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Decarbonizing airport using solar and wind farm: A case of Biratnagar, Nepal

Bharosh Kumar Yadav [a,*], Ramhit Yadav [b], Mehdi Jahangiri [c], S. Shanmuga Priya [d,*], Tri Ratna Bajracharya [e], K. Sudhakar [f,g,h,*]

[a] Department of Mechanical Engineering, Purwanchal Campus, Dharan-08, Tribhuvan University (TU), Institute of Engineering (IOE), Nepal
[b] Surya Narayan Satya Narayan Marbaita Yadav Multiple Campus, Siraha, Nepal
[c] Department of Mechanical Engineering, Shahrekord Branch, Islamic Azad University,Shahrekord, Iran
[d] Department of Chemical Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal 576104, Karnataka, India
[e] Department of Mechanical & Aerospace Engineering, Pulchowk Campus, Tribhuvan University (TU), Institute of Engineering (IOE), Nepal
[f] Centre for Automotive Engineering, Universiti Malaysia Pahang Al Sultan Abdullah, Pekan 26600, Pahang, Malaysia
[g] Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang Al Sultan Abdullah, Pekan 26600, Pahang, Malaysia
[h] Centre for Research in Advanced Fluid & Processes, Universiti Malaysia Pahang Al Sultan Abdullah, Gambang 26300, Pahang, Malaysia

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ABSTRACT

Airports strive for a greener energy transition to minimize their carbon footprint and greenhouse gas emissions. The installation of solar or wind turbines is gaining significance among stakeholders working in sustainable airports. This study focuses on developing Biratnagar airport as a completely greener airport by identifying suitable sites for installing Solar and wind farms within the premises without compromising on safety aspects, including glare occurrence and environmental and electrical safety. PVSYST V6.8.7 and HOMER V2.81 software are used to simulate the performance of PV and wind turbine power plants. Three sizes of Vertical axis wind turbines (VAWT) of EOLO 15 kW, Tree tree-shaped wind Turbine (TSWT) 58.5 kW and TSWT 585 kW have been used for the Simulation. A sensitivity analysis of various parameters, including interest rates, wind speed, and wind turbine types, has been carried out to study the cost of energy generation in grid-connected mode. According to the study, a 157 kWp solar PV power plant is sufficient for Biratnagar Airport to become Nepal's first fully green-powered airport. The project's Levelized Cost of Electricity (LCOE) equals 0.141 $/kWh if wind energy is used to supply part of the electricity with the annual wind electricity production of 23,184 kWh. The combined 15 kW wind turbine-grid scenario is superior to the grid scenario for wind speeds of more than nine m/s and interest rates of less than 10 %. These findings increase airport authorities' and stakeholders' confidence in the investment in greener airports.

1. Introduction

Over the last 20 years, the aviation industry's growth has increased by 5 % due to favorable policies and growing travel needs. Aviation is a rapidly growing industry that has contributed to global environmental degradation. Because of rigorous standards and the International Civil Aviation Organization (ICAO) environmental regulations, there is an increasing need to develop sustainable and green airports by 2030 [1]. Global artificial carbon dioxide emissions are expected to increase by 2–3 % by 2050, and other major environmental concerns include noise pollution, waste management, and energy conservation [2]. Scientists worldwide are working to find ways to reduce the ecological footprint of Airport operations. Developing a green and sustainable Airport with a low environmental impact is one such direction [3]. Various researchers worldwide have conducted studies on the performance of solar photovoltaic (PV) systems on airport premises. Sreenath et al. studied the installation of solar photovoltaic systems for Kuantan Airport, Malaysia, with the help of computational software. They also proposed a general sitting procedure for an airport-based solar PV system compatible with airport and aviation sectors. Land utilization, airport weather, and soil conditions are significant technical challenges of airport-based solar PV applications that can be overcome by prior planning, glare assessment, and careful implementations [4]. Farooq Sher et al. developed a mathematical model to evaluate the feasibility of a 12 MWp solar PV plant at

* Corresponding authors.
E-mail addresses: bharosh@ioepc.edu.np (B.K. Yadav), shan.priya@manipal.edu (S.S. Priya), sudhakar@umpsa.edu.my (K. Sudhakar).

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Doncaster Sheffield Airport, UK [5]. Yildiz and Yılmaz studied a 1 MWp PV grid-connected system for Gaziantep airport in Turkey and analyzed the performance, economic, and environmental benefits. Airport sustainability and sustainable practices in airport operations are gaining significant international attention [6]. They extensively studied the influence of Sun position, tilt angle, surface texture, color, and location of solar PV modules. Moreover, Sreenath et al. studied the effect of PV material, texture, orientation, and tracking on glare impact on an Indian airport to estimate the theoretical and technical power potential. They assessed the procedures and metrics for the glare impact from the solar PV array in the airport. 7E performance of solar PV plants on seven airport sites in India was explored through the energy-exergy-economic-environmental-energo-exergo-enviroecono analysis of the Airport [7-9]. Hydrogen, solar, and energy storage at the airport as a microgrid energy system was proposed to promote the concept of future greener airports minimizing the total investment cost and its benefit [10].

Xu et al. quantified the annual airport emissions with aircraft performance data of Shanghai Pudong International Airport and compared them with other airports [11]. Particle number size distribution (PNSD) for four European cities using Matrix Factorization (PMF) was identified [12]. It was revealed that airport emissions contributed to the highest emission concentration in the towns as the pollution carried away from the airport to the city. Energy, emission, and economic analysis of the 5 MW grid-connected solar-powered at Hazrat Shahjalal International Airport and Shah Amanat International Airport of Bangladesh were introduced [13].

The importance of energy-saving potential analysis and energy audits extends beyond the food production industry and can be applied to other sectors to improve energy efficiency opportunities [14]. By using the principles of energy-saving potential analysis and energy audits in the aviation sector, companies can unlock opportunities for improving energy efficiency, reducing costs, and mitigating environmental impact. The key developments in energy storage technologies to overcome the intermittent nature of solar and wind energy systems include electromechanical, mechanical, electromagnetic, thermodynamics, chemical, and hybrid methods. These energy storage methods provide reliable energy supply, stabilize power quality, and address ancillary power services when integrated with solar and wind systems [15].

Studies on the performance analysis of solar systems, wind systems, hybrid energy systems, and geothermal studies have been carried out based on energy analysis, exergy analysis, thermo-economic analysis, artificial intelligence approach, and 3E analysis [16-25]. For instance, Elshurafa et al. conducted a pilot study on the economic analysis of solar PV on mosque rooftops in Saudi Arabia, resulting in a 22 % reduction in net electricity bills [26]. Mah et al. suggested policy measures for the Hong Kong government to regulate PV prices, reduce the payback period and increase public interest in installing solar PVs [27].

1.1. Research /Knowledge gap

After conducting a comprehensive literature review, several research gaps were identified. Firstly, there is a lack of studies that evaluate the potential and performance of solar and wind farms in meeting airport demand in terms of energy, economic, and ecological parameters. Although some researchers have analyzed airport solar power plants, these studies have primarily focused on the techno-economic aspects of the solar farm. Moreover, there is a dearth of information on the performance feasibility of wind farms in Nepal for airport applications. The feasibility of Solar and wind systems based on economic and environmental benefits for application on airport premises has not been adequately reported in the literature. Given the variable performance of solar and wind Energy, it is crucial to evaluate specific local conditions to ensure the reliability of such energy systems. Therefore, the present study aims to address these research gaps by conducting a performance analysis of a solar and wind farm in the context of Nepal. By doing so, this study aims to provide valuable insights into the feasibility and effectiveness of renewable energy systems for airports, particularly in the Nepalese context.

1.2. Problem statement, research objective and research question

1.2.1. Problem statement

Nepal and its border nations, China and India, are ranked as the most polluted country globally. In particular, the Biratnagar region of Nepal has been grappling with chronic air pollution caused by rapid urbanization, construction activities, and a growing number of vehicles [28]. As the aviation industry is one of the significant contributors to greenhouse gas emissions, developing green airport infrastructure has gained considerable attention for reducing carbon footprints and promoting sustainable economic growth.

Research questions:

The research focuses on addressing the following research question.

- ✓ Is building a sustainable airport using solar and wind resources technically feasible in Biratnagar, Nepal?
- ✓ How can the Biratnagar airport in Nepal be decarbonized using solar and wind farms?
- ✓ How do the interest rate and wind speed variation influence wind farm feasibility?

Research objective:

The primary objective of this study is to explore the feasibility of a green and sustainable airport in Biratnagar, Nepal. Specifically, the study aims to:

- Evaluate the solar and wind power potential at Biratnagar Airport
- Assess the technical feasibility of implementing solar and wind farms to meet the airport's energy needs
- Perform a sensitivity analysis of wind farms for different interest rates and wind speeds at the site

By answering these research questions and meeting the research objectives, this study aims to contribute to the knowledge of the feasibility of green airport infrastructure in developing countries, specifically for Biratnagar, Nepal. The findings of this study will also provide insights to policymakers, airport management, and investors on the potential benefits and challenges of implementing solar and wind farms at airports.

1.3. Significance and organization of the study

1.3.1. Significance and contribution

The manuscript discusses the scientific significance of developing a greener airport in Nepal to achieve a clean energy transition, carbon neutrality, and long-term economic development. The authors conducted a comprehensive assessment of the feasibility factors, including solar and wind resources, land availability, specific technologies, and technology costs, to model and estimate solar and wind farms' energy yield and financial aspects using PVsyst and HOMER software, respectively. The study predicts potential energy savings of wind systems compared to the grid-only electricity supply based on the airport's four-year energy consumption. The manuscript's significant contribution is its first attempt to address the feasibility of solar and wind systems using actual airport energy consumption in the literature. The authors comprehensively assessed the project's energy, economic, and environmental viability at Biratnagar Airport, Nepal. The study's findings can help policymakers in Nepal make informed decisions on developing solar and wind Energy and contribute to much-needed research on greener airports in Nepal.

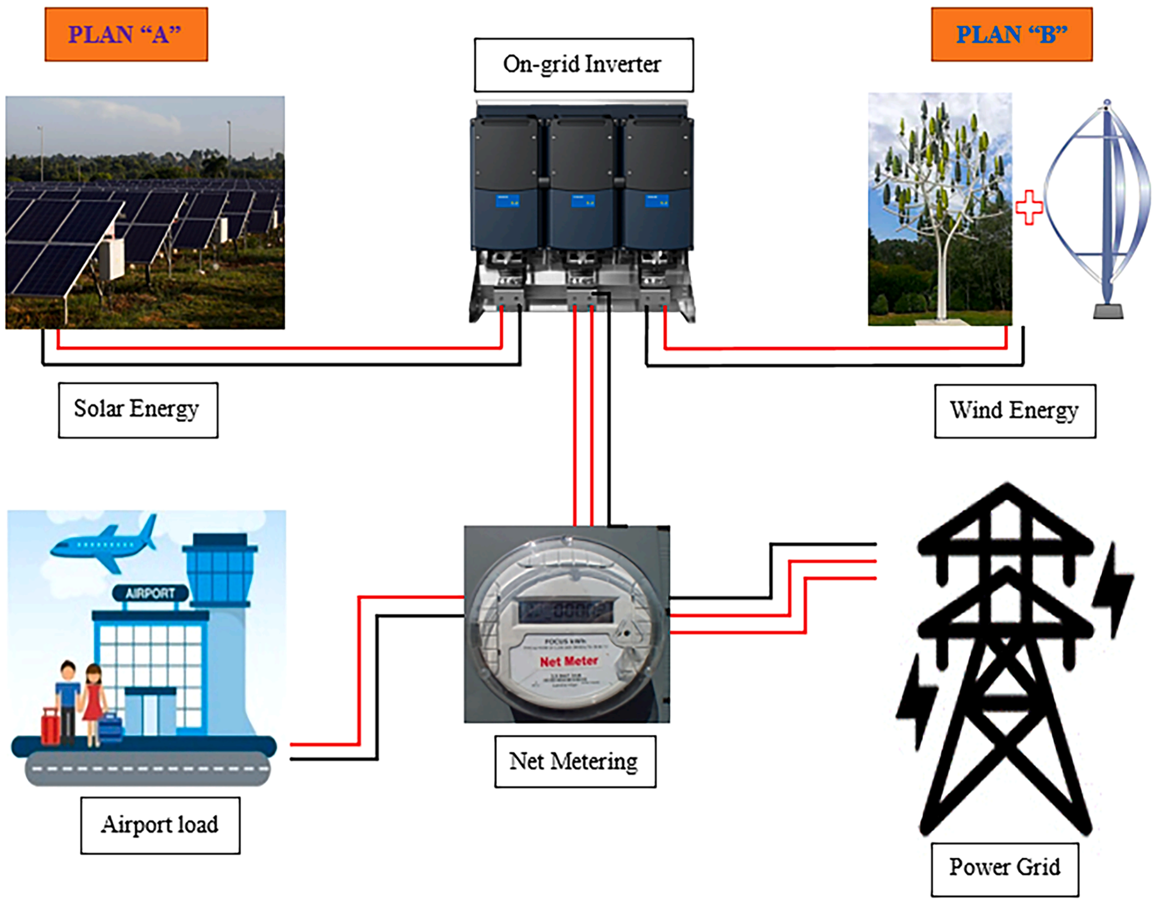


Fig. 1. Schematic of solar and wind-based energy systems.

1.3.2. Organization of the manuscript

This research paper is organized into five sections. The first section, the introduction, provides a brief overview of the importance of developing a greener airport in Nepal and the research objectives. The second section, "Solar and Wind Power Plants," describes the proposed solar and wind power plants' technical specifications and theoretical concepts. The third section, "Methodology," outlines the methodology used for the feasibility assessment, including the airport site assessment, airport energy demand analysis, and the 3E analysis framework using PVsyst and HOMER software. The fourth section, "Results and Discussion," presents the research findings, compares the results of the solar and wind power plants, and discusses the project's feasibility in terms of energy, economic, and environmental factors. This section also discusses wind farm challenges based on financial and ecological considerations. The fifth and final section, "Conclusion and Future Directions," summarizes the significant research outcomes, highlights the key findings, and provides recommendations for future research on greener airports in Nepal.

2. Description of the solar and wind power plant

2.1. Site selection criteria

Nepal is a landlocked country in South Asia encircled by the People's Republic of China to the north and India to the south, east, and west. Its total land area of 147,181 km^2 spans three ecological zones from east to west (the Southern Range, the Mid-Range, and the Northern Range). The elevation ranges from 60 m (m) to 8848 m (m), and the climate ranges from tundra to polar. Nevertheless, Nepal has an abundance of renewable energy resources. In particular, wind energy is an abundant, most efficient, cost-effective, and dependable solution for Nepal Energy [29]. The site selection for installing solar and wind farms in an airport is critical to ensure the optimal performance of renewable energy systems. Several criteria must be considered when selecting a site, such as solar or wind resource availability, land availability, shading and obstruction, distance from the power grid, and other environmental factors. Therefore, the airport's flat rooftop or any available land without obstructions should be prioritized. Wind turbines, however, require a consistent wind flow and should be installed in locations with unobstructed wind exposure. The airport's open areas, such as parking lots, free space near runways, or other available lands, could be potential sites for wind turbine installation. In addition, environmental factors such as noise and visual impact should also be evaluated to ensure the system's social acceptance and minimize the impact on local communities. The schematic of the solar PV and wind turbine energy system based on the tree shape and vertical axis wind turbine to meet the airport load is shown in Fig. 1.

2.2. PV module

Risen Energy Co. Ltd.'s polycrystalline PV module SYP2955 was chosen for the Simulation due to its availability, reliability, and cost. The polycrystalline panels were selected over monocrystalline panels. As a thumb rule, the optimum tilt angle for maximum solar energy collection equals the location's latitude. Therefore, for the Biratnagar Airport location with the coordinates (26°28′60″ N and 87°16′60″), 30 ° were chosen based on solar irradiation analysis.

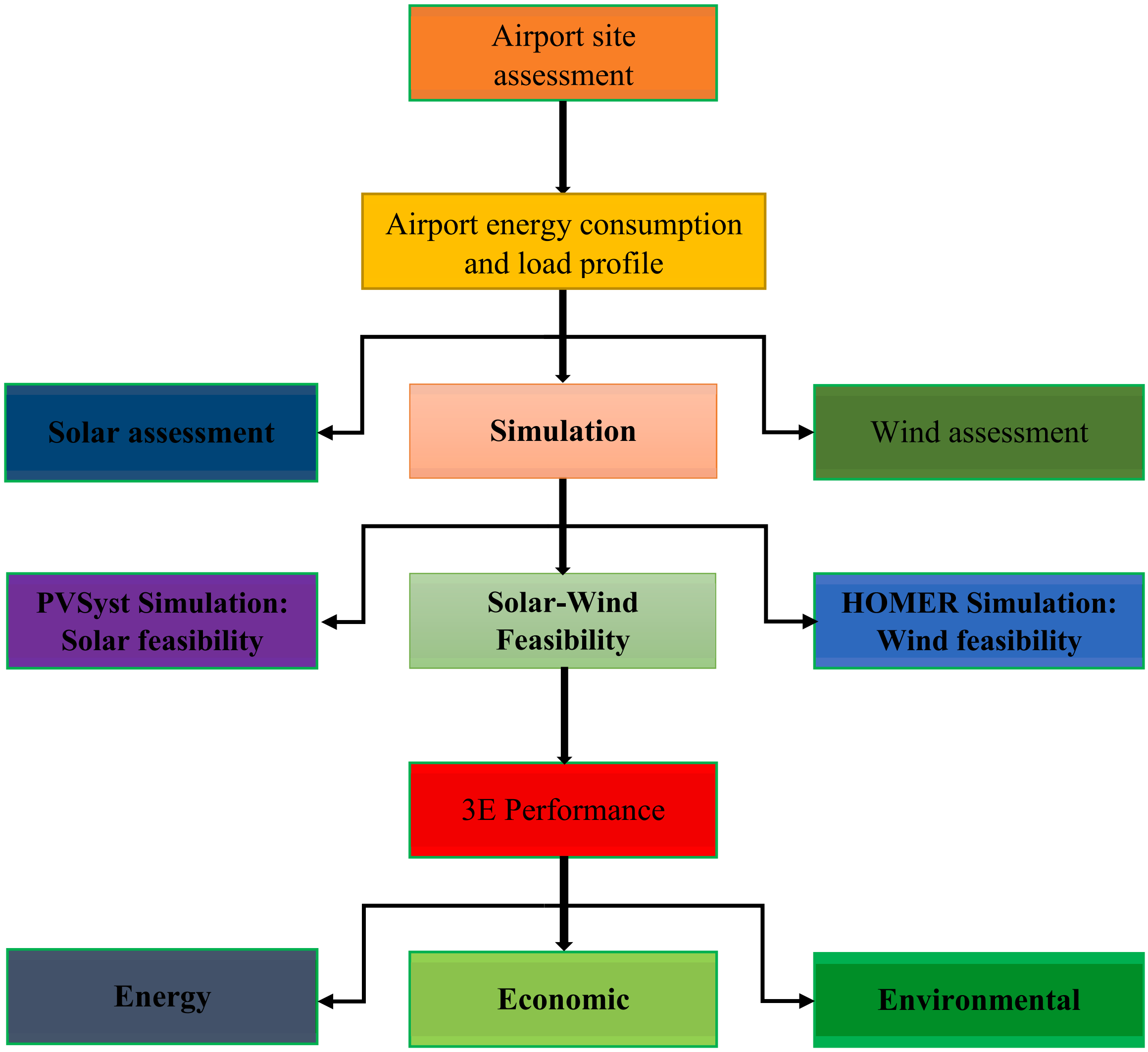


Fig. 2. Flowchart illustrating the methodology of the 3E analysis.

2.3. *On-grid inverter*

In solar PV power plants, the inverter is one of the major components. The maximum power capacity of the solar plant for the airport load is 159.9 kWp. The minimum size of the inverter should not be less than 70 % of the total installed capacity (i.e., 109.8 kWp). Considering a safety factor of 20 %, an inverter capacity of 200 kW (570–800 V) single unit grid-tied inverter is selected for this Simulation.

2.4. *Wind turbine and its components*

The major components of the vertical wind turbine and their working function are discussed in this section. Vertical axis wind turbine (VAWT: 15 kW @ 5* EOLO 3 kW) and Tree shape wind turbine (TSWT: 58.5 kW @ 5* Aeroleaf 11.7 kW and TSWT: 585 kW @ 50* Aeroleaf 11.7 kW) are considered for the feasibility of the wind farm. A vertical-axis wind turbine typically requires a guidewire to keep the rotor shaft in place and minimize mechanical vibration. The hub is the rotor's center, to which the blades are attached [30]. The rotor is the heart of a wind turbine and comprises multiple rotor blades connected by a hub. It includes various rotor blades connected by a hub [31]. The turbine component's role is to collect wind energy and convert it into mechanical motion. A wind turbine's rotor blades are a crucial component primarily made of aluminum, fiberglass, or carbon fiber due to their superior strength-to-weight ratio [32]. The primary function of the gearbox is to step up the shaft's low rotational speed and the generator's rotational speed. Two or more gear types, primarily made of aluminum alloys, stainless steel, and cast iron, can be combined in multiple stages. Wind turbines typically use asynchronous machines directly connected to the power grid to generate electricity [33].

2.5. *Grid*

The Nepal Electricity Authority (NEA) is responsible for generation, transmission, and distribution. Most solar and wind installation energy is used to meet the airport load. However, net metering can feed the excess Energy generated into the power grid. Efficient grid infrastructure is necessary to integrate solar or wind power successfully.

3. Methodology

The feasibility of the airport's solar and wind power plant is studied using the 3E approach. The research framework of the simulation study is presented in Fig. 2. A grid-connected solar and wind power plant is simulated to analyze the 3E performance parameters, i.e., Energy, Economic, and Environmental.

3.1. *Airport site assessment*

Biratnagar is the fifth largest city, the third-most populous metro-

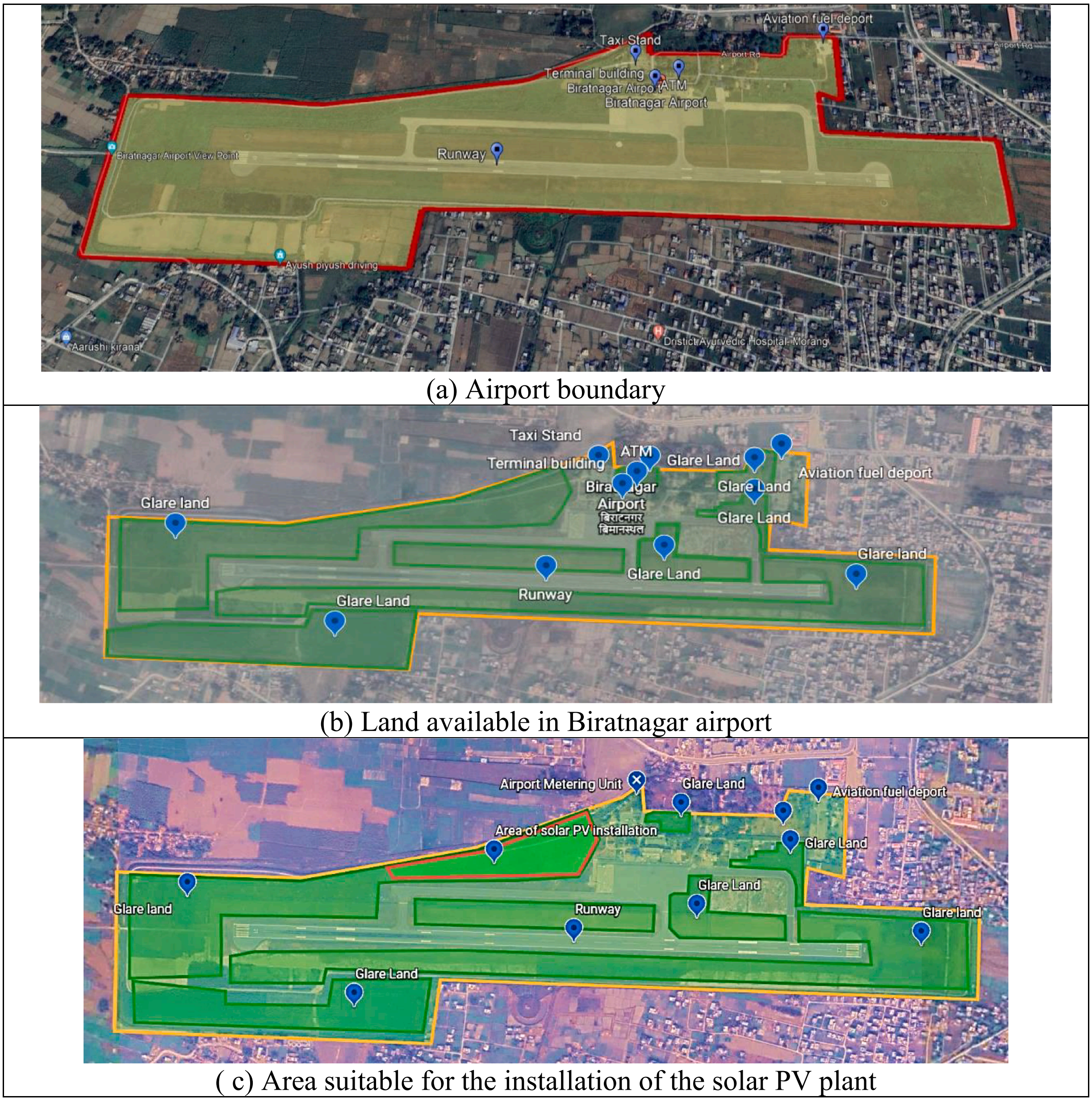


Fig. 3. Details of Biratnagar Airport (Source: Google map).

Table 1
Biratnagar Airport Energy consumption statistic (2017–2019).

S.N.	Month	Airport energy consumption (kWh)			
		2016	2017	2018	2019
1	January	9685	11,564	10,569	16,555
2	February	9075	11,552	10,030	15,591
3	March	9489	12,493	10,864	16,810
4	April	11,860	15,306	15,825	18,935
5	May	12,822	16,404	20,759	21,892
6	June	13,674	18,477	24,530	25,492
7	July	14,679	21,802	27,494	21,598
8	August	18,655	20,385	24,131	24,413
9	September	20,274	21,269	22,961	26,677
10	October	16,164	22,227	23,079	23,840
11	November	13,847	17,457	18,278	20,857
12	December	11,368	13,043	13,329	16,118
Total	**Yearly**	**161,592**	**201,979**	**203,849**	**248,780**

Table 2
Irradiance and temperature variation.

Months	Global (kWh/m^2)	Diffuse (kWh/m^2)	Temperature (°C)
January	136.2	29.1	8.7
February	131.9	38.4	13.1
March	177.3	55.2	18.6
April	180.9	68.8	23.5
May	189.3	88.0	24.9
June	166.9	75.4	24.1
July	155.0	86.5	23.2
August	153.2	78.1	23.1
September	135.0	63.0	23.2
October	138.5	58.6	20.1
November	129.4	35.3	15.4
December	129.9	21.4	10.9
Year	**1823.5**	**697.8**	**19.0**

Table 3.
PV array and inverter characteristics [38].

PV Array		Inverter	
Model	Risen energy Co., Ltd/SYP295S	Model	ABB/PVI-200.0-TL
Nom. Power	295 W_P	Operating voltage	570–800 V
No. of PV modules in series and parallel	19 modules and 28 strings	Unit Nom. power	200kWac
Total no. of module	532	Inverter pack	2
Array Nom. power	157 kWp	MPPT	33 %
Total module area	1032 m^2	Total Power	133 kWac
Total cell area	1.932 m^2	Pnom. ratio	1.18
Output current and voltage of module	V_{MP} 35.6 V I_{MP} 8.29 A	Output	3 phase,50 Hz
Efficiency	15.2 %	Efficiency	97.94 %

politan city, and Nepal's Province 1. It is located in the Morang District (Koshi Zone) of Nepal's easternmost Terai region, at the coordinates 26°28′60″ N 87°16′60″ E. This airport is considered the second busiest domestic airport in passenger movement after Pokhara Airport. The Provincial government of Biratnagar has opined to acquire land to develop Biratnagar Airport into a regional international airport. Biratnagar Airport is the first certified aerodrome among domestic airports in Nepal and second, after Tribhuvan International Airport, which is spread over an area of approximately. 812,715 m^2(120 bighas or 200.8220 acres) of land, as shown in Fig. 3 [34]. While inaugurating the program to mark the 20th anniversary of the Civil Aviation Authority of Nepal, the province's Chief Minister, Sherdhan Rai stated that roughly 400 acres of land had to be acquired to extend the airport runway [35].

This study proposes a solar PV system with plenty of vacant land within airport premises. The airport runway is bituminous paved (Asphalt Concrete) with a runway of 1500 m X 30 m with an apron size of 14,445 Sq.m [34]. The entire airport can run on solar Energy to power the air traffic room, security check, taxiway lights, ground control rooms, and passenger terminal. Several indicators and new environmental regulations encourage airports to develop sustainable green airports. Installing PV solar plants at the airport should follow FAA sustainability guidelines and airport management of glare land to ensure its use for economic viability, operational efficiency, and proper resource utilization [36]. The Biratnagar airport site experiences low temperatures of 10 °C and high temperatures of 40 °C. The solar PV power plant needs a total area of 1052 m^2iles for installation. It is essential to reduce costs using PV panel design, selection, and installation engineering methods for the appropriate site location and construction [37].

3.2. Airport energy consumption and load profile

To determine the total solar Energy required to operate the airport, yearly electrical energy consumption bills from 2011 to 2019 were collected from the Nepal Electricity Authority (NEA), Biratnagar branch [38]. The airport uses the Time-of-Day (TOD) meter to measure its electrical energy usage for each month is the best and the most reliable data source for finding this out. According to the airport authority, construction work significantly added electrical loads. The years before 2011 were excluded from the analysis (due to COVID-19) for realistic airport consumption. Table 1 shows the corresponding annual electric

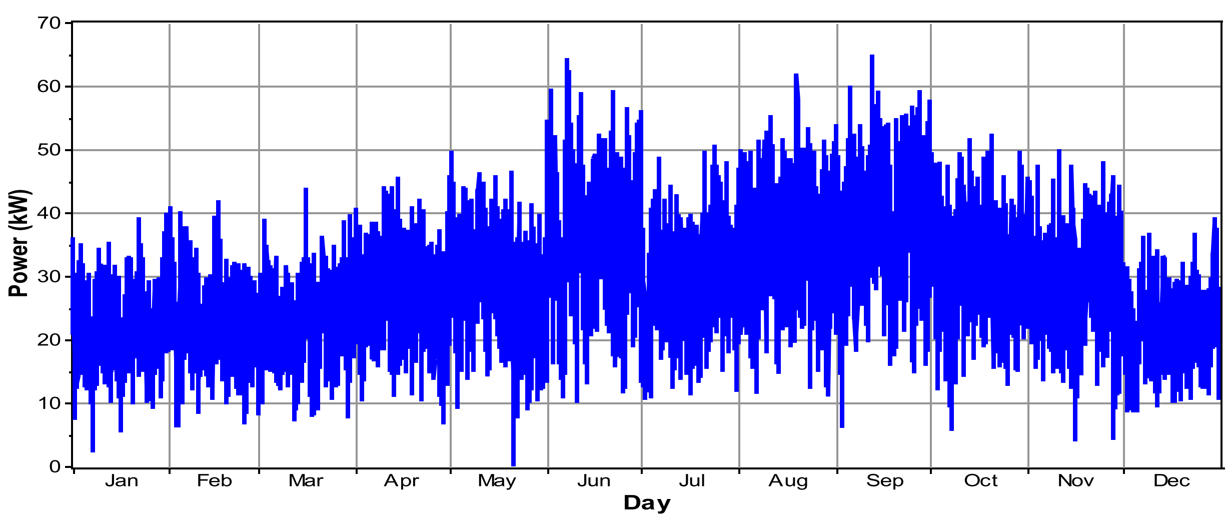


Fig. 4. Annual electricity consumption (kWh).

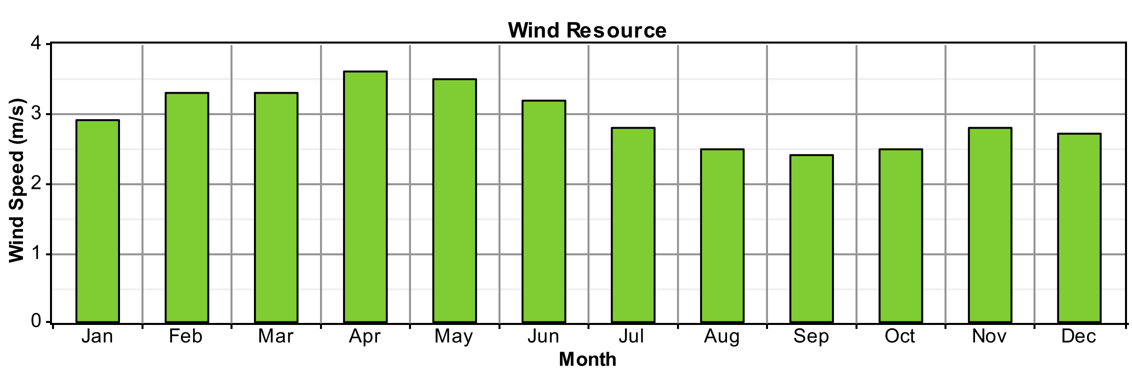


Fig. 5. Monthly average of the wind speed (m/*sec*).

Table 4
Detail cost of wind farm.

Equipment	Cost ($)			Quantity	Other information
	Capital	Replacement	O&M		
Converter	20,000	20,000	1000	0, 200	Lifetime: 25 year Inverter Efficiency: 97.94 %
VAWT-EOLO [46]	5269	5269	130	0–50	Lifetime: 20 year Hub height: 6.8 m Rated power: 3 kW DC
TSWT-Aeroleaf [46]	35,000	35,000	200	0–50	Lifetime: 19 year Hub height: 10 m Rated power: 11.7 kW AC

consumption data from 2016 to 2019.

According to the above values, the total Energy required to meet the airport load demand was 161,592 kWh, 201,979 kWh, 203,849 kWh, and 248,780 kWh, respectively. Furthermore, the maximum Energy consumed in 2019 is chosen for the analysis to estimate the realistic PV solar plant capacity. The airport's total annual electrical energy consumption in 2019 was 248 MWh/year, equivalent to 680 units per day [38].

3.3. Feasibility of the solar PV plant: PVSYST simulation

The PVSYST V7.0 simulation software was utilized to simulate the grid-connected power plant to meet the complete airport's load consumption. The monthly energy consumption was calculated based on energy consumption. The airport site encounters a low temperature of 10 °C (min.) to 40 °C (max.) with an average low wind speed of 5 km per hour yearly. Table 2 summarizes the irradiance and temperature profiles of Biratnagar Airport. Global Irradiance is observed to be highest in April and May. It is lowest in November and December. The site's average global Irradiance is 1823.5 kWh/m^2/year, and the average diffuse radiation is 697.8 kWh/m^2/year, with an average temperature of 19 °C.

The PV array and inverter parameters used for the Simulation of the solar power plants are shown in Table 3.

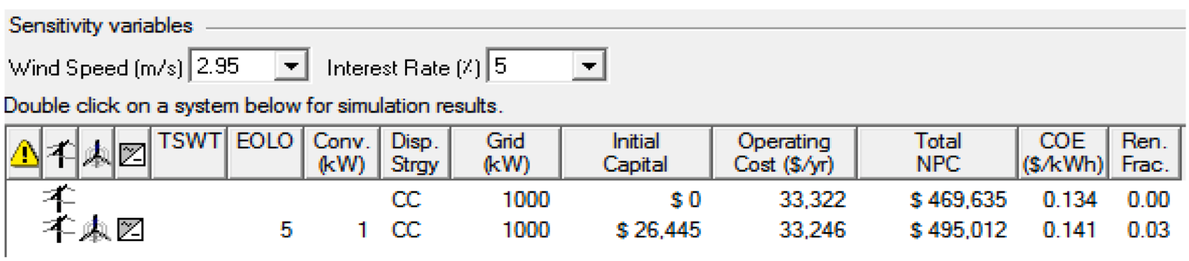


Fig. 6. Cost analysis of the grid scenario and wind turbine-grid scenario.

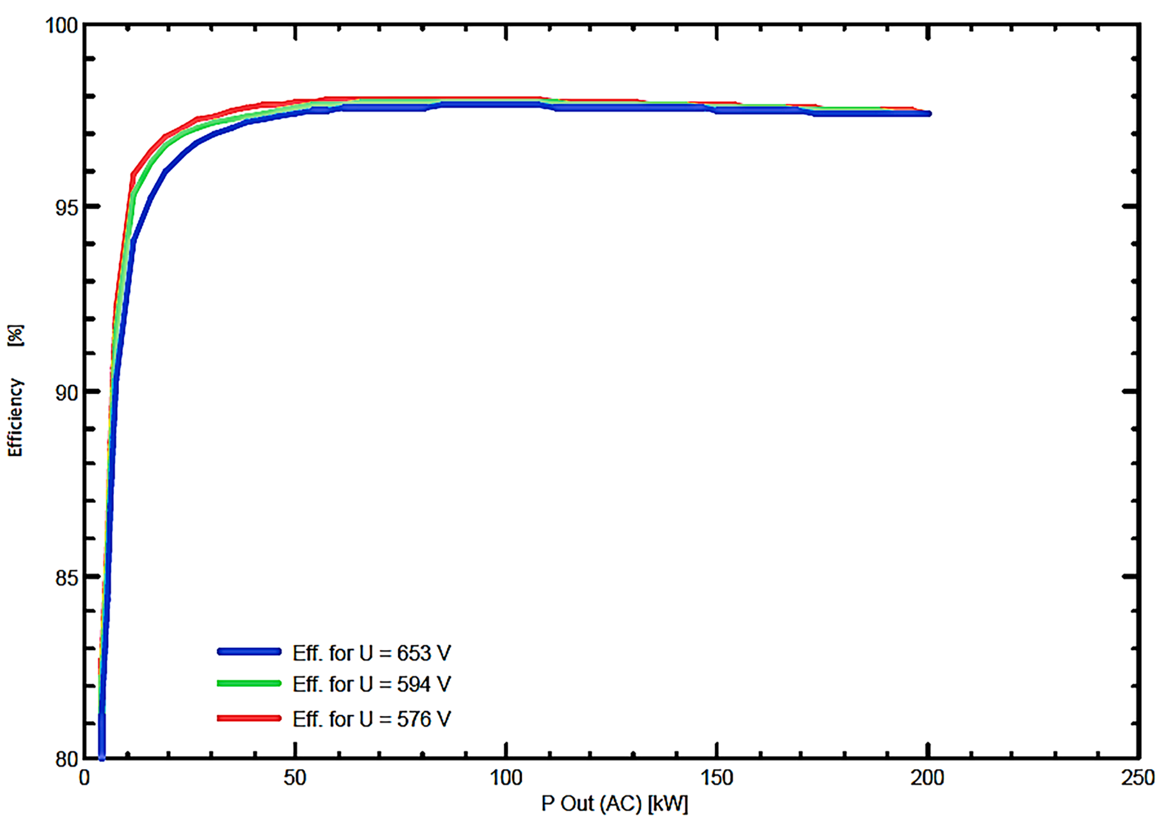


Fig. 7. Solar Inverter Efficiency.

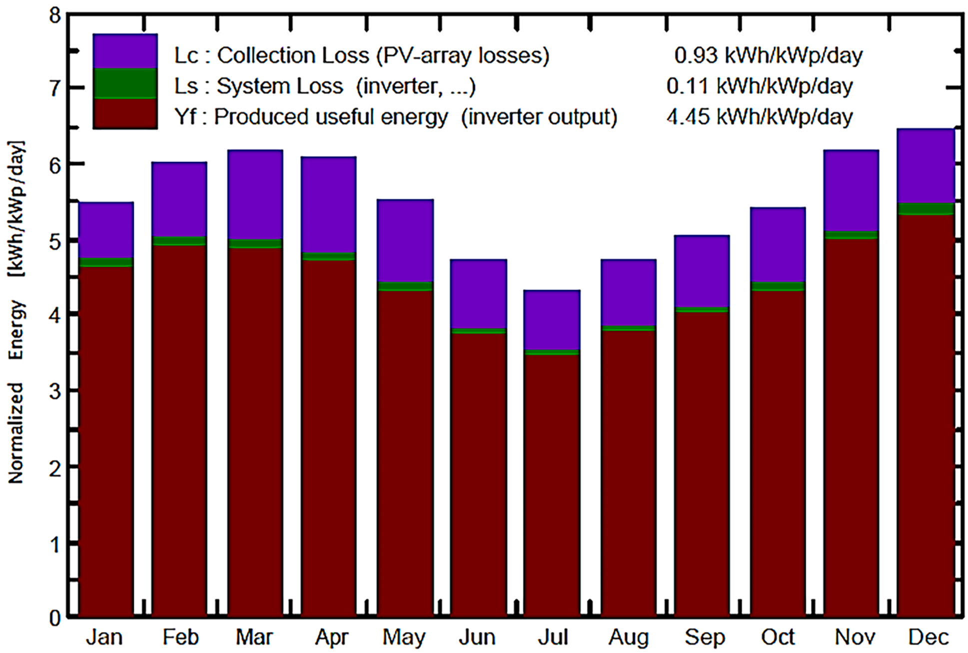


Fig. 8. Monthly variation of normalized productions (per installed kWp).

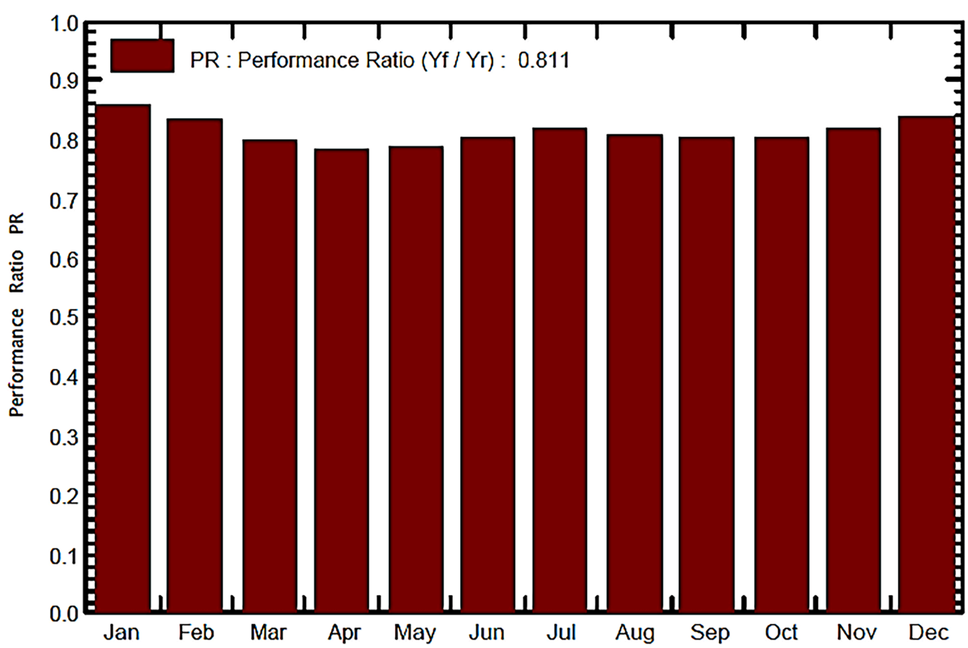


Fig. 9. Monthly variation of Performance ratio (PR).

3.4. Feasibility of wind plant: HOMER simulation

HOMER software developed by NREL is a powerful tool for evaluating hybrid energy systems. The unique feature of this software is the simple presentation of the system cost function. This cost analysis includes installation, recovery, repair, and emission costs [39,40]. The software lists options based on the lowest net present cost (NPC) by examining all possible modes of supply required for the load [30,41]. The most critical data needed for the Simulation is the daily energy consumption of the airport. Fig. 4 illustrates the annual electricity requirements of the study location, considering the random variability coefficients of 15 % and 20 % from day to day and hour to hour, respectively [31]. The peak electricity demand of 64.7 kW occurred in September at 11AM.

The essential criteria for the feasibility assessment are long-term wind speed data for the study location. As shown in Fig. 5, the site's average wind speed is around 2.95 m/s.

3.5. Energy assessment

The performance parameters of solar PV plants, such as yield factor, performance ratio, and energy efficiency, are defined by IEC 61,724:1998 Standard and the International Energy Agency (IEA) [42,43]. The various performance parameters for solar and wind plant energy analysis are presented in the following section.

Table 5
Main results and Balances of the proposed grid PV solar power plant.

YEAR	GlobInc kWh/m^2	EArray MWh	E_User MWh	E_Solar MWh	E_Grid MWh	EFrGrid MWh
January	169.1	23.32	16.55	6.77	16.00	9.79
February	167.6	22.34	15.59	6.41	15.39	9.18
March	191.2	24.46	16.81	7.16	16.71	9.65
April	182.0	22.84	18.93	8.40	13.92	10.54
May	171.5	21.64	21.89	9.65	11.48	12.24
June	140.9	18.16	25.49	10.27	7.44	15.22
July	133.0	17.41	21.60	9.07	7.90	12.53
August	145.9	18.96	24.41	9.96	8.55	14.46
September	151.3	19.51	26.68	10.34	8.70	16.33
October	167.7	21.66	23.83	9.40	11.74	14.44
November	185.0	24.32	20.86	8.36	15.39	12.49
December	199.4	26.75	16.12	6.71	19.42	9.41
Yearly Total	**2004.5**	**261.37**	**248.78**	**102.49**	**152.63**	**146.29**

3.5.1. Maximum power output

$$P_{max} = VOC \times ISC \times FF = V_{mp} \times I_{mp} \quad (1)$$

Where, P_{max} is the electrical power generated for a particular instant of solar irradiation, VOC is the open-circuit voltage, ISC is the short-circuit current, FF depicts the fill factor of the cell, V_{mp} is the maximum power voltage, and I_{mp} is the maximum power current.

3.5.2. Total specific energy production

$$\text{Total specific production} = \text{Total Energy Obtained} \;/\; \text{Array Nominal Power} \quad (2)$$

3.5.3. Energy efficiency of the solar array

And, η_{en} can be calculated using the formula

$$\eta_{en} = \frac{P_{max}}{E_{in}} = \frac{P_{max}}{I \times A} \quad (3)$$

3.5.4. Performance ratio

$$\text{Performanceratio} = Y_f / Y_r \quad (4)$$

Where, Y_f is the system yield, and Y_r is the reference yield.

$$Y_f = E / P_o \quad (5)$$

E is the net energy output (kWh), and P_0 is the installed PV array (kW).

$$Y_r = H / G \quad (6)$$

H is the total plane irradiance (kWh/m^2), and G is the PV reference irradiance (kW/m^2).

3.5.5. Power output of the wind turbine

HOMER software uses Eq. (7) to calculate the output power of wind turbines [44].

$$P_{WTG} = \frac{\rho}{\rho_0} \times P_{WTG,\ STP} \quad (7)$$

Where ρ is the density of actual air, ρ_0 is the air density at standard pressure and temperature, P_{WTG} is the wind turbine's power output, and PWTG, STP is the wind turbine's power output from the power curve.

3.6. Economic analysis

The LCOE is the most commonly used energy metric. It is also a benchmark tool to assess the cost viability of different energy projects. LCOE states the unit energy price by considering the present value of total incurred cost over the project's lifetime, such as investment cost, O&M cost, and replacement cost. In general, the LCOE is calculated as [13]

$$\text{LCOE} = \text{Life cycle cost} \;/\; \text{Lifetime energy production} \quad (8)$$

Economic calculations include the parameters of total net present cost (NPC), and the equipment prices & information used during the Simulation are depicted in Table 4. The cost of Energy (COE) is estimated based on the following Eqs. (9) and (10), respectively [45].

$$\text{Total NPC} = \frac{C_{ann,\ total}}{\frac{i(1+i)^N}{(1+i)^N - 1}} \quad (9)$$

$$\text{COE} = \frac{C_{ann,\ total}}{E_{Load\ served}} \quad (10)$$

Where, $C_{ann,\ total}$ is the total annual cost ($), i is the annual real interest rate (%), N is the number of years, and $E_{Load\ Served}$ is the actual

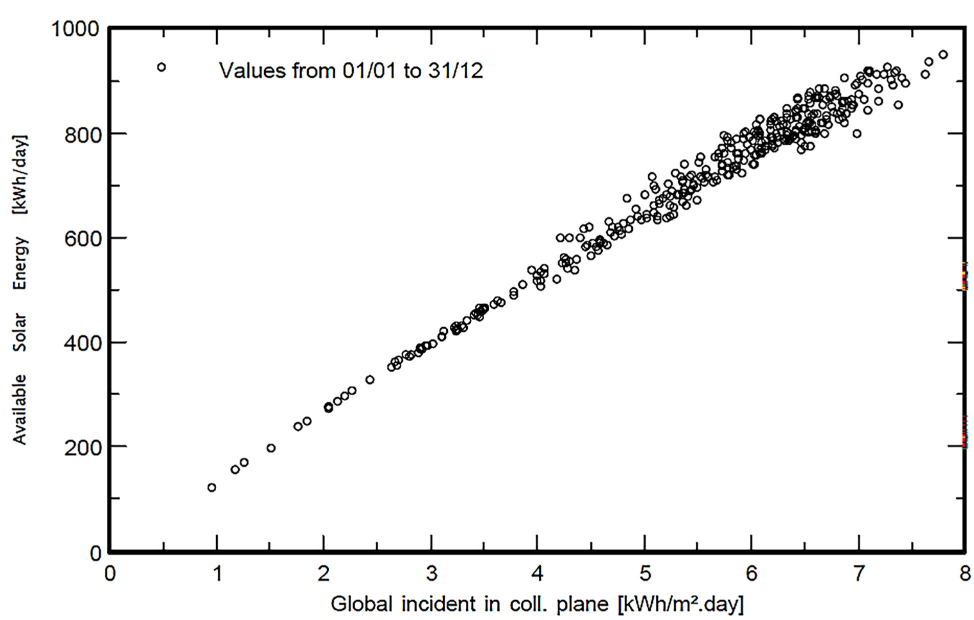


Fig. 10. Variation of Global incident radiation with solar Irradiance (kWh/m^2-day).

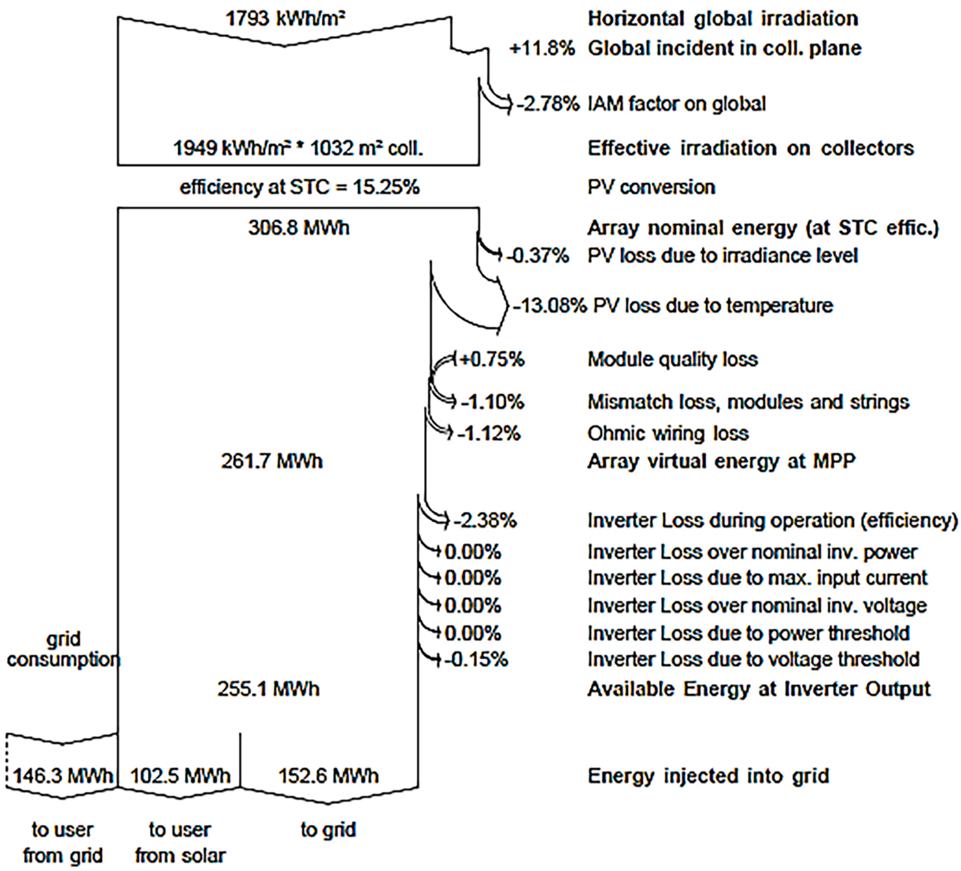


Fig. 11. Energy loss diagram.

electrical load (kWh/year) [45]

During peak hours (10AM - 5PM), the grid's power cost is 0.110 \$/kWh. During off-peak hours, the grid's power cost is 0.108 \$/kWh. Selling power to the grid is 20 % cheaper than buying electricity from the system. The following assumptions were made for the Simulation: The project will last 25 years [47], with a 5 % annual interest rate [48]. The sensitivity cost analysis of the grid and wind turbine plus grid scenarios is shown in Fig. 6.

The following Wind speed (2.95, 6, 9, 12, 15) m/*sec*, Interest rate (5 %, 10 %, 15 %) and Type of Turbine (EOLO 15 kW, TSWT 58.5 kW and 585 kW) are considered for the sensitivity analysis. HOMER optimization algorithms selected the best conditions to reduce the COE (USD/kWh).

3.7. Environmental analysis

Life cycle CO_2 mitigation of the plant is given by [48].

$$CO2_{mitigation} = E_g \times E_{annual} \times n = 22,960.8\ tCO_2 \tag{11}$$

Where, $CO2_{mitigation}$ is the carbon mitigation of the plant (tCO_2), E_g is the grid emission factor (tCO_2/MWh), E_{annual} is the annual energy generation (MWh), and n is the plant's life.

The life cycle CO_2 generation of the plant is given by [48].

$$CO_{22g\ generation} = E_{annual} \times CO_2 \text{per kWh} \times n \tag{12}$$

Where $CO_{2\ generation}$ is the carbon generation of the plant (tCO_2), E_{annual} is the annual energy generation (MWh), and n is the plant's life [48].

$$NetCO_{2BalanceorSavings} = LifecycleCO_{2mitigation} - -LifecycleCO_{2generation} \tag{13}$$

$$LifecycleCO_{2credits} = NetCO_2saving \times CO_{2trading} \tag{14}$$

CO_2 trading is 40 \$/ton [49]. The amount of pollutants the grid produces per kWh of electricity generated is 632 g of CO_2, 2.74 g of SO_2 and 1.34 g of NO [50].

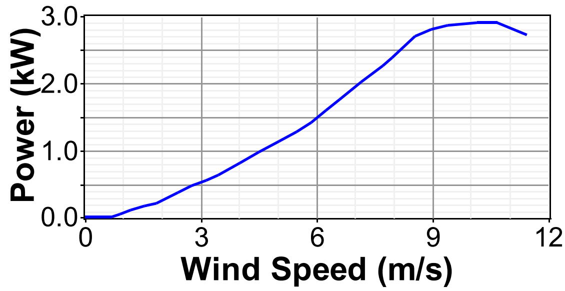
4. Result and discussions

4.1. Energy analysis

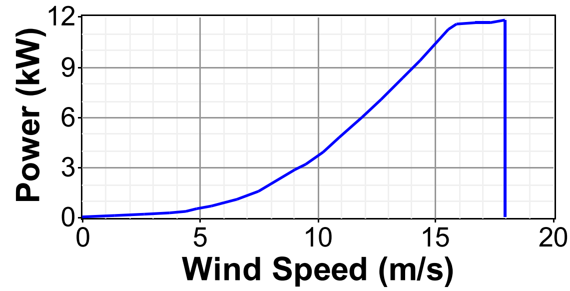
4.1.1. Solar plant performance

Preliminary estimates of a 180 kWp solar PV system provide annual Energy, approximately 250 MWh, to meet the airport's energy consumption requirements. Also, it is observed that the residual Energy can be fed to the grid in certain months. Inverter efficiency is one of the most critical parameters in this study. This study uses ABB, PVI-200.0-TL grid inverter, which produces an efficiency of 97.94 % at maximum. Fig. 7 depicts the efficiency versus DC Power (kW) and the efficiency values for various conditions. Also, the effective nominal power is found to be 200 kW. Above this, the efficiency declines drastically. The solar grid comprises 28 strings of 295 Wp solar panels. Each string consists of 19 panels connected in series, for 532 panels with a 157Wp array nominal power at STC.

The nominal 157 kWp solar PV grid-connected plant can generate 255.1 MWh/year of Energy, with a specific production of 1626 kWh/kWp/year, a performance ratio (PR) of 81.10 percent, and a solar fraction (SF) of 41.20 percent. Figs. 8 and 9 and Table 5 show the normalized productions (per installed kWp), performance ratio (PR), ambient temperature (T_amb), global incident in the collector plane (GlobInc), the energy output of the PV array (EArray), performance ratio (PR), (EFr Grid) Energy from the grid, Energy injected into the grid (E_Grid for each month of the year as well as the overall energy balance of the solar PV grid-connected power plant.



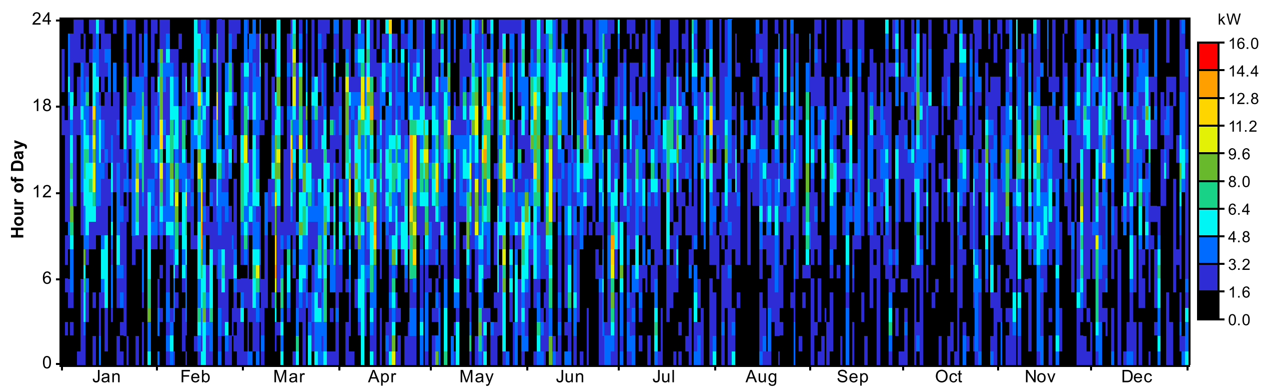
(a) Power curve of EOLO



(b) Power curve of tree-shape

Quantity	Value	Units
Total rated capacity	15.0	kW
Mean output	2.6	kW
Capacity factor	17.6	%
Total production	23,184	kWh/yr

Quantity	Value	Units
Minimum output	0.0	kW
Maximum output	14.1	kW
Wind penetration	9.31	%
Hours of operation	8,760	hr/yr
Levelized cost	0.121	$/kWh



(c)VAWT-EOLO Output

Fig. 12. Performance of VAWT-EOLO wind turbine.

Based on the simulated data, the annual global Irradiance at the proposed Biratnagar airport site is 1792.8 kWh/m^2. Annually, solar PV power can generate 261.37 MWh of Energy, with 102.49 MWh of Energy from Solar to load, 146.29 MWh of Energy from the grid, and 152.63 MWh of Energy to the grid. As a result, the net solar power exported to the grid will be 6.34 MWh. The system is designed to import Energy from panels and inject Energy into the load for increased reliability, as the instant output of solar PV panels varies with Irradiance. On the other hand, the daily fluctuations in solar PV generation are unpredictable. Fig. 10 depicts the daily Input / Output global irradiance.

The total solar radiation incident on the PV panel surface is 1949 kWh/m^2. With a PV efficiency of 15 %, 306.8 MWh energy is generated by a 157kWp array over the year. The total energy losses for the entire year include losses due to Irradiance (0.37 %) and temperature (13.08 %). As shown in Fig. 11, module quality loss (0.75 percent), mismatch loss (1.10 percent), Ohmic wiring loss (1.12 percent), converter loss during operation (2.38 percent), and inverter loss due to voltage threshold (0.15 percent) are other losses. As a result, the total net Energy available at the inverter output is 255.1 kWh. 152.6 MWh of generated solar Energy is injected into the grid, and 102.5 MWh is supplied to the load. Also, the load is provided with 146.3 MWh of Energy from the grid. The high loss due to temperature at the site is due to the local weather conditions and higher ambient temperature.

4.1.2. *Wind plant performance*

The performance of wind turbines and realistic power production are presented in Fig. 12 and Appendix 1. According to the HOMER software results, 23,184 kWh of electricity, or about 9 %, is generated annually by wind turbines (15 kW) VAWT-EOLO. As we can observe, the TSWT (585.5 kW) model has the highest power output (1631,027 kWh) generated among the selected turbines. The blade size, hub height, rotor diameter and wind velocity are the important factors influencing the power generation of the turbines. The amount of power generation varies throughout the year. It should be noted that based on software output, the average capacity factor is 17.6 %.

4.2. *Economic analysis*

4.2.1. *Cost analysis of solar plant*

The economic investment evaluation of the Biratnagar airport utilizing PVSYST tool software to make it fully green is analyzed in Table 6. According to the Nepal Electricity Authority norms, the total net investment will be 112,874.10 USD (Rs. 1 crore 36 lakhs Nepali Rupee) for a 157 kWp grid-connected solar PV power plant [51]. The long-term detailed financial balance and the return on investment of the project lifetime of considering 20 years are shown in Table 7. The exact economic performance values include sold Energy, running cost, taxable income, after-tax profit, depreciation, dividends, Self-consumption saving, cumulative profit and% amortization. The airport's net profit

Table 6
Economic investment analysis.

S. N.	Item	Unit	Unit cost (USD)	Capital costs (USD)
1.	**PV modules (SYP295S)**	532	150.00 /unit	79,800.00
2.	**Module support**	532	10.00 /unit	5320.00
3.	**Inverter (PVI-200.0-TL)**			20,000.00
4.	**Studies and analysis**			
	Engineering			1000.00
	Permitting other admin fees			500.00
	Environmental studies			500.00
	Economic analysis			500.00
5.	**Installation**			
	Grid connection			1000.00
	Wiring			750.00
	Settings			500.00
	Transport			1000.00
	Accessories, fasteners			500.00
6.	**Gross Investment**			**111,370.00**
7.	**VAT**			**1504.10**
8	**Net Investment (CAPEX)**			**112,874.10**
9.	**Operating costs**			
	Reparation			700.00/year
	Cleaning			300.00/year
	Taxes			
	Federal taxes			13.00/year
	Total (OPEX)			1013.00/year
	Operating costs (OPEX) incl. Inflation (4.00 %)			1452.20/year
10.	**System summary**			
	Net investment			**112,874.10 USD/ year**

of 263,793.33 USD, more than double the project's net investment of Rs. Three crores 17 lakhs (Nepali Rupees). The project has a payback period of 5.9 years and a return on investment (ROI) of 233.7 percent. The grid-connected PV system's annual net profit and cumulative cash flow are shown in Fig. 13 and Fig. 14, respectively.

4.2.2. *Cost analysis of wind plant*

The economic feasibility of the wind plant mainly depends on the cost of Energy (COE Per kW) generation. The system's total cost (including the capital, construction, operation and maintenance costs) and the COE can be considered the best indicator of the project's feasibility. A sensitivity analysis to study the effect of the average wind speed (2.95, 6, 9, 12, and 15 m/s), annual interest rate (5 %, 10 %, and 15 %) and VAWT /TSWT wind turbines on COE are carried out. Table 10 shows the sensitivity analysis of wind speed, annual interest rate, and turbine type on COE. According to the results, COE increases when the yearly rate rises and drops as wind speeds increase. In other words, the influence of wind speed on the outcome is decreased at higher annual interest rates. The most important finding is that the preference to use EOLO turbines reduces when the yearly interest rates increase from 5 % to 10 %. As the annual interest rate increases from 10 % to 15 %, there will be a preference for EOLO vertical axis turbines over TSWT wind turbines. Fig. 15 illustrates the Cash flow diagram for the grid scenario and Wind turbine plus the grid scenario. In the wind turbine-grid scenario case, 5 EOLO vertical axis wind turbines (VAWTs) and a 200-kW electric converter are used. According to the results, if wind energy is used to supply part of the required electricity, COE equals 0.141 $/kWh. It is clear from the results that using the electrical grid with a COE of 0.134 $/kWh is the most cost-effective option. This might be due to two reasons: First, the cost of grid electricity in Nepal is lower than renewable electricity, and the other is that the wind potential of the study area is moderate. Fig. 16 shows the cumulative cash flow diagram for the grid scenario and the grid + wind turbine scenario for the project over 25 years. According to the results, when the EOLO turbine's lifetime expires in the 20th year, a new wind turbine must be acquired, which increases

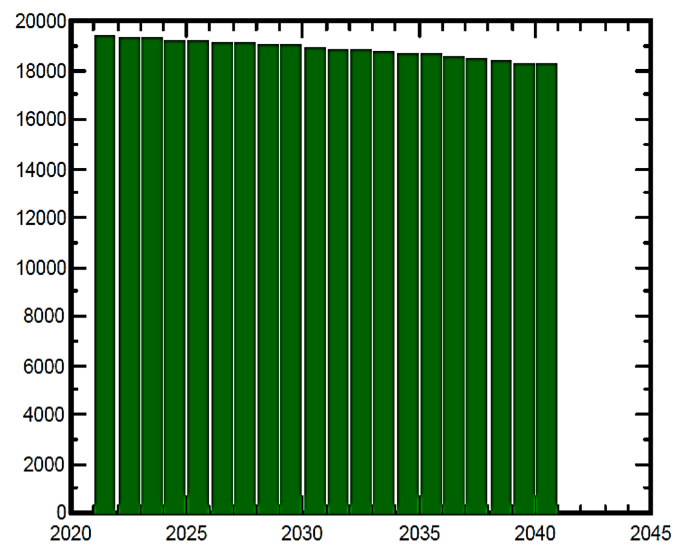


Fig. 13. Annual net profit (USD).

Table 7
Detailed economic performance (USD).

Year	Sold energy	Run. costs	Deprec. allow.	Taxable income	Tax 0.00 %	After-tax profit	Self-cons. saving	Cumul. profit	% amorti
2021	12,210	1013	5569	5629	0	11,197	8132	19,329	17.1 %
2022	12,210	1054	5569	5588	0	11,157	8132	38,617	34.2 %
2023	12,210	1096	5569	5546	0	11,114	8132	57,863	51.3 %
2024	12,210	1139	5569	5502	0	11,071	8132	77,065	68.3 %
2025	12,210	1185	5569	5457	0	11,025	8132	96,221	85.2 %
2026	12,210	1232	5569	5409	0	10,978	8132	115,331	102.2 %
2027	12,210	1282	5569	5360	0	10,928	8132	134,390	119.1 %
2028	12,210	1333	5569	5309	0	10,877	8132	153,399	135.9 %
2029	12,210	1386	5569	5255	0	10,824	8132	172,354	152.7 %
2030	12,210	1442	5569	5200	0	10,768	8132	191,254	169.4 %
2031	12,210	1499	5569	5142	0	10,711	8132	210,096	186.1 %
2032	12,210	1559	5569	5082	0	10,651	8132	228,878	202.8 %
2033	12,210	1622	5569	5020	0	10,588	8132	247,598	219.4 %
2034	12,210	1687	5569	4955	0	10,523	8132	266,253	235.9 %
2035	12,210	1754	5569	4887	0	10,456	8132	284,841	252.4 %
2036	12,210	1824	5569	4817	0	10,386	8132	303,358	268.8 %
2037	12,210	1897	5569	4744	0	10,313	8132	321,802	285.1 %
2038	12,210	1973	5569	4668	0	10,237	8132	340,171	301.4 %
2039	12,210	2052	5569	4589	0	10,158	8132	358,460	317.6 %
2040	12,210	2134	5569	4507	0	10,076	8132	376,667	333.7 %
Total	**244,202**	**30,165**	**111,370**	**102,666**	**0**	**214,036**	**162,631**	**376,667**	**333.7 %**

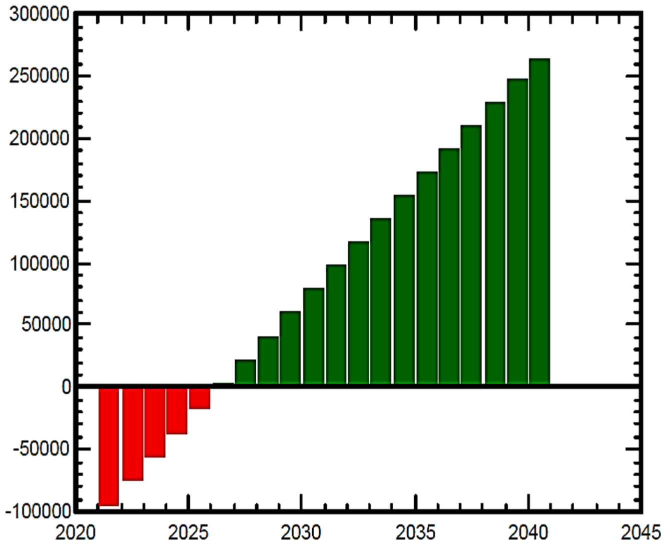


Fig. 14. Cash flow diagram (USD) of the Grid-connected PV system.

the cost. Throughout the project's 25-year lifespan, there is also an actual maintenance expense, most of which is tied to the national grid. At the end of the project life, there is also a favorable salvage cost for the remaining operational equipment. Compared to the base case (grid scenario), as illustrated in Fig. 16, the current system (wind turbine-grid scenario) has a higher negative cost, and there is never a return on investment. Also, the difference is minimal and constant throughout the 25 years of the project's lifetime.

4.3. Environmental analysis

4.3.1. CO_2 mitigation of the solar plant

The CO2 mitigation from the grid-connected system is computed using PVSYST software during a 30-year lifetime with a 1.0 percent annual degradation. Total CO_2 emissions of 268.90 tonnes were entirely replaced by 23.0 tonnes, resulting in a total CO_2 emission balance of −249.0 tonnes. Table 8 and Fig. 17 illustrate the details of lifecycle emissions and CO_2 savings over time.

4.3.2. CO_2 mitigation of wind plant

The sensitivity analysis results and their effect on the CO_2 emission parameter are shown in Fig. 18. Based on the results, It has been revealed that the combined wind turbine-grid scenario is superior to the grid scenario for wind speeds of more than nine m/s and interest rates of less than 10 %. Also, for these conditions, the electricity sold to the grid is more than the amount purchased from the grid. The amount of CO_2 emission becomes negative. In other words, the harmful pollutants from fossil fuels electricity are prevented because the sale of wind energy to the grid is more than purchasing electricity from the national grid.

4.4. Performance comparison

Airports can use the surplus area to build solar energy facilities to generate and export power. Because the study site was an airport, using sizeable horizontal axis turbines was impossible. Generally, wind turbines aren't a good fit for use on airport property due to the height of their towers. However, vertical-axis wind turbines (VAWTs) are preferred over horizontal wind turbines due to their esthetic appearance, fewer space requirements, and less noise generation at airport sites. There is a considerable probability of the wind speed exceeding 9 m/sec at an altitude of 10 m. It is suggested that a low-speed VAWT wind turbine be applied at the airport location. The excess electricity may be transmitted to the grid to supply the nearby area and be self-sufficient. The results obtained from the study are summarized in Table 9.

5. Discussions, limitations and challenges

This study examined the feasibility of implementing solar and wind farms to decarbonize the Biratnagar airport in Nepal. Our analysis of the airport's current energy consumption showed that renewable Energy could be viable to meet its energy needs. The techno-economic-environmental benefits of the solar and wind farms were discussed, and recommendations for their adoption were provided.

While our study did not cover the technical aspects of the installation and operation of the solar and wind farm, it is worth noting that small-scale, low-speed wind turbines can be an attractive option for

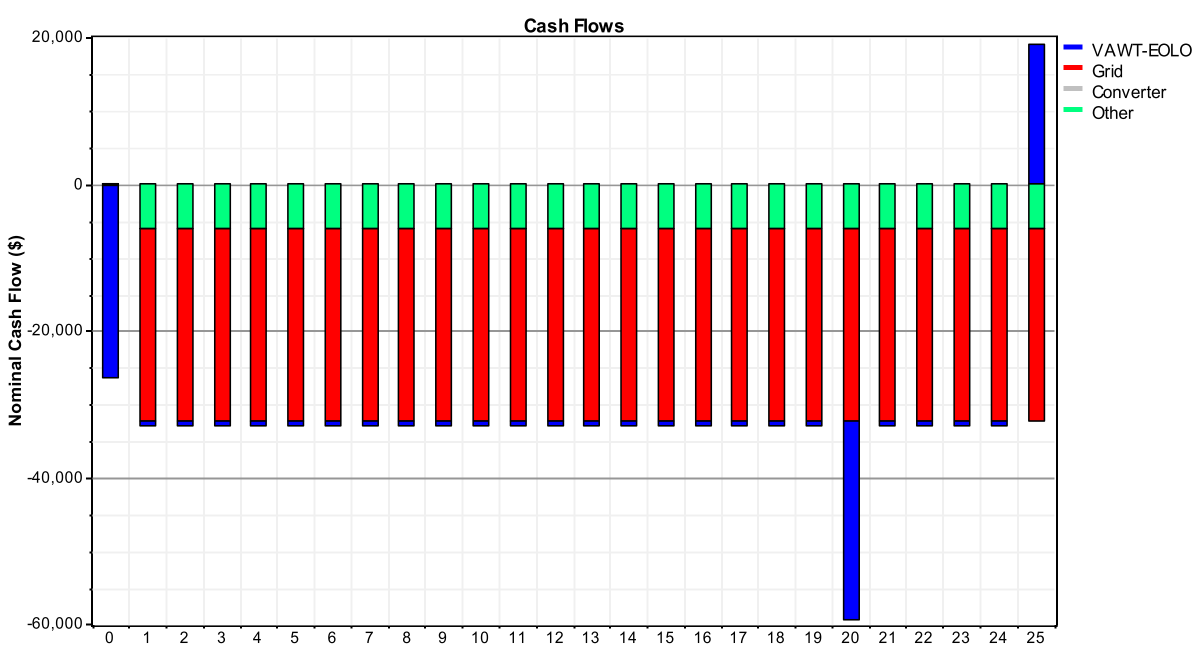


Fig. 15. Cash flows diagram for wind turbine-grid scenario.

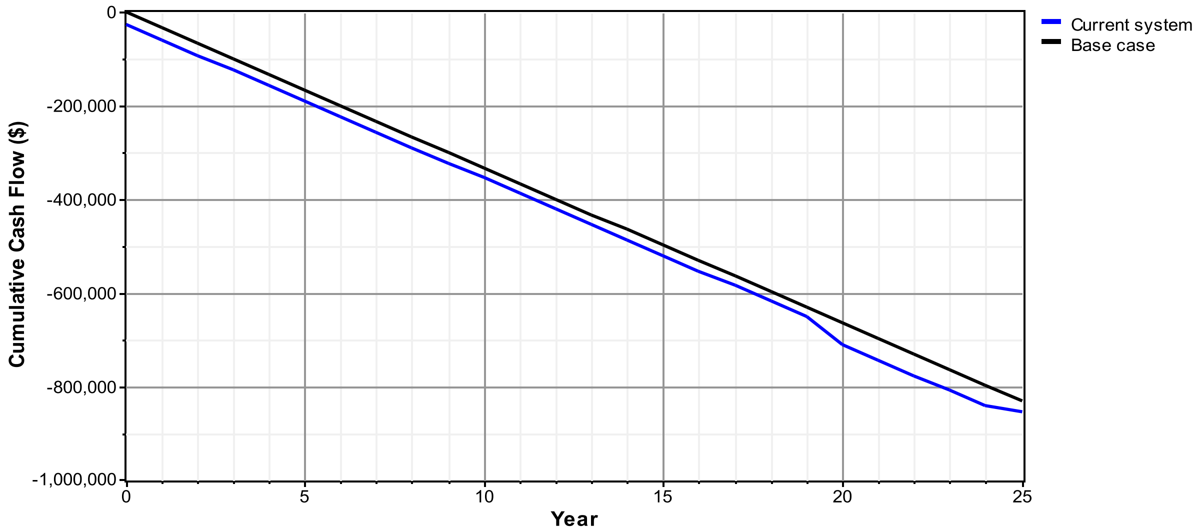


Fig. 16. Cumulative cash flow for grid scenario and wind turbine plus grid scenario .

Table 8
System Lifecycle emissions.

S.N.	Item	Modules	Supports
1.	LCE	1713 kg CO_2/kWp	0.02 kg CO_2/kg
2.	Quality	157 kWp	5320
3.	Sub-Total (kg CO_2)	268,794	106

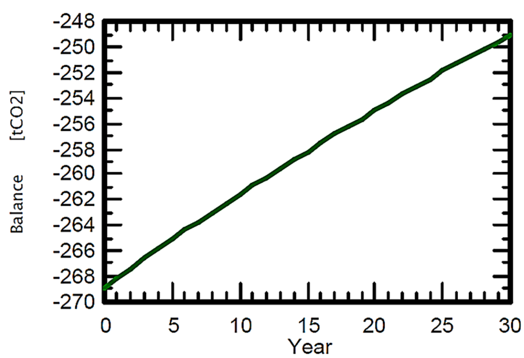


Fig. 17. Life cycle CO_2 reduction.

decentralized power generation. These turbines operate at lower wind speeds, typically between 3 and 5 m/s, making them suitable for locations where wind resources are not very strong. The advantage of low-speed turbines is that they capture wind energy in areas often overlooked by more giant wind turbines. However, the prospects of small-scale, low-speed wind turbines operating at 3 m/s depend on several factors, such as the design and efficiency of the turbine, wind resource availability, cost, and maintenance requirements. It is essential to carefully evaluate the available options and consider each project's needs and constraints before choosing a wind energy solution.

While small-scale turbines are often cheaper to install and maintain than larger ones, they typically generate less Energy than their larger counterparts. They may not be suitable for areas with high wind speeds. Therefore, it is crucial to consider the trade-offs between cost, energy production, and project-specific requirements when choosing a wind energy solution. While small-scale, low-speed wind turbines may offer advantages in certain locations, carefully considering each project's specific needs and constraints is necessary to choose the best renewable energy solution.

6. Conclusions

The study looked into the possibility of building a solar PV and wind energy plant to meet the airport's energy needs and feed excess Energy back into the grid. The following are the significant findings from the study.

1. Throughout the year, the location at Biratnagar Airport receives a total global irradiation of 1949 kWh/m^2, illustrating the immense potential of solar installation. The airport has a vast potential for Solar Energy. A solar PV system with a capacity of 157 kWp can meet Biratnagar Airport's energy consumption. The simulation results show that the designed solar PV system can generate 255.6 MWh of sufficient annual Energy.
2. The PV plant's performance ratio is expected to be around 81.1 percent, with a specific production (Yield Factor) of 1626 kWh/kWp/year. Battery storage should be included to provide a few hours of power backup, increasing reliability in the absence of solar power and grid failure. The significant loss seen in the system is due to temperature (13.08 %). It is possible to reduce it by using advanced cooling techniques.
3. Although Biratnagar Airport has moderate wind potential, with an average annual wind speed of 3 m/s, its potential for wind energy is considered low. However, due to the recent advancements in low-speed wind turbines, it is feasible to consider installing them at the site. The airport can increase its energy production by utilizing low-speed wind turbines, even with its relatively low wind potential.
4. According to the HOMER simulation results, using wind turbines (specifically EOLO and TSWT) to supply some of the airport's required electricity is cost-effective when wind speeds are above nine m/s, and annual interest rates are less than 10 %. This suggests that wind energy can be a viable solution for the airport if the appropriate conditions are met.
5. It was observed that there is a minimal difference in cost, considering the wind turbine-grid system (5 EOLO wind turbines and a 200-kW electric converter). The COE of the wind turbine-grid system is about 5.2 % more than the national grid electricity.
6. Solar PV power plant installation at the airport would be profitable considering the various 3E analyses, such as the energy, economic, and environmental aspects. The energy generated by the airport can offset the airport's CO_2, CO, and other crucial greenhouse emissions.

In conclusion, our study has demonstrated the feasibility of implementing solar and wind farms to decarbonize the Biratnagar airport in

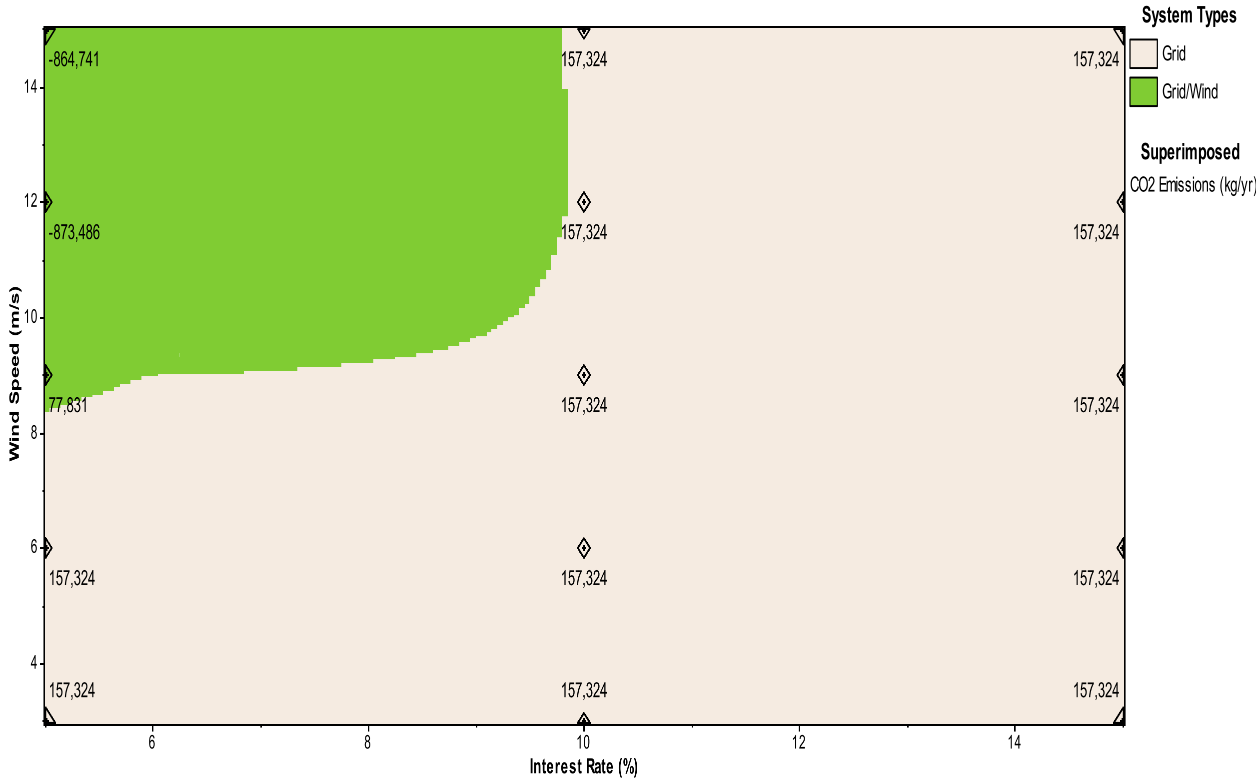


Fig. 18. Grid and Grind/Wind scenario of CO_2 mitigation.

Table 9
Summary of the energy, economic and environmental parameters obtained from the study.

S. No.	Parameters	Solar farm	Wind farm	Remarks
1.	Capacity of the plant	157 kWp	15 kW,58.5 kW,585 kW	Three-capacity wind turbines are used for the optimization
2.	Energy (Annual energy output)	255.1 MWh	23 MWh to 1631 MWh	9 % –62 % of the power can be met through the wind
3.	Economic indicator	5.9 years payback	COE of 0.134 $/kWh	The cost of electricity generation is used for wind power
4.	Environmental (CO_2 mitigation)	268.90 tonnes	77,831 kg/year	N/A

Nepal. This study contributes to the growing body of research on greener airports in Nepal and provides valuable insights for policymakers and researchers seeking to promote sustainable energy development. The above findings will increase confidence among various stakeholders, including airport authorities. Further study is needed to determine the optimal small-scale low-speed wind turbine capacity and the effect of wind turbulence on the wind turbine. The safety aspects of Installing solar and wind plants within the airport premises must be studied in detail. The impact of connecting the solar and wind power systems to the local grid at the airport has to be identified.

CRediT authorship contribution statement

Bharosh Kumar Yadav: Writing – original draft. **Ramhit Yadav:** Funding acquisition, Formal analysis, Data curation. **Mehdi Jahangiri:** Visualization, Validation, Methodology, Investigation. **S. Shanmuga Priya:** Visualization, Supervision, Methodology. **Tri Ratna Bajracharya:** Methodology, Investigation, Funding acquisition, Formal analysis. **K. Sudhakar:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The opinions/ views/ discussions in the manuscript are sole of the authors and do not necessarily reflect the opinion of any organization involved directly or indirectly. This article's assumptions and case studies are only examples based on minimal open-source information. The authors are not responsible for any consequences thereof with the use of information presented in work.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.prime.2024.100583.

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Bharosh Kr. Yadav is an academician (Assistant Professor) at the Purwanchal Campus of the Department of Mechanical Engineering, Institute of Engineering (IOE), Tribhuvan University (TU), Nepal. He was previously the deputy head of the department. From 2009 to 2013, he completed his studies as an aeronautical engineer at Northwestern Polytechnical University, located in Shaanxi Province P.R., Xi`an City, China. He received his MSc in Specialty Solid Mechanics from the Department of Aircraft Structural Engineering at the School of Aeronautics in 2017. Assist. Prof. Yadav works full-time at IOE, TU, where he teaches BE core subjects including Strength of Material, Mechanics of Solid, Turbo-Machines (Jet Engine), Basic Aircraft & Airframe, Aircraft Avionics, Aircraft Dynamics, and Material Science under the Department of Mechanical and Aerospace Engineering. Awarded certificate in recognition of the review manuscript from various SCI journals (Elsevier) as well as reputed Scopus journals. "Recent Assessment of Optimal Regional Renewable Energy-Based Systems" is the title of his Special Issue (SI) on SciencePG (Science Publishing Group) as Lead Guest Editor. His-current primary research areas include technologies for sustainable development, Energy modeling, Performance evaluation of clean energy projects, and sustainability.