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Techno-economic feasibility analyses of grid- connected solar photovoltaic power plants for small scale industries of Punjab, Pakistan

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The globally soaring energy prices and electricity shortfall are major hurdles in the economic development of Pakistan. To cope with periodic power outages, small and medium enterprise (SME) business owners have to fall back on alternate power sources such as backup generators and uninterruptible power supplies (UPS), which further increase the per kWh cost of electricity, power quality issues, and greenhouse gas (GHG) emissions. On the contrary, grid-tied solar photovoltaic (PV) systems are not only economical and sustainable but support the national power grid to mitigate environmental emissions. This study aims to investigate and compare the techno-economic viability of grid-connected solar photovoltaic power plants for the manufacturing SME sector in four different districts of Punjab, Pakistan. Based on the technical, financial, and environmental indicators, a detailed techno-economic, sensitivity, and GHG emission analysis is conducted using RETScreen Expert software. The research findings clearly show that the proposed solar PV projects for all four locations are technically, financially, and environmentally viable, however, Sargodha as compared to other sites is the most feasible location with the highest capacity factor of 17.8 %, highest internal rate of return 14.9 %, lowest payback period 7.7 years, and least levelized cost of electricity 8.5 ¢/kWh. For validation, the simulation results are compared with performance metrics from PV plants erected in various parts of the world. Applying the same research approach to the whole industrial sector of Punjab recommends adding 13,469 MW of PV capacity to satisfy the industry's 20446.21 GWh annual energy consumption and to cut emissions by 90,17,581 t CO_2 per year. This research work presents guidelines for researchers to evaluate the feasibility of suitable PV technologies for the SME sector thereby helping investors to have a holistic view of potential investment zones.

KEYWORDS

small and medium enterprise (SME), greenhouse gas (CH4), techno-economic analysis, solar photovoltaic, grid-connected PV system

1 Introduction

In the current era of globalization, electricity generation, per capita electricity consumption, and energy footprint of a country are considered indicators to assess the development, economy, industrial growth, exports, and living standards of its inhabitants (Arto et al., 2016; Khan et al., 2020). According to the "World Bank Database of Sustainable Energy for All" (1998–2019), only 73.914 % population in Pakistan has access to electricity (THE WORLD BANK, 2022). This number is the lowest among all other South Asian countries including Maldives, Sri Lanka, Bhutan, India, Afghanistan, Bangladesh, and Nepal as shown in Figure 1. This situation intimates a lack of a holistic approach to power sector expansion planning and implementation to ensure reliable and indiscriminate access to electricity amid growing energy demands. To meet growing energy needs Pakistan heavily relies on carbon-intensive fossil fuels as its primary source of energy (Babar et al., 2021). As of May 2021, thermal power plants in Pakistan constituted 66 % of the total installed generation capacity, the hydel share was 29 %, and variable renewable energy sources such as bagasse, wind, and solar collectively accounted only for 5 % of total power generation mix as shown in Figure 2 (National Electric Power Regulatory Authority (NEPRA), 2022).

About 47 % of electricity generation assets in the country are dependent on imported fossil fuels which is why Pakistan has to import one-third of its energy resources to accomplish a balance between power generation and demand (National Electric Power Regulatory Authority (NEPRA), 2022). Back in the year 2017–2018 Pakistan's net energy imports were USD 14.4 billion compared to USD 10.9 billion in the preceding year. Out of this recorded USD 3.5 billion increase, only 25 % was due to increased energy imports while the rest of 75 % was reported due to inflated energy prices (Malik et al., 2020). The prices of these fuels keep on fluctuating in the international market and cause the per unit electricity generation cost to increase (Yasmeen et al., 2019). This increment in turn reflects in electricity bills as a fuel price adjustment. The fuel price volatility and an increased risk of energy insecurity have not only put socio-economic sustainability at stake but also made Pakistan vulnerable to global and regional geopolitics (National Electric Power Regulatory Authority (NEPRA), 2022; Nawaz and Alvi, 2018). In terms of energy security, the "World Energy Council" has ranked Pakistan 83 among 101 countries for the year 2021 (WORLD ENERGY COUNCIL, 2022).

The troubling situation of economy, energy insecurity, and stochastic fuel price volatility are posing a serious threat to the survival of the manufacturing industry in the country especially when it comes to small and medium enterprises (SMEs), already struggling with limited resources and technical expertise to compete with local and international markets (Small and Medium Enterprises Development Authority (SMEDA), 2021a).

SMEs play a key role in the socio-economic and industrial uplift of a country. Particularly in Pakistan, being a developing economy, the role of SMEs cannot be overemphasized. Pakistan is known to have 3.2 million SME units which account for about 90 % of all enterprises operating in the country, takes into employment about 78 % of the non-agriculture labor force, has a 30 % share in the export sector and approximately 40 % share in annual GDP of the country (Ali et al., 2020; Arshad et al., 2020). Punjab with a population of 110 million is the most populous province of Pakistan (Quick Stats, 2021). It is an industrial hub of the country and houses about 65.26 % of SME units making it the biggest consumer of electricity. In the meantime, SMEs in the said province suffer from several constraints such as the risk of investment loss due to high uncertainty, limited financial and intellectual resources, and above all seasonal power crises leading to recurrent and extended power outages (Arshad et al., 2020; Qazi et al., 2020). Among these constraints load shedding is the most critical one as it disrupts the production process by making equipment go offline leading to spoilage of raw material, idle time labor wages, delayed fulfillment of customer orders and opportunity loss, etc. (Bukhari Institute of Public Policy (BIPP), 2021).

According to "National Transmission and Dispatch Company" (NTDC) in the year 2021, 24,106 MW of electricity demand was recorded in Pakistan whereas, the installed generation capacity was reported to be 34,100 MW. Despite a 9994 MW gap between installed capacity and load demand, the country observed hours-long load shedding on daily basis to manage 2500–3000 MW of load demand. "National Electric Power Regulatory Authority" (NEPRA) investigation disclosed the core reason of load shedding was underutilization of RLNG power plants due to unavailability of fuel, poor governance, and weak transmission and distribution network (National Electric Power Regulatory Authority (NEPRA), 2021a). These power cuts caused permanent cessation of several SMEs while left many other ailing (Qazi et al., 2020).

Thus, to ensure a consistent supply of electricity at the SME end, the SME business owners usually switch to alternate sources of electricity such as UPS and backup generators, etc. No doubt UPS serves the purpose for the time being but in a long run, it is believed to be a major source of harmonics and consequently line losses in the power distribution network (Ahmad et al., 2016; Arshad and Ali, 2017). Whereas backup generators are noisy and pollution pervasive, run-on fossil fuels, and are again subjected to

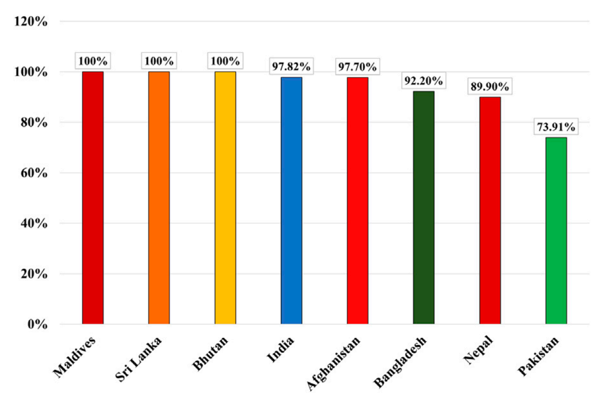

FIGURE 1
Population having access to electricity in South Asia (THE WORLD BANK, 2022).

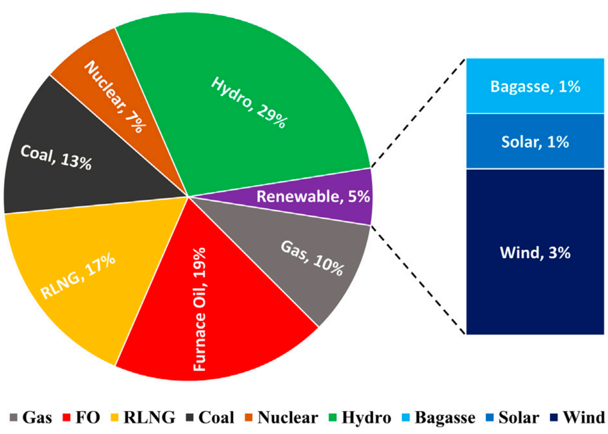

FIGURE 2
Percent share of installed generation capacity in Pakistan (National Electric Power Regulatory Authority (NEPRA), 2022).

the same constraint of fuel price volatility. As reported by "Institute for Energy Economics and Financial Analysis", after hydroelectric power solar and wind are the cheapest renewable energy sources in Pakistan (Ahmed et al., 2021). Hence, to indigenize the generation mix and to ensure energy security, the techno-economic feasibility study of other sustainable energy resources must have to be explored.

Several literature studies highlight energy crises as a major and common issue faced by SMEs in Punjab and other provinces of Pakistan. However, to the best knowledge of authors not even a single case study was found that discusses in detail a sustainable solution to help SMEs tackle the problem of energy crises considering their actual energy needs. Therefore, to fill this research gap this paper undertakes case studies of four export-oriented SME businesses dealing in marble processing, commercial textile embroidery, rock salt products, and plastic products manufacturing. The clusters of said SMEs are located in Multan, Lahore, Sargodha, and Rawalpindi respectively (Small and Medium Enterprises Development Authority (SMEDA), 2021b; Small and Medium Enterprises Development Authority (SMEDA), 2022a; Small and Medium Enterprises Development Authority (SMEDA), 2022b; Small and Medium Enterprises Development Authority (SMEDA), 2022c). The geographical locations of these districts are indicated in Figure 3 and coordinate details are given in Table 1.

The main objective of this study is to assess the techno-economic feasibility of grid-connected PV systems for these four SME sectors at their respective clusters. The core focus is on solar PV technology as it is not only time-tested and mature but is clean, sustainable, and scalable too. RETScreen Expert - Professional—8.1.2.13 software is used to perform techno-economic feasibility and performance evaluation analysis. Also, a detailed emission analysis is performed to estimate the GHG mitigation potential of each project site under study. The results of this research are equally important for other developing economies in the region facing similar challenges of energy crises.

2 Methodology

2.1 Literature review

The techno-economic feasibility studies of grid-connected solar PV plants at different locations in the world have been investigated in the recent past. Khalid et al. (2013) investigated the economic viability of a 10 MW solar PV plant at Quetta, Pakistan using RETScreen software. For single-axis tracking mode, the electricity production cost of 0.157 USD/kWh and net present value of USD -14.9 million were calculated (Khalid and Junaidi, 2013). Obeng et al. (2019) evaluated the techno-economic feasibility of a 50 MW PV system for monocrystalline, polycrystalline, and thin-film PV technologies at the UENR campus in Nsoatre. The findings revealed that the electricity generation costs 10.9 to 12.4 ¢/kWh and the payback period ranges between 6.4 and 7.2 years (Obeng et al., 2020). The authors analyzed the performance of the 15 MW grid-tied PV plant at the University of Jordon. The analysis results indicated an annual specific yield of 1668 kWh/kWp and a payback period of about 3 years for a fixed axis PV system (Ayadi et al., 2018). The researchers carried out a techno-economic analysis of a 2.5 MW on-grid PV plant for a garment zone in Jaipur, India. The results manifested an electricity generation cost of 0.228 USD/kWh, a payback of 6.29 years, and a net present

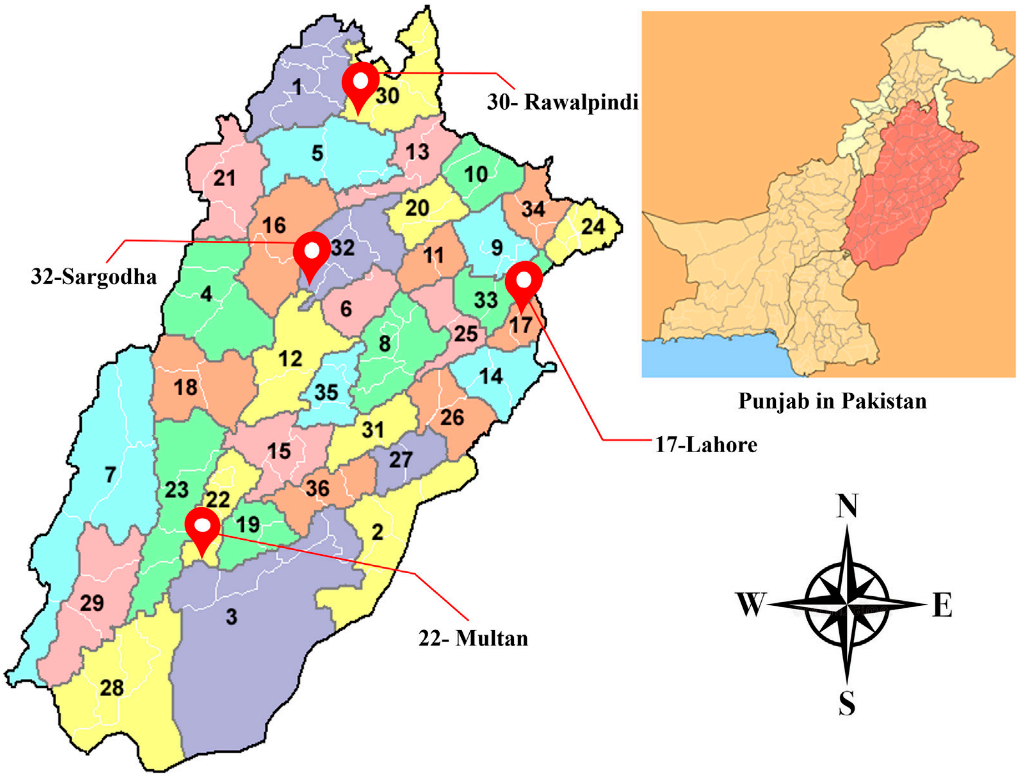

FIGURE 3
Geographical locations of selected SME clusters in Punjab, Pakistan.

TABLE 1 Coordinate details of selected locations.

Location	Latitude	Longitude	Altitude (m)
Multan	30° 12′ N	71° 25′ E	124
Lahore	31° 34′ N	74° 16′ E	207
Sargodha	32° 16′ N	72° 54′ E	190
Rawalpindi	33° 40′ N	73° 3′ E	519

value of USD 4.99 million for an off-site power plant (Chandel et al., 2014).

The author explored the techno-economic potential of a 5 MW grid-connected PV plant at 35 locations in Ethiopia using HOMER and RETScreen software. The findings revealed an annual average yield of 8674 MWh and an average capacity factor of 19.8 % for all locations (Kebede, 2015). The 29 potential sites in Egypt were subjected to techno-economic feasibility analysis for the placement of a 10 MW grid-tied PV plant using RETScreen software. The results confirmed maximum annual energy yield and capacity factor values of 29.493 GWh and 33.7 % respectively for the Wahat Kharga site (EL-Shimy, 2009). The six states in Nigeria were subjected to a detailed techno-economic feasibility assessment of installing a 6 MW grid-connected PV plant. Among selected sites, Yobe state was found to have the highest per annum life cycle savings of 205,928 USD, an energy production cost of 0.128 USD/kWh, and the least payback period of 13.6 years (Owolabi et al., 2019).

Abas et al. (2022) investigated the techno-economic feasibility of installing 100 MW grid-tied solar PV plant in Pakistan. The results revealed 180 GWh of annual energy yield, 11.89 years SPBP, and 90,225 t CO_2 mitigation per annum (Abas et al., 2022). Nkuriyingoma et al. (2022) explored the techno-economic viability of grid-tied PV system supported with battery storage for 100 households in Rwanda. The proposed system was able to achieve direct power consumption and self-sufficiency marks of 68.65 % and 64.38 % respectively, for an annual energy demand of 82.34 MWh and peak load of 30.4 kW (Nkuriyingoma et al., 2022). Bukar et al. (2020) investigated the optimal sizing of PV and energy storage system to be integrated with diesel generators installed in ship to minimize fuel cost and CO_2 emissions (Bukar et al., 2020). Bukar et al. (2017) evaluated economic viability of hybrid energy system consisting of PV, diesel, and battery storage system for remote rural site in Nigeria (Bukar et al., 2017). Isa et al. (2019)

optimized cogeneration of fuel cell and PV with battery storage system using hybrid particle swarm optimization and genetic algorithm with objective function taken as life cycle cost to be minimized to meet load demand (Isa et al., 2019).

The authors investigated the energy efficiency of a Turkish sugar factory. The annual energy demand for this sugar factory was optimized to be 43,590.25 tons of oil equivalent (toe) whereas, the per unit energy cost was calculated 688.22 USD/toe (Taner et al., 2018). (Taner, 2015) improved the energy-efficient procedures for a drying facility (Taner, 2015a), (Taner and Sivrioglu, 2015). The authors evaluated the techno-economic feasibility of turbine power plant by developing a sugar production process model for a sugar production plant. The results suggested unit cost of 0.87 USD/kWh and payback period of 4.32 years (Taner and Sivrioglu, 2017). (Taner, 2018) performed experimental optimization for proton exchange fuel cell with core aim to improve performance efficiency. The research findings revealed exergy and energy efficiencies of 50.4 % and 47.6 % respectively (Taner, 2018). The performance efficiency of PEM fuel cell could be improved by adjusting parameters such as pressure, voltage, flow rate and cleaning process (Taner, 2017). The PEM fuel cell has certain advantages such as low operating temperature, high power density, alternative catalysts, water and heat management etc. (Taner, 2015b; Taner et al., 2019). However, it has several disadvantages as well including degradation, gas diffusion and flow field layers, catalyst problems etc. (Taner, 2015b; Taner et al., 2019). The techno-economic analysis revealed that the cost of PEM fuel cell with higher power density decreases however, the initial capital investment stays high (Taner, 2019).

2.2 Case study

To evaluate the techno-economic viability of energy transition in the SME sector, four export-oriented SME clusters were identified and surveyed in far-flung districts of Punjab to incorporate the effect of climate diversity into research findings. Based on the survey, an SME in each cluster was designated as a representative SME. Grid-tied solar PV systems were designed considering the actual load profile of all four representatives SMEs. RETScreen energy management tool was used to model designed PV systems. Finally, techno-economic, sensitivity, and GHG emission reduction analyses were carried out for all project sites.

Figure 4 illustrates the six-step methodology flowchart. These steps are: 1) Literature review 2) Case study 3) Data collection 4) Simulation 5) Analysis and comparison 6) validation of results.

2.3 Data collection

The very first step involved in the design and feasibility assessment of a PV system is to determine the energy requirements of the facility. One way to establish energy demand is to perform an energy audit of the facility site and list down continuous power ratings of all loads that are supposed to be run on the PV system. Multiplying the nameplate power rating (in watt) of each load with its daily time of use (in hours) yields the daily energy demand of the facility in Watt-hour (Wh). Whereas the more realistic and practical approach followed by solar PV system installers to estimate the energy requirements of a facility is to make use of per month/year energy consumption data available on utility bills. Therefore, to obtain actual energy consumption data of selected SME sectors a questionnaire was designed. The principal purpose of this questionnaire was to document the monthly energy consumption of selected SMEs for the past 12 months.

Further, to have better industry insight and to broaden the scope of study other fields such as the number of employees, seasonality constraints, working hours, and product range were also included in the questionnaire. Ten SMEs were chosen for this survey in each SME cluster. The business owners of selected SMEs were then approached in this regard and those who gave positive responses were then interviewed. After conducting surveys data was compiled and statistically analyzed. Based on the analysis of survey data, one SME in each cluster that best suited the applied methodology was chosen as a representative SME. All four representative SMEs were then considered for PV system design at their respective clusters. Table 2 and Figure 5 show the monthly electricity consumption statistics of each representative SME.

2.4 Climate data of facility locations understudy

To establish reference climate conditions for each facility location, RETScreen derives meteorological data either from the global satellite database of the National Aeronautics and Space Administration (NASA) or nearby ground-based weather monitoring stations or both (Sreenath et al., 2021; Owolabi et al., 2019). Climate data from local ground-based weather monitoring stations are preferred over satellite data from NASA due to its lower uncertainty. The monthly average climate data of selected facility locations are listed in Table 3. District Sargodha has the highest monthly average solar radiation of 5.62 $kWh/m^2/d$ followed by Multan and Lahore with 5.54 $kWh/m^2/d$ and 5.09 $kWh/m^2/d$ respectively. Rawalpindi has the least value of 4.39 $kWh/m^2/d$. Also, the monthly variance of average daily solar irradiation and ambient air temperature of chosen facility locations is shown in Figure 6, Figure 7 respectively. The daily average solar irradiation magnitudes range from 4.43 $kWh/m^2/d$ (December) to 6.08 $kWh/m^2/d$ (April) in Multan, 3.77 $kWh/m^2/d$ (January) to 5.95 $kWh/m^2/d$ (May) in Lahore, 4.67 $kWh/m^2/d$ (December) to 6.61 $kWh/m^2/d$ (May) in Sargodha, and 2.84 $kWh/m^2/d$ (January) to 5.45 $kWh/m^2/d$ (October) in Rawalpindi.

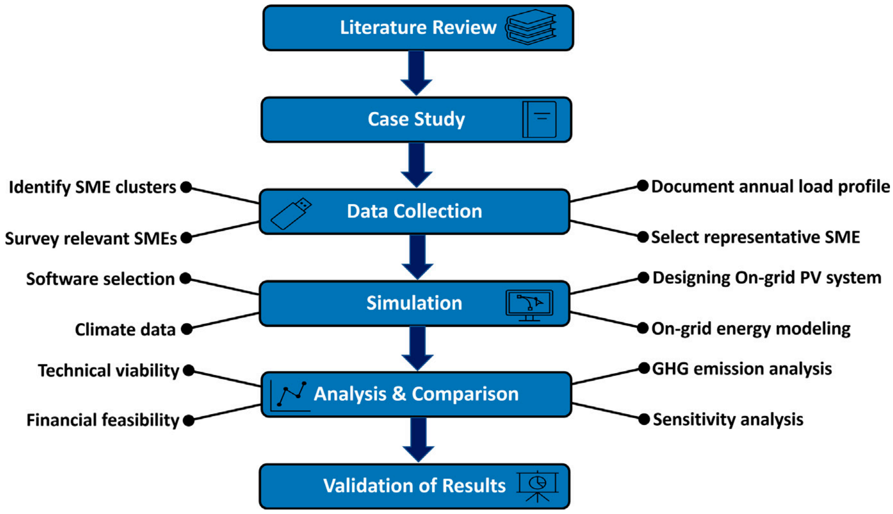

FIGURE 4
Research methodology flowchart.

TABLE 2 Twelve-months energy consumption data of representative SMEs.

Month	Marble processing (kWh)	Textile embroidery (kWh)	Rock salt products (kWh)	Plastic molding (kWh)
January	970	897	1979	1122
February	1207	1113	3533	2362
March	1200	2643	4004	1768
April	1273	1434	1492	1347
May	805	6285	2486	1479
June	965	3413	668	1736
July	1149	248	5322	1726
August	833	4951	3257	0
September	1406	2253	5385	0
October	943	1294	1331	2778
November	1965	1688	1176	4098
December	1150	3151	1989	2023

The ambient air temperature of a facility location has a significant effect on the efficiency of PV modules and therefore plays a key role in the performance evaluation of PV systems (Ahmed et al., 2021). The minimum and maximum values of ambient air temperature are 12.7°C, 12.8°C, 12.2°C, and 10°C (in January) and 35.5°C, 33.9°C, 37.2°C, and 31.3°C (in June) for Multan, Lahore, Sargodha, and Rawalpindi respectively. Figure 8 shows the variation of the monthly average wind speed of sites under study. Multan shows the highest monthly average wind speed of 4.0 m/s followed by Rawalpindi, Lahore, and Sargodha having average wind speeds of 3.8 m/s, 3.1 m/s, and 2.7 m/s respectively.

2.5 Simulation tool

RETScreen is an Excel-based clean energy management platform developed by "Canmet Energy Research Center" and "Natural Resources Canada" (Khalid and Junaidi, 2013). This study uses an updated version of this software called RETScreen Expert 8.1. It is a validated simulation tool and is widely used for its outstanding ability to perform a preliminary assessment of renewable energy projects with an accuracy of 0–6% of actual energy yields (Khalid and Junaidi, 2013). It contains several worksheets required to perform a comprehensive project analysis. It is easy to use

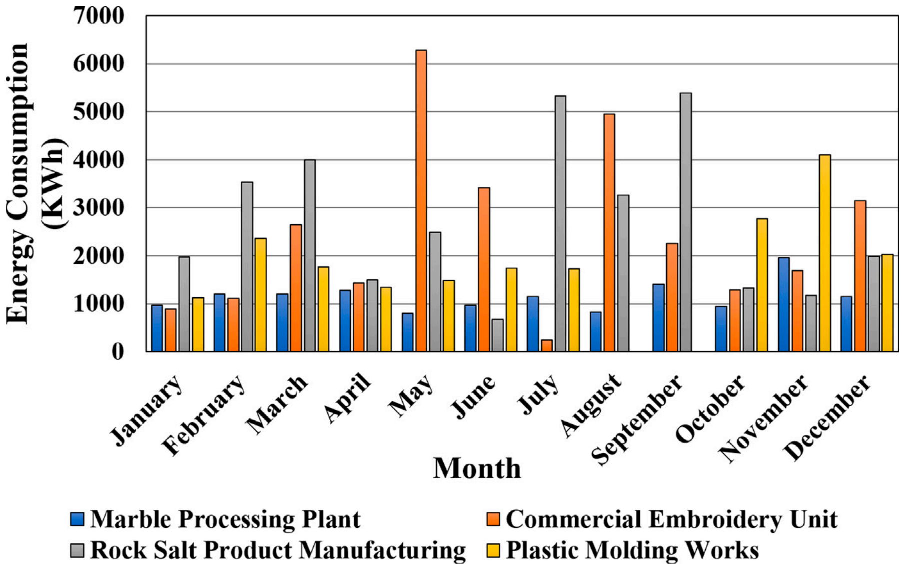

FIGURE 5
Monthly averaged electricity consumption of representative SMEs.

TABLE 3 Monthly average climate data of selected facility locations.

Location	Multan	Lahore	Sargodha	Rawalpindi
Air temperature (°C)	25.30	24.40	25.60	21.60
Relative humidity (%)	27.50	61.60	34.10	62.00
Precipitation (mm)	173.73	551.78	416.95	775.19
Solar irradiation (kWh/m²/day)	5.54	5.09	5.62	4.39
Atmospheric pressure (kPa)	99.40	98.40	97.60	91.10
Wind speed (m/s)	2.90	2.10	2.40	2.40
Earth temperature (°C)	28.30	25.80	25.90	20.10
Climate Zone	1B- Very Hot—Dry	1B- Very Hot—Dry	1B- Very Hot—Dry	2A- Hot—Humid

Climate zones in the above table are defined as per ASHRAE, standard 169:2013.

and is also available free of cost in viewer mode (Sreenath et al., 2021).

The following steps describe a systematic simulation approach to establish the techno-economic feasibility of a grid-connected photovoltaic power system.

- Select the location of the proposed facility site.
- Provide technical details e.g., tilt and azimuth angle, PV technology and module rating, Inverter rating and losses, etc.
- Enter values required for economic analysis of PV project e.g., initial cost, operation, and maintenance (O&M) cost, electricity export rate, interest and discount rate, etc.
- Input the values required for environmental analysis e.g., base case energy mix and T&D losses, etc.
- Perform energy, cost, emission, financial and risk analysis.

Figure 9 shows the flowchart for a better understanding of the simulation approach adopted in this study.

2.6 Design of grid-tied solar PV system

The grid-tied PV system (Figure 10) modeling in RETScreen requires the user to specify the power capacity of the PV system and inverter in its energy modeling worksheet. Therefore, to calculate the PV power capacity, the number of solar panels, the rated power capacity of inverters and batteries, this section discusses in detail the design methodology and technical

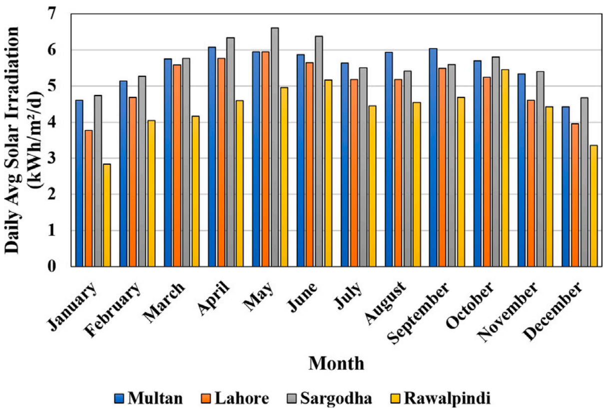

FIGURE 6
Monthly variance of average daily solar irradiation.

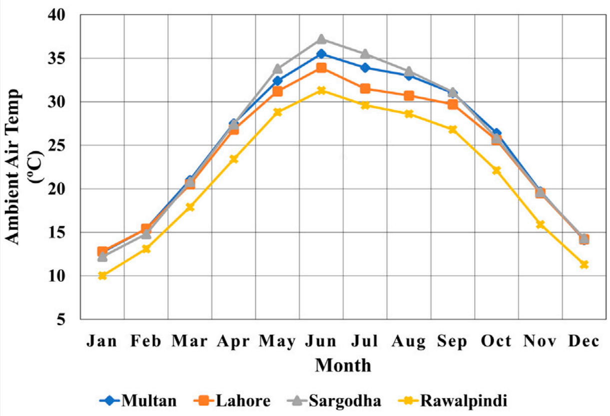

FIGURE 7
Monthly variance of ambient air temperature.

specifications of proposed grid-tied solar PV systems considering the actual load profile data of selected SMEs.

2.6.1 Panel generation factor

The panel generation factor (PGF) is regarded as an essential parameter in the calculation of the total watt peak rating of PV modules (Chandel et al., 2014). PGF is a function of solar irradiance which is site-specific. Hence, PGF varies from site to site (Ikoiwak et al., 2021).

$$\text{PGF} = \frac{\text{Daily solar radiation at project site}}{\text{Standard test conditions irradiance}} \tag{1}$$

The PGF values for Multan, Lahore, Sargodha, and Rawalpindi are calculated as 5.54, 5.09, 5.62, and 4.39 respectively using solar irradiance values given in Table 3.

2.6.2 Energy needed from PV panels

The energy required from the PV system is calculated by multiplying the peak energy demand of the concerned facility in kWh/day times the safety factor of 1.3 (Owolabi et al., 2019; Chandel et al., 2014; Ikoiwak et al., 2021). The safety factor compensates for the energy losses associated with the PV system by incrementing the installed PV system capacity by 30 %.

$$E_{PV} = E_{Peak} \bullet 1.3 \tag{2}$$

Where:

E_{PV} is the energy required from PV modules and E_{Peak} is the peak energy demand of the facility. As shown in Figure 5 peak energy demands of marble processing, commercial textile embroidery, rock salt products, and plastic products manufacturing SMEs are 1965 kWh/month (65.5 kWh/day), 6285 kWh/month (209.5 kWh/day), 5385 kWh/month (179.5 kWh/day), and 4098 kWh/month (136.6 kWh/day) therefore energy needed from PV modules comes out to be 85.15 kWh/day, 272.35 kWh/day, 233.35 kWh/day, and 177.58 kWh/day respectively.

2.6.3 Watt peak rating of PV modules

Watt peak capacity of PV modules is used to determine the number of PV modules required to meet the energy demand of each SME. The ratio of E_{PV} to PGF yields total watt peak rating of PV modules as follows:

$$W_{T,Peak} = \frac{E_{PV}}{PGF} \tag{3}$$

Where, $W_{T,Peak}$ is the total watt peak rating of PV modules and for each representative SME it is calculated by inserting the values of E_{PV} and PGF in Eq. 3. Hence, $W_{T,Peak}$ values obtained for marble processing, commercial textile embroidery, rock salt

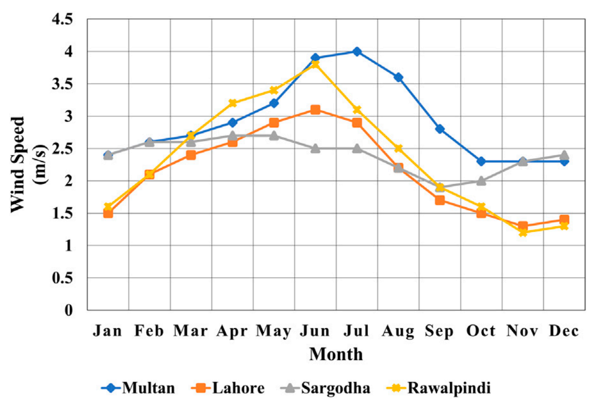

FIGURE 8
Monthly average wind speeds.

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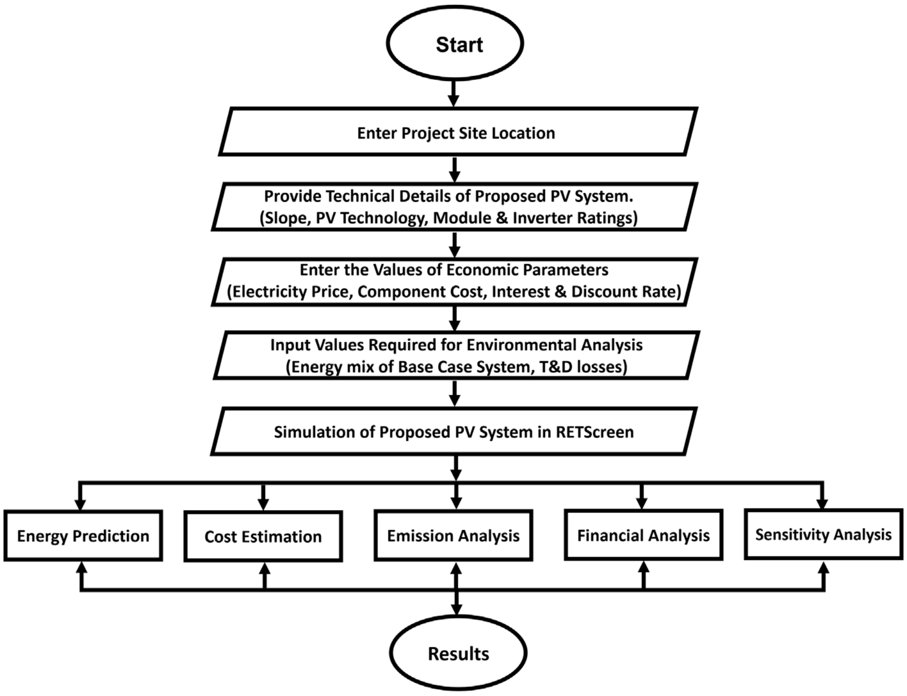

FIGURE 9
RETScreen simulation flowchart.

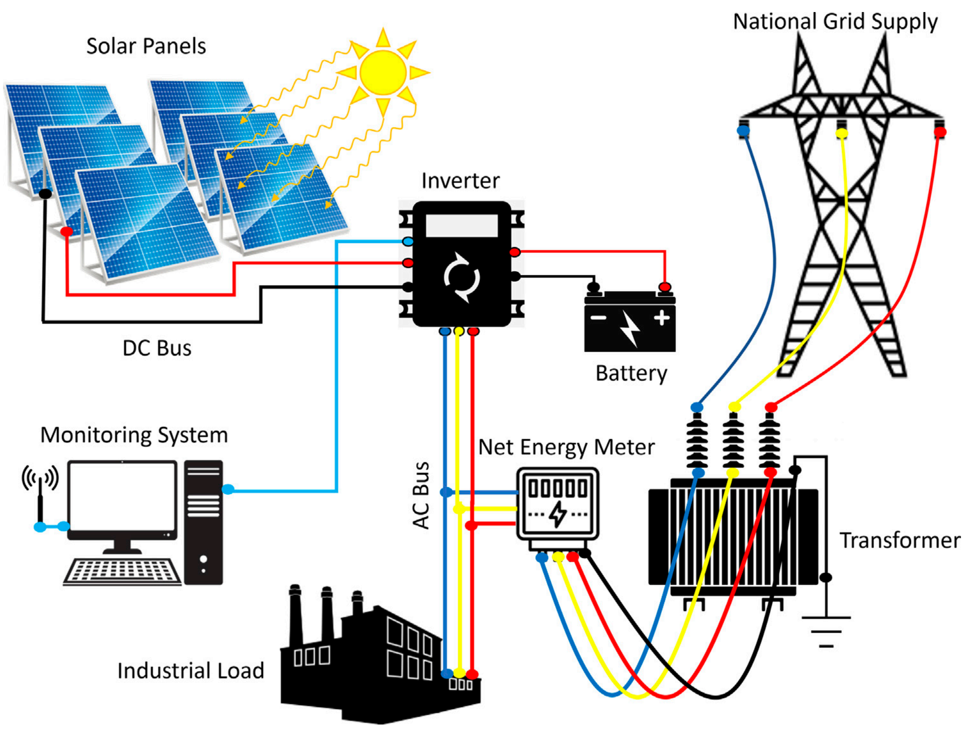

FIGURE 10
Schematic diagram of a grid-connected solar PV system.

TABLE 4 Electrical characteristics of CS6X-310P-MaxPower PV module.

Parameter	Unit	Value
Nominal Power (Pmax)	W	310
Power Tolerance	W	0 ~ + 5
Module Efficiency	%	16.16
Operating Voltage (Vmpp)	V	36.4
Operating Current (Impp)	A	8.52
Open-Circuit Voltage (Voc)	V	44.9
Short-Circuit Current (Isc)	A	9.08
Max. System Voltage (Vdc)	V	1000
Maximum Series Fuse	A	15.00
Power Temp Coefficient (Pmax)	%/°C	-0.43
Voltage Temp Coefficient (Voc)	%V/°C	-0.34
Current Temp Coefficient (Isc)	%A/°C	0.065
Nominal Operating Cell Temperature	°C	45 ± 2

products, and plastic products manufacturing SMEs are 15.37 kW, 53.51 kW, 41.52 kW, and 40.45 kW respectively.

2.6.4 PV module selection

CS6X-310P-MaxPower modules were considered for all four project sites. Each module has a rated peak power output of 310 W and average panel efficiency as high as 16.16 %. The ability of this module to sustain extreme weather conditions, no light-triggered degradation, and high efficiency even at elevated temperatures make it an ideal choice for selected locations. The electrical characteristics of the polycrystalline CS6X-310P-MaxPower PV module are summarized in Table 4 (CanadianSolar, 2022b).

2.6.5 Number of PV modules

Finally, the ratio of total watt peak rating to the rated maximum power output of the selected PV panel gives the number of PV modules required to meet the energy demand.

$$N_{module} = \frac{W_{T,Peak}}{P_{max}} \tag{4}$$

Where, P_{max} and N_{module} are rated peak power output of PV Panel and umber of PV panels required. Substitution of $W_{T,Peak}$ and P_{max} values in Eq. 4 return the number of modules needed to accomplish the energy requirements of each representative SME. The N_{module} values obtained for marble processing, commercial textile embroidery, rock salt products, and plastic products manufacturing SMEs are 49.58 (≈50), 172.60 (≈173), 133.93 (≈134), and 130.48 (≈130) therefore, actual rated PV system capacities are 15 kW, 53.63 kW, 41.54 kW, and 40.3 kW respectively.

2.6.6 Inverter size optimization

$$\text{ILR} = \frac{W_{T,Peak}}{P_{inv}} \tag{5}$$

Inverter Loading Ratio (ILR), also known as Optimum Sizing Ratio (OSR), is used by PV system designers as an optimization approach for solar inverter sizing. ILR is the quotient of installed DC power capacity of PV array to AC power output rating of the inverter (Zidane et al., 2021).Where, P_{inv} is the Inverter AC output power rating.

The United States "Energy Information Administration" (EIA) suggests the ILR value for an individual PV system to be somewhere between 1.13 and 1.30 (Marcy, 2021; Aurora, 2021). PV system design with an ILR value greater than unity indicates an undersized inverter. An undersized inverter is prone to a phenomenon called inverter clipping at times when DC power from an oversized PV array exceeds the inverter's output power limit causing power loss (Aurora, 2021). However, to ensure the efficient and safe operation of the PV system general principle is to select ILR unity (Ikoiwak et al., 2021). Therefore, considering the ILR value equal to unity in Eq. 5, the inverter power ratings for marble processing, commercial textile embroidery, rock salt products, and plastic products manufacturing SMEs are calculated as 15.5 kW, 53.63 kW, 41.54 kW, and 40.3 kW respectively.

2.6.7 Inverter selection

CSI-T400GL01-E inverter series is considered for all four locations due to its high degree of compatibility with selected PV modules in terms of technical specifications. The selected PV module has a 1000 Vdc rated maximum system voltage, exactly equal to the inverter's rated maximum input voltage. The selected inverters have a frequency range of 50/60 Hz and rated maximum power outputs of 12 kW, 15 kW, and 20 kW. In marble processing SME inverter operation is centralized whereas, in commercial textile embroidery, rock salt products, and plastic products manufacturing SMEs inverters function in string configuration. However, the selection of standard-sized inverter makes the actual ILR values slightly deviate from unity but still fall between a minimum of 1.01 to a maximum of 1.04, a safe range as recommended by IEA (Marcy, 2021). The technical specification data of CSI-T400GL01-E inverter are provided in Table 5 (Canadian Solar, 2022a).

2.6.8 Battery sizing

The peak energy demand of each SME is taken as reference to calculate optimal Ampere-hour (Ah) capacity of battery system using the below equation (Owolabi et al., 2019).

$$BC = \frac{E_{Peak} \bullet D}{\eta_b \bullet DoD \bullet V_{nom}} \tag{6}$$

10.3389/fenrg.2022.1028310

TABLE 5 Technical specification of CSI-T400GL01-E inverter series.

Parameter	Unit	Value
Rated AC Power Outputs	KW	12/15/20
Max. AC Output Currents	A	19.1/23.8/31.8
Rated AC Output Voltage	V	220/380, 230/400
Rated Output Frequency	Hz	50/60
Efficiency	%η	98.10
Max DC Input Voltage	VDC	1000
Start-up DC Input Voltage	VDC	180
MPPT Voltage Range	VDC	160–850
Max. Input Current (Imp)	A	22
Max. Short Circuit Current (Isc)	A	34.3

Where, D represents the days of autonomy and is taken as 0.25 to provide up to 6 hours backup during power outages. η_b is battery efficiency and is taken as 0.85 to account for battery loses (Bila et al., 2016). DoD is depth of discharge which in case of Lithium-ion battery is up to 90 % (Zubi et al., 2016). Whereas V_{nom} represents the nominal battery voltage which in this case is 12 V. Using E_{Peak} values of 65.5 kWh, 209.5 kWh, 179.5 kWh, and 136.6 kWh for marble processing, commercial textile embroidery, rock salt products, and plastic products manufacturing SMEs, Eq. 6 yields battery capacities of 1783 Ah, 5705 Ah, 4888 Ah, and 3720 Ah respectively.

3 On-grid solar photovoltaic model

The RETScreen on-grid photovoltaic energy model is briefly described in this section. The model has fewer input data requirements and speeds up the calculations by maintaining an acceptable accuracy level.

3.1 Energy delivered by PV array

The PV array is normally characterized by its efficiency η_P and in turn, the energy delivered by it E_P (Retscreen International Clean Energy Decision Support Centre (Canada), 2005).

$$E_P = S \bullet \eta_P \bullet \bar{H}_t \tag{7}$$

Where S is the area occupied by the PV array and $\bar{H}_t$ is the average hourly solar irradiance. η_P is the function of average module temperature T_c, and is given as (Evans, 1981):

$$\eta_P = \eta_r \left[1 - \beta_p (T_c - T_r)\right] \tag{8}$$

Where, η_r and β_p represent the efficiency and temperature coefficient of the PV module, T_r (=25 °C) is the reference temperature. However, T_c is the module temperature is related to the monthly average ambient temperature T_a as follows (Retscreen International Clean Energy Decision Support Centre (Canada), 2005):

$$T_c - T_a = (219 + 832\bar{K}_t)\frac{NOCT - 20}{800} \tag{9}$$

Where NOCT is nominal operating cell temperature and $\bar{K}_t$ is monthly average clearness index. β_p, η_r, and NOCT are specific to the type of PV module selected. For standard polycrystalline silicone technologies, these values are assumed as 0.40 %/°C, 11 %, and 45 °C respectively. Also, the user can enter the customized values for these parameters.

3.2 Energy available to load

The energy delivered by the PV array is attenuated by power conditioning losses λ_c and miscellaneous PV array losses λ_p. Thus, the energy available to load E_A is given as (Retscreen International Clean Energy Decision Support Centre (Canada), 2005):

$$E_A = E_p\left(1 - \lambda_p\right)(1 - \lambda_c) \tag{10}$$

Whereas the overall efficiency of the array η_A is defined as:

$$\eta_A = \frac{E_A}{S \bullet \bar{H}_t} \tag{11}$$

3.3 Energy delivered to grid

The energy available to the grid is what is generated by the PV array, attenuated by inverter losses and load Retscreen International Clean Energy Decision Support Centre (Canada), 2005):

$$E_{grid} = E_A \bullet \eta_{inv} \tag{12}$$

Where, η_{inv} is inverter efficiency. Based on the grid configuration, not all the energy available to the grid may be absorbed by it. Therefore, the actual energy delivered to the grid is as follows (Retscreen International Clean Energy Decision Support Centre (Canada), 2005):

$$E_{dlvd} = E_{grid} \bullet \eta_{abs} \tag{13}$$

Where, η_{abs} is the rate of PV energy absorption of the grid.

4 Techno-economic performance indicators

4.1 Yield factor

The net electricity generated by a PV system over a year is referred to as the yield factor or specific yield (Imam and Al-Turki, 2020).

10.3389/fenrg.2022.1028310

$$YF = \frac{E_{grid}}{W_{T,Peak}} \tag{14}$$

It is used to compare the operational performance of different technologies and helps estimate their financial worth.

4.2 Capacity factor

The ratio of the actual annual energy yield of a PV plant to the energy it would produce when operating at nominal capacity over 1 year (Imam and Al-Turki, 2020).

$$CF = \frac{E_{grid}}{8760 \bullet W_{T,Peak}} = \frac{YF}{8760} \tag{15}$$

The capacity factor of a solar PV power plant is primarily influenced by three key variables: inverter size, tracking ability, and resource quality (Mayes, 2022). The inverter size and tracking ability are design parameters that can be optimized to have higher energy yield however, resource quality is site specific and varies from site to site. Capacity factor shows the likelihood of a facility to operate at nominal capacity and therefore helps energy experts to assess the reliability of power plants. Power plants with higher capacity factor tend to have higher annual energy yield and lower per unit energy cost. Thus, capacity factor has great physical importance in power system planning, operation, and economics.

4.3 Net present value

The net present value (NPV) of a project is the measure of net future cash flows discounted at the present value of the discount rate (Retscreen International Clean Energy Decision Support Centre (Canada), 2005).

$$NPV = \sum_{n=0}^{N} \frac{\widetilde{C_n}}{(1+r)^n} \tag{16}$$

Where $\widetilde{C_n}$ is the after-tax cash flow, n is the specific year under consideration, N is the project life, and r represents the discount rate.

The NPV is a decisive financial metric that assesses whether a project is a financially sound investment or not. Generally, a project with any positive value of NPV is regarded as financially viable.

4.4 Internal rate of return

The discount rate that makes the project's NPV to be zero is called the internal rate of return (IRR). The following formula is used to compute the IRR (Retscreen International Clean Energy Decision Support Centre (Canada), 2005):

$$0 = \sum_{n=0}^{N} \frac{C_n}{(1+IRR)^n} \tag{17}$$

Where C_n is pretax cashflow for year n.

IRR infers the profitability of a project and therefore plays an important role to assess the economic viability of a project. The value of IRR is obtained by solving Eq. 17.

4.5 Simple payback period

The simple payback period is the time in years it takes for the cash flow (excluding loan payments) to match the entire investment (which is the sum of debt and equity) (Retscreen International Clean Energy Decision Support Centre (Canada), 2005):

$$SPBP = \frac{C - IG}{(C_{ener} + C_{capa} + C_{RE} + C_{GHG}) - (C_{O\&M} + C_{fuel})} \tag{18}$$

Where C is the net initial project cost, IG is the incentive and grants, C_{ener} is annual income or energy savings, C_{capa} is the annual capacity savings, C_{RE} is the annual credit for renewable energy production, C_{GHG} is the GHG emission mitigation income, $C_{O\&M}$ is the annual operation and maintenance cost, C_{fuel} is the annual electricity or fuel cost.

4.6 Levelized cost of electricity

The levelized cost of electricity, also known as energy production cost, is the per-unit cost of electricity required to have zero NPV (Ikoiwak et al., 2021).

$$LCOE = \frac{\sum_{n=0}^{N} \frac{C_n}{(1+r)^n}}{\sum_{n=0}^{N} \frac{E_n}{(1+r)^n}} \tag{19}$$

Where E_n and C_n are energy generated for n [kWh] and the total cost of the project for n [$].

5 Results and discussion

In this section, a comparative techno-economic analysis of PV projects at four facility sites is presented followed by the sensitivity analysis of the facility site with least potential. Moreover, the GHG mitigation potential of each project site is discussed in detail.

5.1 Technical viability

The modeling of proposed PV projects at four selected locations was done considering fixed solar tracking mode. The choice of fixed solar tracking mode was made based on its

 10.3389/fenrg.2022.1028310

TABLE 6 Technical input variables used in the PV system modeling.

Location	Multan	Lahore	Sargodha	Rawalpindi
Installed capacity	15.5 kW	53.63 kW	41.54 kW	40.3 kW
Solar Panel	50 · Canadian Solar CS6X-310P - MaxPower	173 · Canadian Solar CS6X-310P - MaxPower	134 · Canadian Solar CS6X-310P - MaxPower	130 · Canadian Solar CS6X-310P - MaxPower
Misc. PV array losses	12 %	12 %	12 %	12 %
Inverter	CSI-15K-T400GL01-E (1 · 15 kW)	CSI-20K-T400GL01-E CSI-12K-T400GL01-E (2 · 20 kW + 1 · 12 kW)	CSI-20K-T400GL01-E (2 · 20 kW)	CSI-20K-T400GL01-E (2 · 20 kW)
Misc. inverter losses	3 %	3 %	3 %	3 %
Battery capacity	1783 Ah	5705 Ah	4888 Ah	3720 Ah
Tilt angle	28°	27°	30°	30°
Azimuth angle	0°	0°	0°	0°
Solar tracking mode	Fixed	Fixed	Fixed	Fixed
Solar collector area	95.9 m^2	332 m^2	257 m^2	249 m^2
Capacity factor	17.6 %	16.3 %	17.8 %	14.3 %

simplicity, and low initial and O&M costs. It is required to enter miscellaneous losses associated with the PV module and inverter in the energy section of the RETScreen software to get more realistic simulation results. These miscellaneous losses include module mismatch losses, wiring losses, losses due to the presence of snow or dirt on the module surface, etc. (Khalid and Junaidi, 2013). Whereas losses that arise due to operating temperature are calculated by software using the temperature coefficient of selected PV module. The array and inverter miscellaneous losses of 12 % and 3 % respectively were considered in this study. The technical parameters as listed in Table 6 were used as input variables in the energy modeling of PV projects.

Simulation results revealed maximum annual energy yields of 23.90 MWh, 76.60 MWh, 64.9 MWh, and 50.50 MWh when solar PV arrays at Multan, Lahore, Sargodha, and Rawalpindi were sloped at 28°, 27°, 30°, and 30° respectively. However, Figure 11 shows the daily load profile and solar energy generation forecast for 25 June 2022, to evaluate the compatibility of the proposed PV design to meet the daily energy needs of each representative SME. The daily averaged solar energy production of PV projects in Multan, Lahore, Sargodha, and Rawalpindi was forecasted as high as 64.24 kWh, 223.14 kWh, 181.15 kWh, and 188.38 kWh. However, the daily energy demand (load) of marble processing, textile embroidery, rock salt products, and plastic manufacturing SMEs was recorded to be 60.14 kWh, 216.53 kWh, 108.64 kWh, and 124.31 kWh respectively. During solar productive hours, the proposed PV configurations enabled self-consumption of 49.24 kWh load in marble processing, 142.70 kWh load in textile embroidery, 80.46 kWh load in rock salt processing, and 98.91 kWh load in plastic products manufacturing SMEs, achieving self-consumption indices of 81.87 %, 65.90 %, 74.06 %, and 79.56 % and yielding a surplus of 15 kWh, 80.44 kWh, 100.69 kWh, and 89.47 kWh respectively.

To avoid curtailment of surplus energy, surplus energy was supplied to recharge the battery storage system to be used as a backup for grid power outages during undersupply or non-productive solar hours. However, in case the batteries are fully charged the excess energy from PV arrays flows upstream into the grid, as apparent in the case of rock salt and plastic products manufacturing SMEs with grid export of 43.46 kWh and 14.4 kWh respectively. The SME owners get credits for grid energy exports that can be used to offset the cost of grid energy imports for unproductive solar hours. Also, the proposed PV designs were good enough to avoid the halting of industry operations due to periodic grid power outages as highlighted in red for each SME in Figure 11. The detailed technical analysis corroborates that all four PV setups have sufficient potential to curb the dire impacts of prevailing energy crises and therefore ensure the smooth and reliable functioning of SMEs.

5.2 Financial sustainability

The parameters listed in Table 7 were used as input variables in the financial modeling of PV projects. The values of input financial parameters such as average annual inflation rate, debt

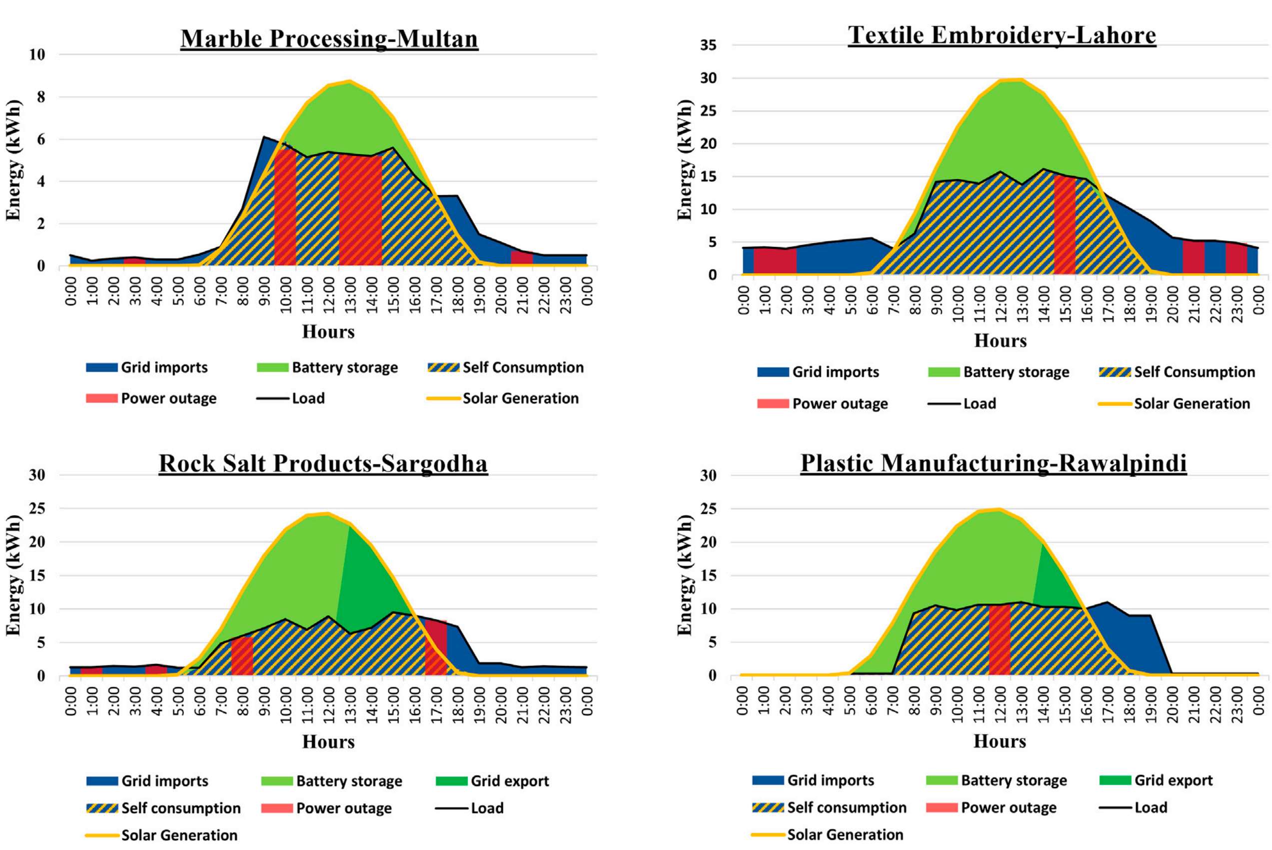

FIGURE 11
Typical daily solar generation and load curves of representative SMEs.

term, and debt interest rate were chosen keeping in view the current economic trends and financing schemes of local banks. Whereas standard values as suggested by the software were considered for the discount rate and electricity export escalation rate. Financial modeling of PV projects also requires initial capital cost and O&M cost. The initial cost is the total capital expense required to enable the proposed facility to start generating revenue. However, O&M cost is required to cover the cleaning expenditures of PV modules, inverter replacement cost, and any possible contingency. The initial capital cost of 1000 USD/kW (Akbar et al., 2020), annual O&M cost of 10.0 USD/kW (Ikram et al., 2021), inflation rate of 10 % (Asad et al., 2022), electricity export rate of 0.09 USD/kWh (Ahmed et al., 2021), debt ratio of 50 % (Khalid and Junaidi, 2013), debt interest rate of 9.75 % (Mehmood et al., 2022), discount rate of 9% (Khalid and Junaidi, 2013), electricity export and fuel cost escalation rate of 2% (Rauf et al., 2022), project life of 25 years (Rauf et al., 2022), and debt term of 10 years (Khalid and Junaidi, 2013) were used in the energy model based on the studies and quotations from PV system installers in the local market. Using defined input economic parameters, annual lifecycle savings, benefit-cost

TABLE 7 Input variables considered in financial modeling.

Parameter description	
Inflation Rate	10.0 %
Debt Ratio	50.0 %
Debt Interest Rate	9.75 %
Discount Rate	9.0 %
Electricity Export Escalation Rate	2.0 %
Fuel Cost Escalation Rate	2.0 %
Debt Term	10 Years
Project Life	25 Years
Initial Capital Cost	1000 USD/kW
O&M Cost	10 USD/kW
Electricity Export Rate	0.09 USD/kWh

ratio, NPV, IRR, SPBP, LCOE, etc. were calculated by running a financial analysis model as shown in Table 8.

NPV, IRR, LCOE, and SPBP are key indicators used to assess the economic viability of a grid-connected PV system (Ahmed et al., 2021), (Owolabi et al., 2019). Figure 12 shows

TABLE 8 Financial output parameters of the proposed PV projects.

Parameter description	Multan	Lahore	Sargodha	Rawalpindi
Net Present Value (NPV) (USD)	5244	11662	14947	1337
Internal Rate of Return (%)	14.60	12.60	14.90	9.60
Simple Payback Period (SPBP) (Years)	7.80	8.40	7.70	9.70
Levelized Cost of Electricity (USD/kWh)	0.086	0.093	0.085	0.105
Benefit Cost Ratio	1.70	1.40	1.70	1.10
Annual lifecycle savings (USD/Year)	534	1187	1522	136

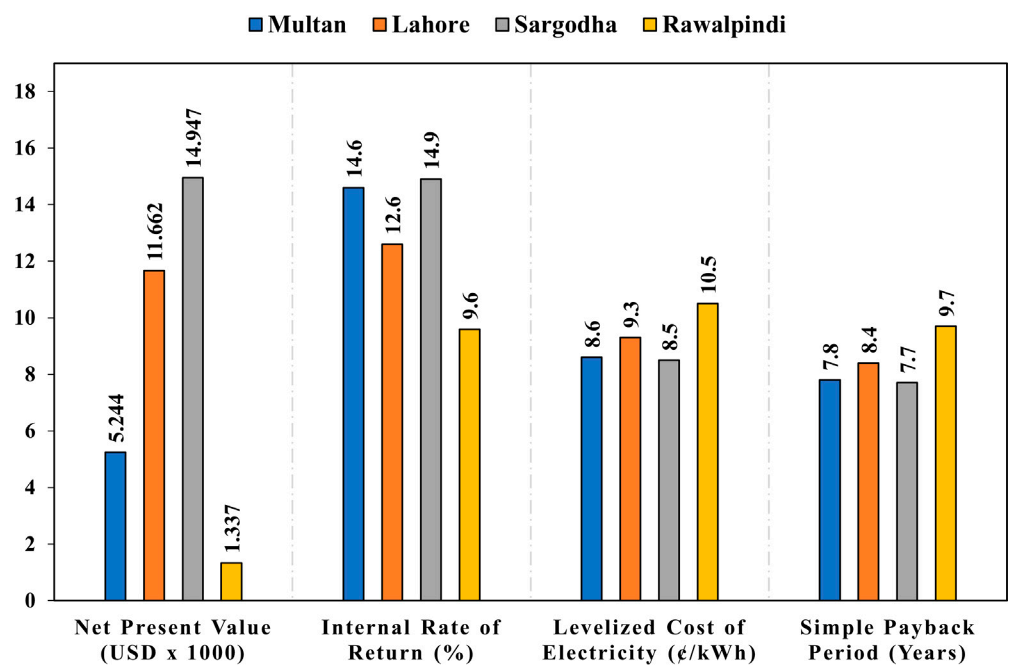

FIGURE 12
Comparison of PV projects based on financial output variables.

the trend of these financial output indicators for all four selected facility locations. Figure 12 depicts that the proposed PV system in Sargodha has the highest NPV of 14947 USD followed by Lahore and Multan with NPV of 11662 USD and 5244 USD respectively. Whereas the PV project in Rawalpindi has the least NPV of 1337 USD. According to (Khalid and Junaidi, 2013), (Owolabi et al., 2019) a project with any positive value of NPV is regarded as financially acceptable. As noted in Figure 12 Sargodha tends to have an uppermost IRR value of 14.9 %. Likewise, the IRR value for the PV project in Multan is 14.6 % followed by Lahore and Rawalpindi with 12.6 % and 9.6 % respectively. Normally, a project is believed to be economically feasible if its IRR is higher than the discount rate (Sreenath et al., 2021), (Owolabi et al., 2019), (Khalid and Junaidi, 2013). All four sites with IRR values higher than the threshold of a 9 % discount rate affirm the profitability of the project investment.

Also, Figure 12 sets forth the comparison of LCOE of PV projects under study. The benchmark electricity cost used in this research is equal to the pretax utility industrial tariff of 12.0 ¢/kWh (National Electric Power Regulatory Authority (NEPRA), 2021b). The proposed PV system in Sargodha has the least LCOE value of 8.5 ¢/kWh compared to Multan and Lahore with LCOE values equal to 8.6 ¢/kWh and 9.3 ¢/kWh respectively. Rawalpindi however has the highest LCOE value of 10.5 ¢/kWh.

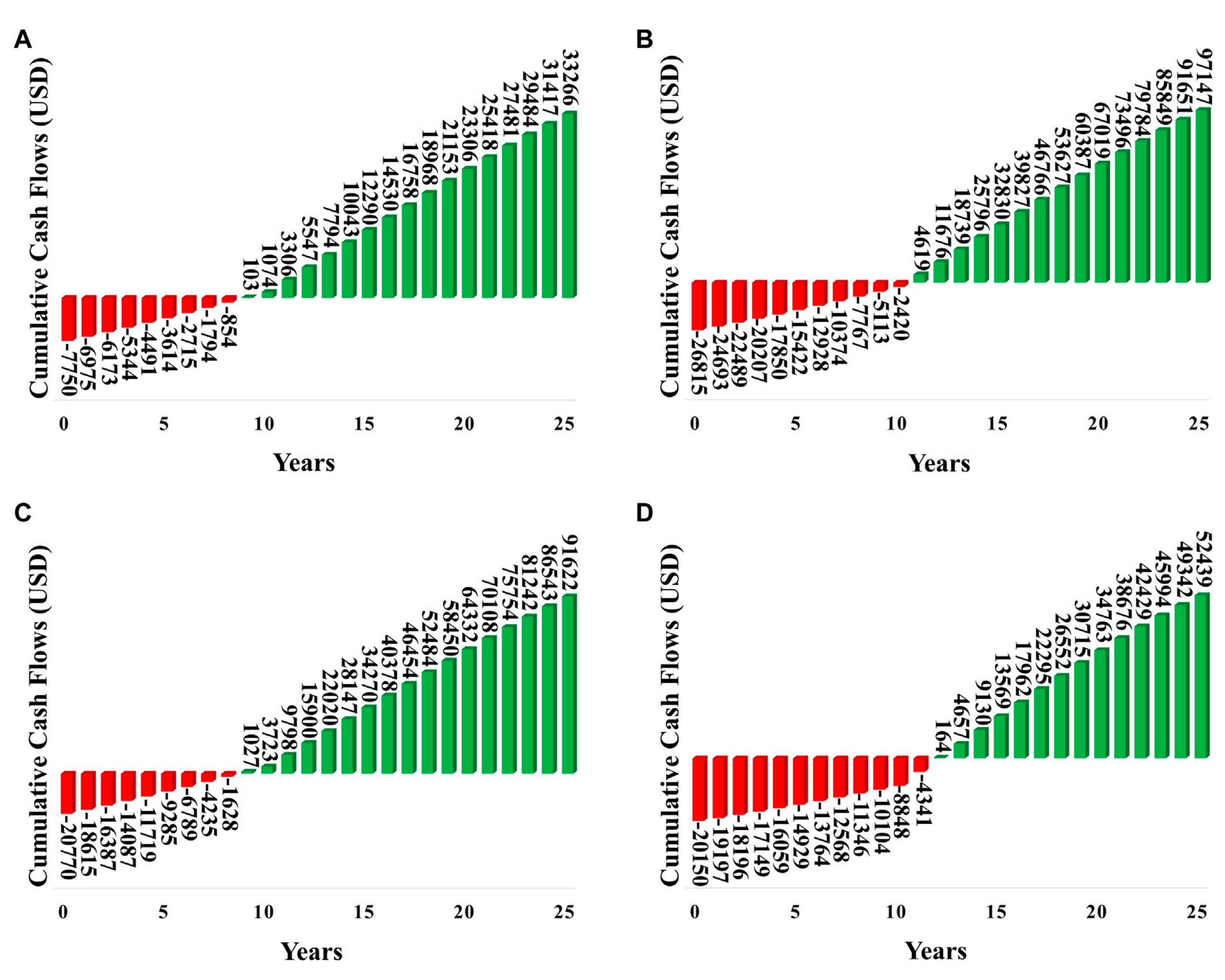

FIGURE 13
Cumulative cash flow for PV projects **(A)** Multan. **(B)** Lahore. **(C)** Sargodha. **(D)** Rawalpindi.

SPBP is an important indicator as it gives investors insight into the probability of an investment (Ahmed et al., 2021). The debt term proposed for all sites was 10 years Figure 12 illustrates the SPBP of all four PV projects for chosen SME locations. The SPBP varies between a minimum of 7.7 years for Sargodha to a maximum of 9.7 years for Rawalpindi. Whereas Multan has 7.8 years followed by Lahore with 8.4 years of payback time. Also, Figure 13 shows the cumulative cash flows and therefore net profit generated by each project location after recovering capital investment at the end of project life. Profit generated by a project is the function of installed PV project capacity in kW, the climate of facility location, and kWh generated by the PV system. This is because the PV project in Lahore with a maximum installed capacity of 53.63 kW accumulated 97147 USD. Whereas Multan with the comparatively lowest installed PV capacity of 15.50 kW generated 33266 USD.

Financial feasibility analysis reveals that all four sites are economically viable as none of the PV designs violated the set criteria of NPV, IRR, LCOE, and SPBP. Sargodha turns out to be the most economical and financially viable site for having the highest IRR and least values of LCOE and SPBP in comparison to other sites. Rawalpindi site however narrowly fulfills the feasibility criteria with the highest LCOE of 10.5 ¢/kWh and therefore, may become vulnerable to slight variations in input financial parameters. Therefore, to estimate the level of its vulnerability it must be subjected to sensitivity analysis.

5.3 Sensitivity analysis

Sensitivity analysis determines the degree of uncertainty associated with financial indicators by evaluating a set of

TABLE 9 Sensitivity analysis results for NPV of solar PV project in Rawalpindi.

Case 1: Variation of debt interest rate vs. annual energy yield

Debt interest rate (%)	Sensitivity range (%)	Annual energy yield (MWh)				
		37.91	44.23	50.55	56.87	63.18
		−25.0 %	−12.5 %	0.0 %	12.5 %	25.0 %
7.31	−25.0	−9940	−3231	3479	10188	16898
8.53	−12.5	−10998	−4288	2421	9131	15840
9.75	0.0	−12082	−5372	1337	8047	14756
10.97	12.5	−13191	−6482	228	6938	13647
12.19	25.0	−14325	−7615	−905	5804	12513

Case 2: Variation of O&M cost vs. initial project costs

O&M Cost (USD)	Sensitivity range (%)	Initial costs (USD)				
		30,225	35,263	40,300	45,338	50,375
		−25.0 %	−12.5 %	0.0 %	12.5 %	25.0 %
302	−25.0	14,422	9,301	4180	−942	−6,063
353	−12.5	13,001	7,880	2758	−2,363	−7,484
403	0.0	11,580	6,459	1337	−3,784	−8,905
453	12.5	10,159	5,037	−84	−5,205	−10,326
504	25.0	8,737	3,616	−1505	−6,626	−11,748

technical and financial input variables for a predefined sensitivity range. The sensitivity model provides the user with an option to perform sensitivity analysis for desired financial viability indicators. Two key input variables are chosen then the sensitivity model generates a table illustrating how simultaneous variation in these input variables affects the selected indicator of financial viability. Only the solar PV system at Rawalpindi was considered for sensitivity analysis as technical viability analysis predicted comparatively least potential for this site among others when it comes to annual energy yield.

Also, the indicators of financial viability were found to have values close to the threshold of acceptability making this project susceptible to slight variations in input financial parameters. The NPV of the solar PV project at Rawalpindi was considered the main financial viability indicator and was subjected to sensitivity analysis by varying debt interest rate against annual energy yield by ±25 % for case1 and O&M cost against initial costs, over the same sensitivity range for case 2 as shown in Table 9.

In the first scenario, the sensitivity model calculates 50.55 MWh annual energy yield but with ±25 % variation, it will be 63.18 MWh and 37.91 MWh respectively. Whereas the actual rate of interest on debt is 9.75 % but with a ±25 % deviation it will be 12.19 % and 7.31 % respectively. Sensitivity analysis was performed to recalculate NPV for multiple combinations of debt interest rate and annual energy yield over a defined ±25 % sensitivity range. The threshold of NPV was chosen zero in sensitivity analysis therefore recomputed values of NPV below this threshold were highlighted with orange color indicating infeasibility of the project for corresponding combinations of input parameters e.g. if annual energy yield attenuates by 25 % from the actual value of 50.55 MWh to 37.91 MWh then even a 25 % reduction of debt interest rate from 9.75 % to 7.31 % will not be sufficient to make the project financially profitable as it will give NPV of -9940 USD. Conversely if annual energy yield swells up to 25 % from the actual value of 50.55 MWh to 63.18 MWh, then even a 25 % increase in debt interest rate from 9.75 % to 12.19 % will not render the project in loss, as it will yield NPV of 12514 USD which is much higher than the threshold of zero. This reflects that NPV is way more sensitive to annual energy yield rather than the debt interest rate.

TABLE 10 GHG emission reduction potential of proposed PV projects at selected facility locations.

Location	Annual GHG emissions (t CO_2)		
	Base case	Proposed case	Gross annual reduction
Multan	11.30	0.80	10.50
Lahore	36.30	2.50	33.80
Sargodha	30.80	2.20	28.60
Rawalpindi	24.00	1.70	22.30

In the second case, again sensitivity analysis was performed but this time considering O&M cost against the initial costs of the project. Careful analysis of recalculated NPV values reveals that a slight synchronal increment of initial and O&M costs will make this project financially infeasible. The project will be financially viable and sustainable if both the initial and O&M costs stay intact or decrease simultaneously. Also, the general trend of recalculated NPV values shows that the initial project cost is dominant financial viability indicator, as a 12.5% increase in initial cost from 43,300 USD to 45,338 USD makes the project a potential investment loss and even a 25 % reduction in the O&M cost from 403 USD to 302 USD fails to make this project financially viable. Hence, the results of sensitivity analysis confirmed that the PV project designed for the plastic product manufacturing enterprise in Rawalpindi has poor resilience against slight variations in financial input indicators and technical output parameters therefore, investment in this project may turn out to be a potential financial loss.

5.4 GHG emission mitigation

RETScreen emission analysis worksheet was used to estimate the potential of each proposed facility to contribute toward the mitigation of GHG emissions. The emission worksheet offers three levels of GHG emission analysis however, this research considers level 2 emission analysis. Level 2 analysis allows the user to manually enter the energy mix values to define the base case electricity system. Also, it is required to enter transmission and distribution (T&D) losses in the emission worksheet to model the base case as well as proposed case systems. GHG emission factor as calculated by emission model of 0.474 t CO_2/MWh and T&D losses of 20.73 % (National Electric Power Regulatory Authority (NEPRA), 2021a) were considered for the base case electricity system. For the proposed case system, it is reasonable to consider T&D losses of anywhere between 3 % and 10 %, this study however uses a value of 7 %. GHG emission model calculates annual GHG emissions for both the base case and proposed case electricity systems in t CO_2/year. Based on these results annual gross GHG emission reduction for each facility was calculated as shown in Table 10.

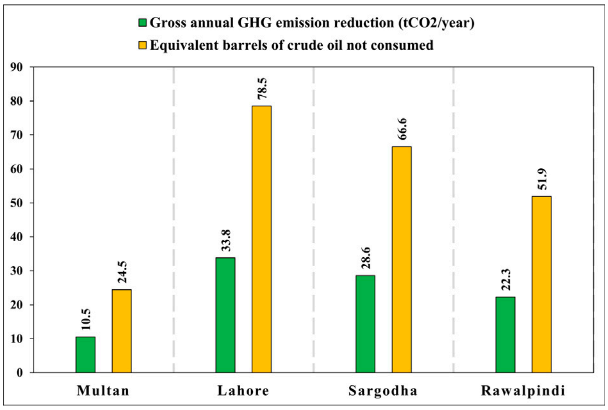

FIGURE 14
Gross annual GHG emission mitigation and equivalent barrels of crude oil not consumed.

The solar PV project in Lahore was found to have the highest GHG emission reduction of 33.8 t CO_2/year that is equivalent to 78.5 barrels of crude oil not consumed. Similarly, proposed PV projects in Sargodha, Rawalpindi, and Multan were found to have GHG emission reduction values of 28.6 t CO_2/year, 22.3 t CO_2/year, and 10.5 t CO_2/year that is equivalent to 66.6, 51.9, and 24.5 barrels of crude oil respectively, which remained unconsumed as shown in Figure 14. In some countries, solar PV investors earn GHG emission reduction revenue through carbon trading. In such trading, if an entity with a certain permitted emission threshold has more to emit then it is subjected to carbon taxes. Similarly, if an entity/organization has lower to emit than what it was permitted to then it gets certain incentives in the name of GHG emission reduction credits. However, in Pakistan, no concept of carbon trading exists yet therefore, while performing emissions analysis GHG reduction credit rate was not considered.

5.5 Validity of research findings and future scope

5.5.1 Performance comparison of different PV plants

To validate simulation results, the performance comparison of all four PV projects was made with solar PV plants installed at different locations as shown in Table 11. The comparative

TABLE 11 Performance comparison of grid-connected solar PV plants in different countries.

References	Location	Size (kW)	PV cell	YF (kwh/kwp/yr)	CF (%)	NPV ($)	LCOE ($/kWh)	SPBP (yrs)
Raghoebarsing and Kalpoe, (2017)	Paramaribo, Suriname	27	Poly-Si	1368.80	15.50	−110527	0.36	180.70
Haffaf et al. (2021)	M'sila, Algeria	1.5	–	1494	17.60	2277.61	0.0655	–
Imam and Al-Turki, (2020)	Jeddah, Saudi Arabia	12.25	Mono-Si	1927	22.00	4378	0.0382	13.80
Mohammed et al. (2022)	Tabuk, Saudi Arabia	10	Mono-Si	1827	20.89	23626.1	0.027	7.60
Sagani et al. (2017)	Athens, Greece	9.87	Poly-Si	1583.00	18.10	1973	0.119	13.20
Mohammadi et al. (2018)	Bandar Abbas, Iran	5000	Mono-Si	1536.24	17.54	3170624	0.126	7.00
Owolabi et al. (2019)	Taraba, Nigeria	6000	Mono-Si	1790.50	20.40	1437841	0.135	14.60
Owolabi et al. (2019)	Adamawa, Nigeria	6000	Mono-Si	1815.50	20.70	1716405	0.133	14.40
Sreenath et al. (2021)	Selangor, Malaysia	5000	Mono-Si	1327.06	15.14	433808.3	0.113	9.30
Present	Multan, Pakistan	15.50	Poly-Si	1541.61	17.60	5244	0.086	7.80
Present	Lahore, Pakistan	53.63	Poly-Si	1427.80	16.30	11662	0.093	8.40
Present	Sargodha, Pakistan	41.54	Poly-Si	1561.84	17.80	14947	0.085	7.70
Present	Rawalpindi, Pakistan	40.30	Poly-Si	1254.27	14.30	1337	0.105	9.70

analysis revealed that the specific yield, energy production cost (LCOE), and SPBP of these PV plants closely matched with performance parameters of proposed PV projects which manifests the authenticity of PV system modeling and obtained simulation results.

5.5.2 Projection of research findings

The findings of the techno-economic feasibility assessment are quite satisfactory and indicate that regions of central and southern Punjab have tremendous solar potential. In the year 2020–21 net industrial energy consumption of Punjab was reported to be 20446.21 GWh/year which is 26.84 % of net provincial energy needs (National Electric Power Regulatory Authority (NEPRA), 2021a). Applying the same research methodology to the whole industrial sector of Punjab suggests 13469 MW of installed solar PV capacity to meet this much energy demand and will mitigate 90,17,581 t CO_2/year emissions.

6 Conclusion

The techno-economic feasibility of installing grid-connected solar photovoltaic power plants in chosen SME sectors of Punjab was evaluated in this study. Making use of actual energy consumption data, grid-tied solar PV system was designed for each representative SME. Subsequently, the techno-economic viability assessment was performed for all four PV projects to calculate annual energy yield, GHG mitigation potential, SPBP, and net profit accumulated at the end of project life, etc. All four facility sites were found to be technically and economically viable for solar PV installation however, Rawalpindi with NPV of 1337 USD showed up least potential compared to Multan, Lahore, and Sargodha with NPV of 5244 USD, 11662 USD, and 14947 USD respectively. Therefore, the PV project in Rawalpindi was subjected to sensitivity analysis to assess its degree of vulnerability against variations in different input parameters. Sensitivity results revealed that the PV project in Rawalpindi was more sensitive to annual energy yield and initial cost compared to interest rate and O&M cost respectively. Also, the results of sensitivity analysis confirmed that reduced initial project cost and an increased annual energy yield significantly mitigate the susceptibility of PV projects against variations in other input parameters. Lastly, the performance indices of each PV design were compared with performance parameters of grid-tied solar PV plants installed at different locations in the world to validate the authenticity of simulation results. Extending the same design methodology to the whole industrial sector of Punjab predicted an installed PV capacity of 13469 MW to meet 20446.21 GWh/year of industrial energy demand and consequently 90,17,581 tCO_2/year carbon emission mitigation.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AA, NU, and SK contributed to conception and design of the study and funded the project. AK and KJ supervised the work. MA performed the statistical analysis. MA wrote the first draft of the manuscript. MA, AA, NU, KJ, AK, wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Nomenclature

E_{PV} Energy required from PV modules
E_{Peak} Peak Energy demand of facility
$W_{T,Peak}$ Total watt peak rating of PV modules
N_{module} Number of PV Panels required
E_{grid} Energy available to grid
E_{dlvd} Energy delivered to grid
η_A Overall array efficiency
P_{max} Rated power output of PV Panel
P_{inv} Inverter AC output power rating
$\bar{K}_t$ Monthly average clearness index
$\bar{H}_t$ Average hourly solar radiation
β Slope of PV array
E_P Energy delivered by PV array
η_P Array efficiency
η_r Module efficiency
η_{abs} Grid energy absorption rate
η_{inv} Inverter efficiency
T_c Module Temperature
T_a Monthly average ambient temperature
E_A Energy available to load
λ_c Power conditioning losses
C_{capa} Annual capacity savings
C_{RE} Annual credit for renewable energy
η_b Battery efficiency
V_{nom} Battery nominal voltage
β_p Temperature coefficient of module
C_{fuel} Annual electricity or fuel cost
$C_{O\&M}$ Annual operation and maintenance cost
C_{GHG} GHG emission mitigation income
C_{ener} Annual income/energy savings
C Initial project cost
C_n Pre-tax cash flow
$\widetilde{C_n}$ After-tax cash flow
λ_p Miscellaneous PV array losses
D Days of autonomy
IG Incentive and grants
n Specific year
N Project life
r Discount rate
S Area occupied by the PV array

Acronyms

SME Small and medium enterprise
UPS Uninterruptible power supply
USD United States Dollar
NTDC National Transmission and Dispatch Company
NEPRA National Electric Power Regulatory Authority
NASA National Aeronautics and Space Administration
NOCT Nominal operating cell temperature
PGF Panel generation factor
ILR Inverter loading ratio
tCO2 Tons of carbon dioxide
PV Photovoltaic
O&M Operation and maintenance cost
EIA Energy information administration
T&D Transmission and distribution
YF Yield factor
CF Capacity factor
NPV Net present value
IRR Internal rate of return
SPBP Simple payback period
LCOE Levelized cost of electricity
GDP Gross domestic product
GHG Greenhouse gas
Ah Ampere-hour
BC Battery Capacity
DoD Depth of discharge
toe Tons of oil equivalent