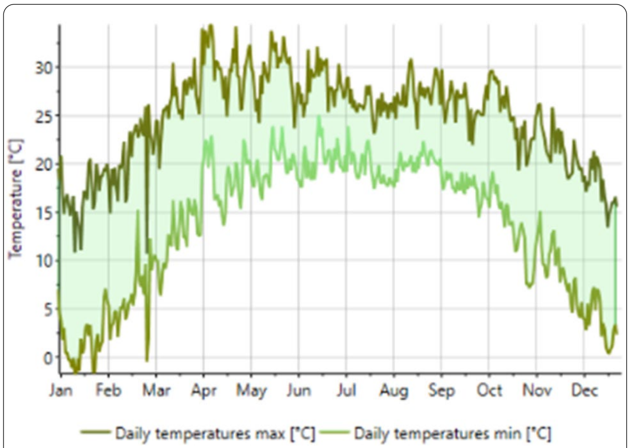

Fig. 6 The daily temperatures in Kathmandu

Case 1: stand-alone (off-grid) system

Energy balances and the performance of the selected PV system are shown in Table 7, which includes variables like global irradiance on the horizontal plane, effective global irradiance considering soiling losses and shading losses, DC energy available, and power unused due to full battery loss. Apart from these variables, energy missed, energy user, energy load, and solar fraction are also calculated. Each variable's values are mentioned in balances, and the main results were obtained in terms of monthly and yearly costs. In the selected study area, the annual global irradiance on the horizontal plane is 1869.2 kWh/m^2, and significant global irradiance after optical losses are 2086.9 kWh/m^2. The yearly DC energy available from the monocrystalline PV array is 5288.2 kWh, energy unused is 1943.7 kWh, and energy missed is 43.66 kWh. The annual average solar fraction is observed to be 0.986.

Normalised energy productions such as unused energy (battery full), collection loss, system loss and battery charging, and power supplied to the user per installed kWh/kWp/day were based on the simulations (Fig. 8). These normalised productions are defined by the IEC norms in the photovoltaic system performance mounting guidelines for measurement, data exchange, and analysis (Commission I-IE, 1998). The parameters selected for calculating the normalised energy production with their values are also shown in Fig. 8.

The arrow loss diagram shown in Fig. 9 helps to analyse the various losses that are to be encountered while installing a PV plant. This result is the gain of 14.2% global incident in the collector plane and loss of energy, i.e. 2.3% due to array incidence angle. After the PV conversion, the produced nominal array energy at standard testing conditions (STC) is 6208 kWh, with the PV array efficiency at 16.93%. Array output power is 3518 kWh. The various losses occur in this stage: 0.4% due to irradiance level, 9.6% losses due to temperature, 1.1% due to module array mismatch, and 1.9% of the Ohmic wiring losses. Available energy on an annual basis at the

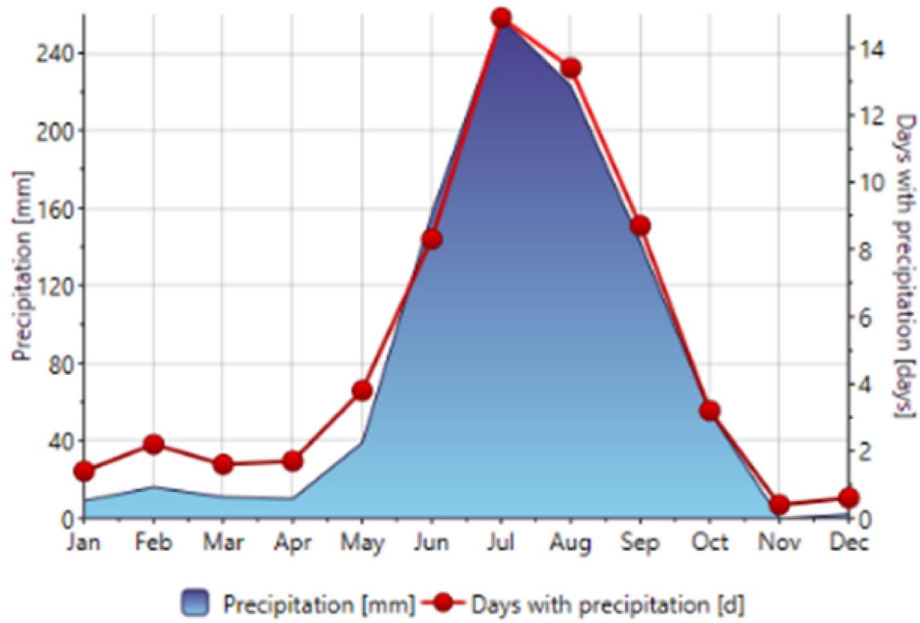

Fig. 7 The precipitation in Kathmandu

converter output and battery storage is 3345 kWh. At this stage, 4.9% is the converter loss. The energy supplied to the user is 2999 kWh. The various losses in this stage are 7.1% battery efficiency loss, 1.5% charge/discharge current efficiency loss, 1.4% electrolyte dissociation, and 0.1% battery self-discharge current. The missing energy current is 44 kWh, and the energy available to the user is 3043 kWh.

The detailed economic results show that the total yearly cost, including 9.90 inflation per year, is $1009.37/year. Total usage solar energy is 2999 kWh/year; excess energy (battery full) is 1944 kWh/year, while the cost of energy produced (sum of the expenses over lifetime/total production over lifetime) is 0.345 USD/kWh.

Case 2: grid-connected PV system

Energy balances and the main results simulated for the off-grid system are illustrated in Table 8. For the study area, the annual global irradiance on the horizontal plane is 1869.2 kWh/m^2, and the universal incident energy and effective global irradiance after optical losses are 2135 kWh/m^2 and 2086.9 kWh/m^2, respectively. The annual DC energy produced from the monocrystalline PV array and annual AC energy injected into the grid is 6111.2 kWh and 5901.1 kWh. The yearly average performance ratio (PR) for the simulated photovoltaic system is observed to be 0.838.

Normalised energy productions such as collection loss, system loss, and produced useful energy per installed kWh/kWp/day are shown in Fig. 10. The arrow loss diagram exhibited in Fig. 11 helps to analyse the various losses that are to be encountered while installing PV plants. Global irradiance on a horizontal plane is 1869 kWh/m^2. Nevertheless, the effective irradiance on the collector is 2087 kWh/m^2. This results in a gain of 14.2% global incident in the collector plane and loss of energy, i.e. 2.3% due to array incidence angle. After the PV conversion, the nominal array energy at STC is 6897 kWh. Array virtual energy at MPP is 6111 kWh. The various losses that occur in this stage are 0.4% due to irradiance level, 9.6% losses due to temperature, 1.1% loss due to module array mismatch, and 1.2% is the Ohmic wiring losses (Fig. 10). Available energy annually at the inverter output facility is 5901 kWh, and the same is available to the grid. Here the inverter loss during inverter operation was 3.4%.

The detailed economic results show that the total yearly cost, including 9.90 inflation per year, is $250.59/year, with a produced energy of 5695 kWh/year, and the cost of the production is $0.060 per kWh. The payback period is 8.7 years, and the net profit at the end of the lifetime is $1992.2. The return on investment (ROI) is 86.6%. It is also estimated that the system will save 10.33 tons of CO_2 emissions (see Fig. 12).

It was observed that the power output from the solar PV is quite significant due to higher solar irradiance throughout the year. The electrical performance analysis and economic consideration in PVsyst for the off-grid system show that the system is feasible in terms of electrical power output, but the system is not viable economically. The payback period is infinite and costly because of the battery price, as the battery must be replaced in every 5 years. On the other hand, the grid-connected system is feasible in terms of electric power output and finance. The economic analysis confirms that the grid-connected PV system's payback period is 8.7 years, the rate of investment is 86.6%, and CO_2 saving is 10.3 tons making it environmentally friendly technology.

The comparative simulation result of the stand-alone and grid-connected system is illustrated in Table 9. The produced energy is 5.9 kWh/year for the grid-connected system, but the used solar power for stand-alone is 2999 kWh/year, almost half. Similarly, the cost of produce energy (sum of the expenses over lifetime/total production over lifetime) is 0.345 USD/kWh for stand-alone, and for grid-connected, it is 0.06 USD/kWh. The result also showed that the stand-alone system's payback period would be indefinite because of the high battery cost and its short life cycle. The

Table 7 Balances and performances of the proposed stand-alone (off-grid) PV system in Kathmandu

	Glob Hor kWh/m^2	Glob Eff kWh/m^2	E_Avail kWh	E unused kWh	E_miss kWh	E_User kWh	E_load kWh	SolFrac kWh
January	138.2	204.9	534.4	186.5	0.00	309.7	309.7	1.000
February	140.7	184.0	469.5	156.1	0.00	279.8	279.8	1.000
March	169.2	189.5	479.0	239.6	0.00	207.4	207.4	1.000
April	183.7	180.7	447.2	223.1	0.00	200.7	200.7	1.000
May	191.3	170.5	425.3	189.1	0.00	207.4	207.4	1.000
June	175.2	151.1	378.4	61.0	0.99	298.7	299.7	0.997
July	156.4	135.9	342.8	25.4	21.90	287.8	309.7	0.929
August	157.5	146.8	368.4	56.5	20.21	289.5	309.7	0.935
September	138.3	141.9	358.9	127.3	0.57	200.2	200.7	0.997
October	148.9	178.5	450.9	214.9	0.00	207.4	2007.4	1.000
November	131.0	184.8	472.0	241.8	0.00	200.7	200.7	1.000
December	139.0	218.3	561.3	222.4	0.00	309.7	309.7	1.000
Total	1869.2	2086.9	5288.2	1943.7	43.66	2999.2	3042.9	0.986

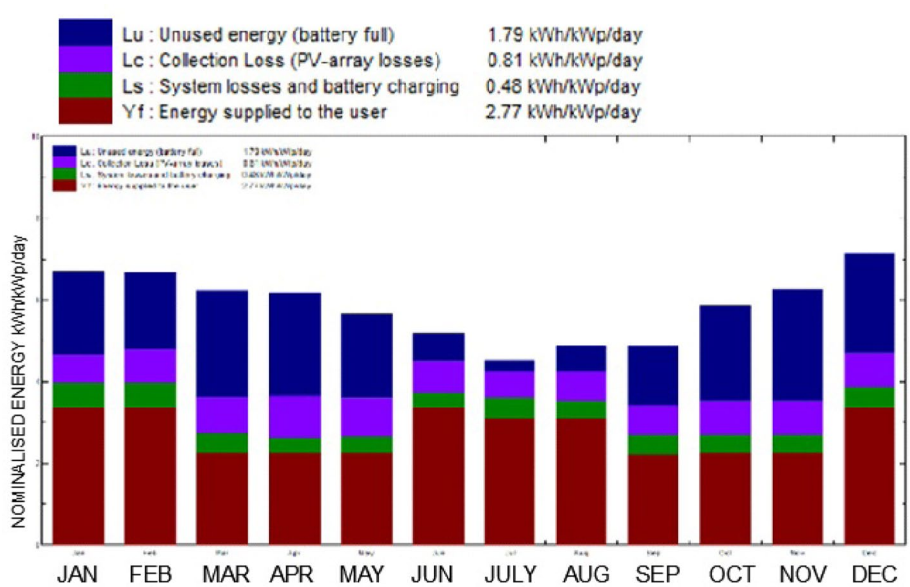

Fig. 8 Normalised energy production per installed kWp of the proposed PV system

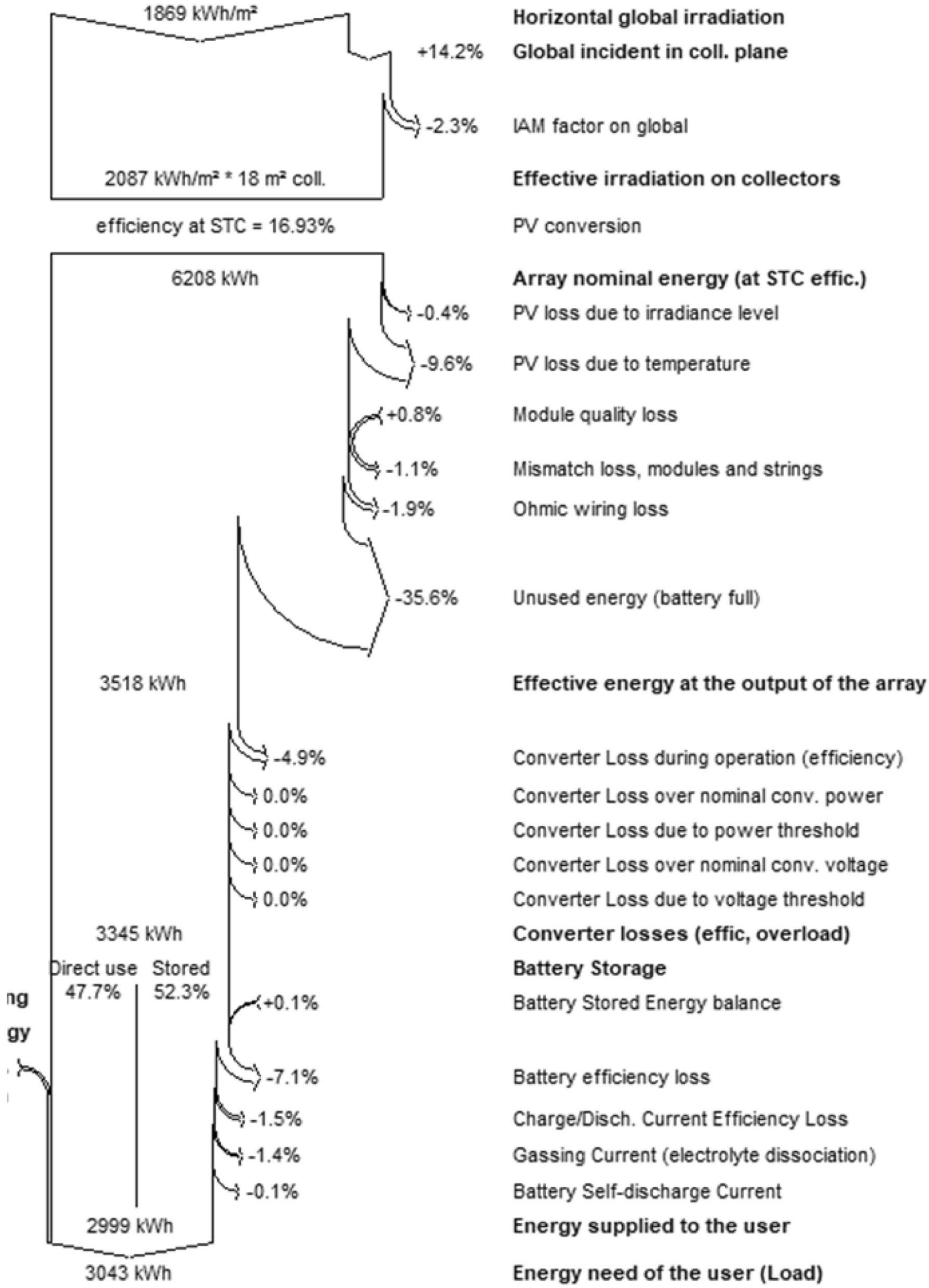

Fig. 9 The arrow loss diagram for the proposed monocrystalline 3kWp stand-alone system

Table 8 Balances and performances of the proposed grid-connected PV system in Kathmandu

	Glob Hor kWh/m^2	Diff Hor kWh/m^2	T_Amb kWh	Glob Inc kWh	Glob Eff kWh	E Arry kWh	E_Grid kWh	PR
January	138.2	25.98	8.90	208.1	204.9	618.5	597.9	0.871
February	140.7	32.69	13.34	186.9	184.0	544.0	525.5	0.852
March	169.2	58.43	18.84	193.7	189.5	550.0	531.3	0.831
April	183.7	66.20	23.70	185.5	180.7	513.3	495.8	0.810
May	191.3	77.28	25.06	175.7	170.5	489.4	472.2	0.814
June	175.2	88.42	24.25	155.9	151.1	441.6	426.0	0.828
July	156.4	82.90	23.41	140.5	135.9	401.7	386.9	0.835
August	157.5	78.17	23.27	140.5	135.9	401.7	386.9	0.835
September	138.3	70.56	22.40	146.0	141.9	414.4	399.8	0.830
October	148.9	55.05	20.34	182.0	178.5	518.6	500.9	0.834
November	131.0	31.37	15.55	187.9	184.8	541.8	523.7	0.844
December	139.0	19.92	11.06	221.5	218.3	648.0	626.4	0.857
Total	1869.2	686.98	19.20	2135.0	2086.9	6111.2	5901.1	0.838

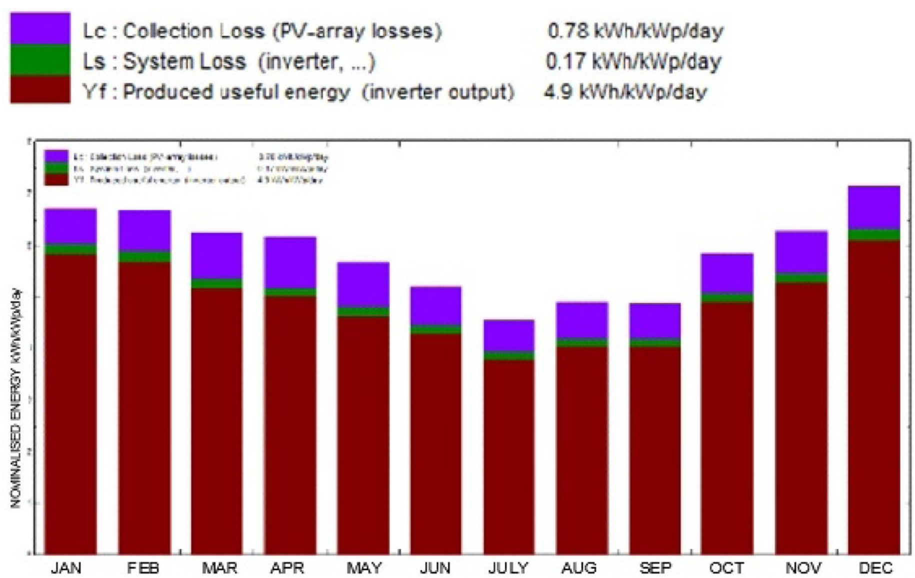

Fig. 10 Normalised energy production per installed kWp of proposed PV system

preliminary investment, operation, and maintenance costs are higher compared to the grid-connected system. The low electricity price also outweighed the cost, therefore, making the investment infeasible.

Nonetheless, this system has the added advantages of supporting reducing CO_2 emissions and a yearly reduction in electricity bills, which will go higher in the coming years. The system is also independent of a grid system; therefore, the power outage and the voltage fluctuation in the grid will not be affected. Furthermore, projections show that the plans can be feasible if the declining trend in PV system prices continues, and electricity prices increase. For the grid-connected system, the payback period is 8.7 years, the net profit at the end of the lifetime is USD 1992.15, and the return of investment (ROI) is 86.6%. The system is, therefore, techno-economically viable.

Hence the effective use of storage and cost of the battery will play a pivotal role in the decision-making of installing the system. The simulated result showed that both systems have advantages and are technically viable. The solar-grid system is the best option between the two proposed systems, exceptionally, when there is a reliable grid connection. Nevertheless, if there is no grid connection, then the stand-alone design can be cheaper than extending power lines like in some remote regions.

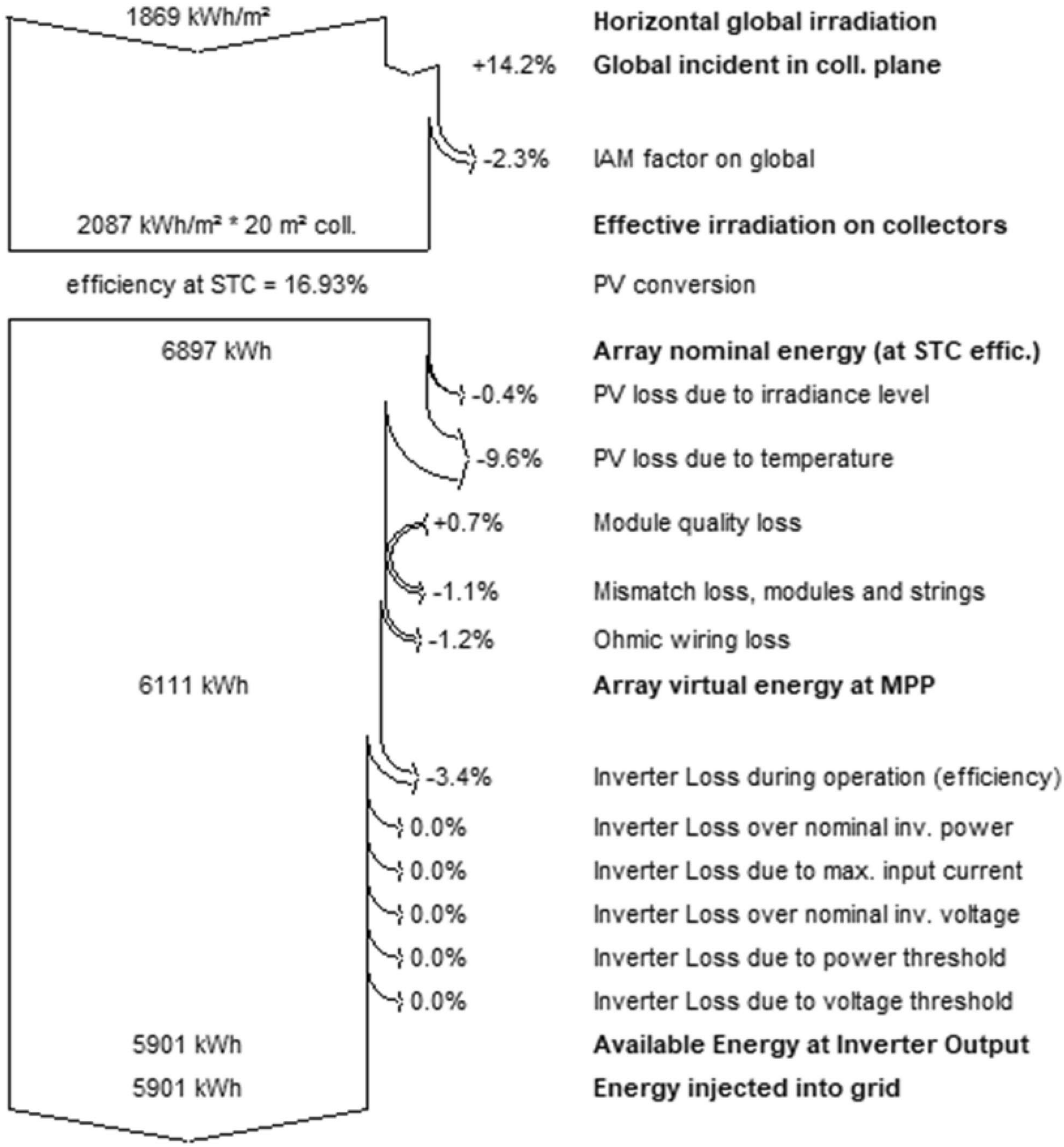

Fig. 11 The arrow loss diagram for monocrystalline solar-grid 3-kWp PV system

Noteworthy, Nepal receives a high amount of solar radiation throughout the year. The data obtained from Meteonorm showed that the horizontal yearly irradiation in Kathmandu is 1950kWh/m^2/year and has moderate temperature throughout the year, having an average maximum temperature of 25.7 °C and a minimum average temperature of 11.4 °C. The weather data analysis demonstrated that the PV power plant is promising in the Kathmandu valley, generating electricity for public consumption. Similarly, the simulation result in PVsyst proved an enormous potential for solar PV systems in Kathmandu.

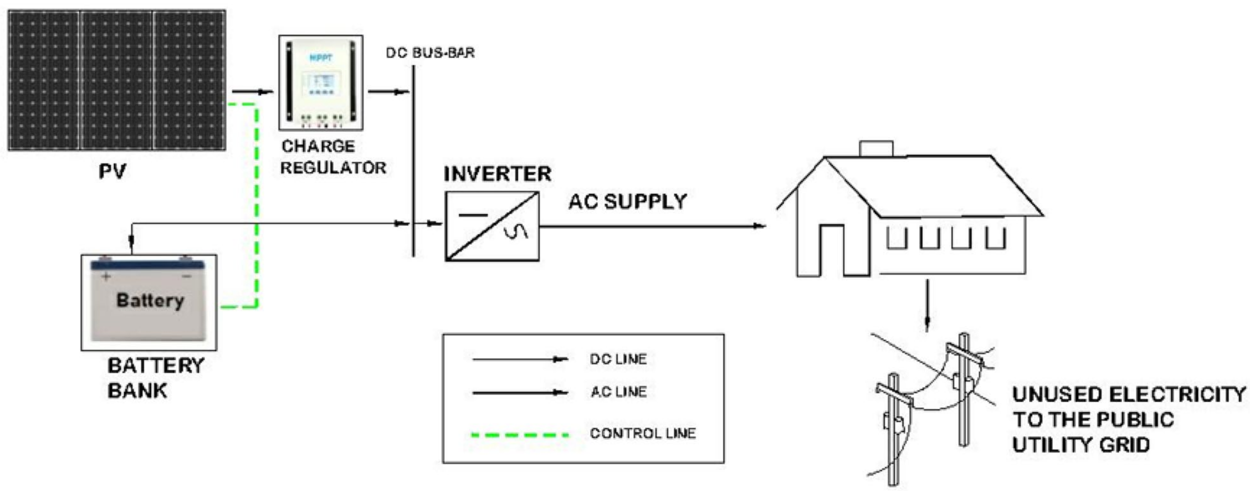

Fig. 12 The block diagram of the proposed PV system for Kathmandu

Table 9 Comparison between of a stand-alone and grid-connected proposed PV system

	Standalone PV system	Grid-connected PV system
Total yearly cost including inflation	$1009.37USD /year	$145.89USD /year
Produced energy	2999kWh/year	5.9 MWh/year
Payback period	Indefinite	8.7 years
Net profit at the end of the lifetime	–	$1992.2USD
Return of investment (ROI)	–	86.60%
Used energy cost	0.345USD /kWh	0.060USD/kWh
CO_2 emissions saved	5.0 tons	10.3 tons

Discussion

Development and challenges in solar PV deployment

Solar energy deployment has experienced unprecedented growth in recent years. Solar prices have decreased considerably over the last decade. New installation of solar PV system surpassed all other renewable energy globally (Cox et al., 2015). Despite these, Surendra. et al. (2011) also argued that solar PV is weather-dependent and fails to provide households with a consistent energy supply. It is not suitable in the region with long and harsh winters as the temperature falls below freezing. Therefore, developing an effective and stable system for evaluating solar PV site selection is an essential and incredibly challenging task. This section illustrates the opportunities and challenges of the proposed method and outlines the management implications. Despite the critical expansion of the solar market in many countries, barriers to solar deployment still exist. Common critical barriers include (Cox et al., 2015) below:

- Restrictive and time-consuming regulatory and permitting processes;
- Technical or infrastructural grid integration challenges;
- Lack of reliable policy signals, which can create uncertainty in markets;
- The concern of utilities related to the integration of distributed or variable power in the grid;
- The higher cost of solar technologies in comparison with other technologies;
- Lack of affordable financing;
- Need for a skilled workforce to design, instal, and operate and maintenance.

Support mechanisms relevant for Nepal

In order to achieve the target set by the GON to reach 100% electrification by 2023 (Poudyal et al., 2020) and maintain the renewable energy contribution to 30%

by 2030 (Poudyal et al., 2019b), the Government has to design policies that support the unique national situation and objective. Many studies that have been done globally showed the viability of promoting solar PV systems in the total energy mix. These studies have investigated the various approaches and techniques to determine PV systems' techno-economic suitability (Chandel et al., 2014; Fan et al., 2017; Garba et al., 2021; Lopez-Vidana, 2021; Sathaye et al., 2011). Among the developing countries, studies are mainly concentrated on countries like India and China (Bhat et al., 2019, Chandel et al., 2014, Kumar et al., 2020, Sontake & Kalamkar, 2016, Sontake et al., 2020a, b, Tang et al., 2010, Thotakura et al., 2020, Tiwari et al., 2020a, b, Verma & Dondapati, 2017). Nepal has also initiated research and development in the sector, but they are minimal (AEPC, 2020; Bajracharya & Maharjan, 2019; Chianese, 2010; Poudyal et al., 2020; Shrestha & Nath Shrestha, 2013). Moreover, Sapkota (2020) provides a comprehensive review of the status of solar PV in Nepal. These studies suggested that the support mechanisms required to promote RET are mostly related to the provision of: flexible financial instruments, ensuring financial innovations, the building of PV systems for concentrated energy loads, adopting standards process of technical appraisals, and local capacity building. Similarly, Bhusal (2019) mentions an incompetent subsidy model for renewable energy investment. Nepal's faltering renewables policy may find its solution in energy trade-hydro, RE from India.

India and China are energy-hungry nations set to consume half of the world's energy by 2030. For this, India has been aggressively investing in solar PV systems with a target of 100 GW of installed solar capacity by 2022, and likewise, China has a similar target within 2020. This is the biggest inspiration for Nepal. Nepal should follow its footstep to enhance its energy system by adapting the solar PV system to its energy mix.

Enhanced penetration of RETs in Nepal requires an improved financial innovation and an upscaled involvement of private sectors (Palit & Chaurey, 2011). Innovative financing schemes, such as increasing access to the lenders to long-term credits or low-interest loans to implementing organisations and households, are also relevant. Indirectly, the Government can facilitate to increase access to credit by information campaigns targeted at financial institutions. There are also concerns due to political stability, good governance, and the implementation of regulatory frameworks to successfully upscale alternative energy technologies, including solar PV (Dhakal et al., 2019). For effective implementation of renewable energy policies, the GoN should also ensure proper budgets, particularly for the country's nationally accredited renewable energy programme and projects. Another essential aspect primarily suggested is, the need to restructure the current institutional frameworks involved in the renewable energy development and promotion sectors, mainly to effectively mobilise regulatory bodies and private sectors (for both promotions and after-sales services) (Parajuli, 2011). Capacity development and institutional strengthening are thus vital (Parajuli, 2011). At the consumer level, it is also imperative that consumer-based awareness towards effective energy utilisation and energy management is facilitated. Based on the experiences observed in the implementation and operation of different policy mechanisms for enhanced use of RETs in various countries, it can be said that the Feed-in-tariff (FIT) can also be highly effective in Nepal. Formulation of effective FIT can help to promote the interconnection of a solar PV system with the grid. Although this could be limited for a small scale and scattered installations at residential dwellings. However, the GoN should need to explore alternative funding mechanisms that can cover the additional costs of generation, mainly to reduce utilities' burden and reduce the unintended cost increase in the consumers' electricity bills. This can be facilitated through different financing options and subsidies that can mainly reduce the cost of generation (i.e. on the grid interconnection equipment costs) (Shrestha, 2017).

Conclusion

This article's novelty considers system optimisation possibilities and the assessment of locally available renewable energy resources, completely based on local weather conditions, irradiations, temperature, and geographic situation. As per the result of this research, it is evident that the grid-connected system is economically available. However, all PV systems could be adapted to make a balance in the annual rising electricity demand. A stand-alone PV system would be beneficial for rural areas where there is no grid connection. Likewise, the grid-connected would be helpful in urban areas. Government policies and necessary implementations can play crucial roles in developing this decentralised energy system. In addition, the GoN should consider the solar-powered PV system from a broader perspective. For example, if 1,00,000 homeowners of Kathmandu valley installed a 3-kW PV system, then 300 MW electricity could be generated. Hence, this can increase attention towards the formulation and implementation of conducive policy and support mechanisms. While solar PV by itself cannot solve future planning and supply issues, it can certainly play a significant role in meeting a sizeable portion of annual demand. However, to our knowledge, an extensive evaluation of rooftop PV solar potential has not yet been undertaken in this city and country on a broader scale.

Several barriers still hinder the full development and installation of solar PV-grid technology in Nepal. This study can be regarded as a milestone for further recommending society towards adopting integrated renewable energy technologies in Nepal.

Abbreviations

AC: Alternative current; BTU: British thermal unit; DC: Direct current; DiffHor: Difference horizontal; E_Avail: Energy availability; E_Grid: Energy grid; E_Load: Energy load; E_Miss: Energy miss; E_User: Energy user; EArray: Energy array; F.Y: Fiscal year; FIT: Feed in tariff; GlobEff: Global efficiency; GlobHor: Global horizontal; GlobInc: Global inclination; Lc: Collection loss; Ls: System loss; Lu: Unused energy; NEA: Nepal electricity authority; NRs: Nepalese rupees; PR: Performance ratio; RETs: Renewable energy technologies; SolFrac: Solar fraction; SPV: Solar photovoltaic; SPC: Solar power company; STC: Standard test condition; T_Amb: Ambient temperature; TPEC: Total primary energy consumption; Yf: Produced useful energy (inverter output); $: US dollar.

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Authors' contributions

RHP conceptualised, analysed, and wrote the original manuscript; RP supported the article preparation, review, and editing; and PL supported in supervision, reviewing, and editing. All authors have read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

We all authors confirm that the appropriate ethics approval and consent to participate are not needed.

Consent for publication

The authors have granted consent for publication.

Competing interests

The authors declare that they have no competing interests.

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