

Evaluating the 7E impact of solar photovoltaic power plants at airports: a case study

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Abstract. The deployment of solar panels at airports offers numerous benefits, such as clean energy production, cost savings, emission reduction, improved energy security, and a positive public image. In this study, the performance of various solar panel technologies is investigated based on the 7E framework (i.e. energy, exergy, economic, energoenviroeconomic, exergoenviroeconomic, energoenviroeconomic, and energoenviroeconomic) at airports in Pakistan. Initially, available spaces at five international airports are identified followed by energy assessments conducted with PVSyst simulation software. Next, a mathematical model is developed to evaluate exergy, economic, energoenviroeconomic, exergoenviroeconomic, energoenviroeconomic, and exergoenviroeconomic parameters. Results show that all airports demonstrate favorable performance ratios. Specifically, Quetta airport emerges as the optimal location as per the 7E assessment, showcasing a reference yield of 2752 kWh/kW, final yield of 2420.8 kWh/kW, 27.63% capacity utilization factor, 0.031 \$/kWh levelized cost of electricity, 5730 tons of CO₂ avoided annually, and \$488,826 per year in greenhouse gas revenue, achieved through thin film-based technology with single axis tracking. Peshawar airport stands out for its high energy efficiency, while Karachi airport excels in exergy analysis. The outcome of the study will provide insights into the potential of these systems to mitigate energy challenges, considering economic feasibility and environmental implications.

Keywords: Airport, Solar, Energy, Exergy, Economic, Environment.

Nomenclature

AAR	Average Annual Return (\$)
A_{pv}	Area of PV array (m ²)
CdTe	Cadmium Telluride
C_{in}	Investment Cost (\$)
DPP	Discounted Payback Period (years)
E_{gen}	Annual Energy Generation (kWh)
ENEN	EnergoEnvironmental (tCO ₂ /year)
ENENEC	EnergoEnviroEconomic (\$/year)
Ex _{el}	Electrical exergy (kW)
EXEN	ExergoEnvironmental (tCO ₂ /year)
EXENEC	ExergoEnviroEconomic (\$/year)
Ex _{in}	Exergy input (kW)
Ex _{out}	Exergy output (kW)
Ex _{th}	Thermal exergy (kW)
FT	Fixed Tilt

H_s	Sunshine hours (hrs)
LCOE	Levelized Cost of Energy (\$/kWh)
mono-cSi	Monocrystalline Technology
n	PV system life
P_c	Plant capacity (kW)
poly-cSi	Polycrystalline Technology
R_h	Solar radiation in horizontal plane (kWh/m ²)
SAT	Single Axis Tracking
T_a	Ambient temperature (K)
T_m	Module temperature (K)
T_s	Sun temperature (K)
U	Overall heat transfer coefficient (kW/m ² K)

1 Introduction

Pakistan faces a persistent electricity supply-demand gap, primarily due to its heavy reliance on imported fossil fuels, leading to high costs, environmental degradation, and

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energy insecurity. The environmental vulnerability of Pakistan is evident from its 8th rank in the Global Climate Risk Index [1] from 2000 to 2019. According to the International Energy Agency [2], Pakistan's annual power demand in 2019-20 was 154,559 GWh/year, projected to increase by 19.6% by 2024-25. However, a report from the National Electric Power Regulatory Authority [3] indicates an annual energy generation of 153,874 GWh/year for 2021-22. To meet the growing demand, there is an urgent need for Pakistan to focus on enhancing power generation. Currently, the Central Power Purchasing Agency heavily relies on Thermal (coal & natural gas) contributing 58.36% of the total power generation [3]. The recent economic crisis has further compounded challenges affecting the import of coal and natural gas. Consequently, there is a projected deficiency of around 19.94% in annual power generation by 2024. This highlights the critical importance of addressing these energy issues and transitioning towards sustainable and resilient solutions.

In response to the challenges outlined, a strategic shift towards renewable energy sources emerges as a crucial focus for enhancing overall power generation in Pakistan. The National Renewable Energy Laboratory (NREL) has conducted an evaluation revealing Pakistan's significant solar power potential, estimated at over 5500 TWh/year [4]. Notably, the regions of Sindh and Balochistan provide an optimal environment for harnessing solar energy. These areas exhibit some of the highest radiation levels globally, ranging around 19-20 MJ/day, accompanied by an average daily sunshine duration of 9.5 hours [5].

In recent years, the government of Pakistan has set ambitious goals to achieve 30% of the electricity from renewable sources by 2030. Therefore, significant efforts are underway to establish solar power facilities nationwide. As per the International Renewable Energy Agency, the total installed solar capacity across Pakistan was 1.24 GW in 2022. With an expected annual growth rate of 49.68% during the forecast period (2023-2028), the solar energy market is predicted to surge from 1.3 gigawatts in 2023 to 9.77 gigawatts by 2028 [6].

Airports in Pakistan offer a promising prospect for PhotoVoltaic (PV) installations. The availability of land within airport premises may facilitate large-scale solar projects. Moreover, airports can enhance their energy resilience and contribute to mitigating energy challenges. The associated benefits of reducing carbon footprint, achieving cost savings, and fostering a positive public image further position airports as ideal candidates for PV installations in Pakistan. The main aim of this study is to conduct a 7E analysis of solar PV systems across major airports in Pakistan. The outcome of the study will provide insights into the potential of these systems to mitigate energy challenges, considering economic feasibility and environmental implications.

2 Literature review

Previous studies by various authors have explored the techno-economic performance of solar PV systems across

different locations, revealing diverse insights and perspectives. Caliskan [7] incorporated multiple factors, including energy, exergy, environmental, enviroeconomic, Exergo Environmental (EXEN), and ExergoEnviroEconomic (EXENEC), concluding that the exergy-based EXENEC approach is more reliable. Results showed that the energy efficiency (25.40%) is higher than the comparable exergy efficiency. The EXEN result (0.0727 kg CO₂/day) was lower than the corresponding environmental result (0.0777 kg CO₂/day), while the enviroeconomic result (0.00112 USD/day) surpassed the EXENEC result of 0.00105 USD/day. This highlights the credibility and trustworthiness of the exergy-based EXENEC approach.

AlZahrani and Dincer [8] conducted an evaluation of energy and exergy studies on a parabolic trough solar power plant resulting in energy and exergy efficiencies of 66.35% and 38.51%, respectively. Sukumaran and Sudhakar [9] conducted a mathematical analysis of utility-scale solar PV power plants at Cochin Airport, estimating energy and exergy efficiencies as 14.58% and 9.77% respectively. Kareem *et al.* [10] investigated the energy and exergy study of a solar PV system in Baghdad, revealing variations in efficiency and exergy destruction throughout the year with exergy efficiency ranging from 10.8% to 15.8%, the energy efficiency between 15.71% and 15.74%, and the exergy destruction varying from 182.8 to 352.3 W/m². Wahab *et al.* [11] assessed the exergetic performance of a graphene nanofluid-based PV/T system, emphasizing the greater impact of electrical performance on overall exergy efficiency. It was concluded that the PV/T-PCM system had the maximum thermal, electrical, and exergy efficiency of 1.87% at 20 L/min, 13.1% at 40 L/min, and 14.7% at 40 L/min, respectively. Additionally, it was stated that electrical performance has a greater impact on overall exergy efficiency than thermal performance.

Poredoš *et al.* [12] conducted an analysis of energy and exergy efficiencies for PV, PV-T, and solar thermal modules, reporting energy efficiencies of 12.7%, 9.2%, and 4.4%, respectively. Choudhary *et al.* [13] proposed grid-connected solar PV power plants for airports in Udaipur, Raipur, and Aurangabad, projecting performance ratios and carbon emission reductions using Helioscope software. Sreenath *et al.* [14] explored the 7E assessment of solar PV power plants at seven Indian airports, with Dehradun airport exhibiting the best metrics. Sher *et al.* [15] assessed the viability of a 12 MWp solar PV power plant at a UK airport, presenting average values for energy yield, performance ratio, and carbon emission reduction as 2585.74 kWh/kWp/month, 82.59%, and 11,643 tonnes, respectively. Sreenath *et al.* [16] estimated 7E characteristics of a 5 MW solar PV power plant at multiple sites in Malaysia, identifying Site 2 as the most favorable. Yousef *et al.* [17] conducted a comparative study of three PV setups, considering factors such as electrical efficiency, energy efficiency, energy payback time, exergoeconomics, and enviroeconomics. The results showed that the electrical efficiency of PV-PCM and PV-PCM/AF systems in summer was improved by 9% and 14%, respectively, compared to the unmodified PV setup. While in the winter, the comparable improvements were 3.7% and 4.8%, respectively.

Additionally, it was discovered that the cost of power generation for PV-PCM and PV-PCM/AF systems was 0.1165 \$/kWh and 0.1145 \$/kWh, respectively, against 0.1162 \$/kWh for the PV system.

Yaghoubirad *et al.* [18] provided a multi-criteria study for six US cities, incorporating energy, exergy, economic, and environmental considerations. Two energy and exergy divisions carried out the environmental impact evaluation. As a result, Portland was chosen as the most effective option for the PVs module because of the EnergoEnvironmental (ENEN) and the EnergoEnviroEconomic (ENENEC) analysis. Mfetoum *et al.* [19] undertook an exergoeconomic analysis of solar PV power plants at Maroua and Douala airports, considering factors such as energy losses and usable exergy production. These diverse studies contribute valuable insights into the performance, efficiency, and economic aspects of solar PV systems, emphasizing the need for comprehensive assessments in various geographical and climatic contexts. In the Maroua PV plant and the Douala PV plant, respectively, the usable exergy production of electricity is expected to be 1585.68 kWh/kWp/yr and 1452.75 kWh/kWp/yr. The losses are estimated to be 37.6 kWh/kWp/yr in Douala and 142.76 kWh/kWp/yr in Maroua, respectively.

From the available literature studies, it is observed that the performance of PV plants through both numerical simulations and empirical investigations, covering analyses in energy, exergy, economics, and the environment have been extensively explored. However, a notable gap exists in the scientific literature concerning a comprehensive evaluation of solar PV power plants specifically located on airport grounds. In the majority of studies, emphasis has predominantly been on energy and economics, neglecting the pivotal role of exergy analysis in enhancing and optimizing design. Exergy analysis proves essential as it precisely identifies thermodynamic losses, offering a more accurate estimate of how closely actual performance aligns with the ideal scenario [20]. Furthermore, only a limited number of studies have explored the economic and environmental benefits of deploying solar PV systems at airports.

This research seeks to address significant gaps in current scientific understanding by conducting a thorough investigation into the performance of solar PV power plants specifically situated at airports. Various technologies, including mono-cSi, poly-cSi, and thin film have been examined while focusing on specific performance metrics such as ENEN, EXEN, ENENEC, and EXENEC that have not received sufficient attention in existing scientific literature. Therefore, the outcome of the study would provide valuable insights into the effectiveness of solar PV systems within airport environments offering a detailed perspective.

3 Materials and methods

3.1 Selection of location in airports

In this study, a 5MW solar power plant has been considered for five major airports in Pakistan. The first phase involves identifying suitable vacant land using Google Earth in the

selected airports. Figure 1 visually represents the proposed locations for these solar power installations.

The monthly Global Horizontal Irradiation (GHI) values for the selected cities are presented in Table 1. In Karachi, the lowest GHI of 116.6 kWh/m² was observed in December, gradually increasing to 201.1 kWh/m² in May. Islamabad, Peshawar, and Lahore follow a similar pattern with the highest GHI values of 203.8, 197.7, and 184.4 kWh/m² in either May or June, respectively. Among all cities, Quetta has the highest monthly GHI values reaching 231.1 kWh/m² in June. According to the annual analysis, Quetta leads with the highest annual GHI at 2039.8 kWh/m², followed by Karachi at 1855.4 kWh/m², Islamabad at 1715.9 kWh/m², Peshawar at 1717 kWh/m², and Lahore at 1637.2 kWh/m².

Similarly, the temperature data in Table 1 highlights the seasonal variations throughout the year. Karachi, being a coastal city, experiences relatively mild temperatures ranging from 18.61 °C in January to 31.57 °C in June. Islamabad, located in the northern region, has colder winters with temperatures ranging from 10.29 °C in January to 31.31 °C in June. Peshawar follows a similar pattern with temperatures ranging from 8.63 °C in January to 30.89 °C in June. Lahore exhibits a slightly different trend, with temperatures ranging from 11.71 °C in January to 32.64 °C in May. Quetta, situated at a higher altitude, experiences colder temperatures throughout the year. The temperatures range from a low of 8.76 °C in January to a high of 29.62 °C in June. The yearly summary highlights the overall temperature patterns for each city, with Karachi having the highest yearly average temperature of 26.84 °C and Quetta with the lowest at 20.9 °C.

3.2 Simulation software

PVSyst is a widely used software tool for designing, analyzing, and optimizing PV systems [21]. The software offers an array of features to evaluate and simulate system performance. Using sophisticated algorithms, the software simulates PV system performance based on variables such as weather information, module specifications, shading effects, and system losses, providing accurate estimates of energy yield and performance ratio [21, 22].

As depicted in Figure 2, the initial step for PV system simulation involves selecting the system type, either standalone (off-grid) or grid-connected configuration. In this study, a grid-connected configuration was selected. Next, the software requires input of geographical coordinates and local weather data from the user. The details of monthly GHI and ambient temperature are shown in Table 1. Considering orientation factors such as tilt and azimuth angles, PVSyst simulates the system's performance. For this study, the PV panels are oriented south-facing for both configurations, with a tilt angle equal to the latitude for the fixed tilt configuration. Users then define specific system specifications, including technology type, inverter details, and array design, with losses being integrated into the simulation. PVSyst subsequently models the impact of these parameters on energy production. The software allows users to analyze various configurations by adjusting relevant parameters. The provision of detailed reports and visualizations by



(a)



(b)

Fig. 1. Available space in the premises of Pakistan's airports (Source: google map). (a) Jinnah International Airport, Karachi. (b) Islamabad International Airport. (c) Bacha Khan International Airport, Peshawar. (d) Allama Iqbal International Airport, Lahore. (e) Quetta International Airport.

PVSyst facilitates a comprehensive assessment of PV potential under different scenarios.

3.3 Selection of PV technologies

To compare performance attributes, particularly in terms of energy and exergy, the study examined three types of PV cell technologies: Monocrystalline PV cells, Polycrystalline PV cells, and Thin film PV cells. The specific details are provided in Table 2.

Monocrystalline PV cells, made from a single silicon crystal, offer advantages in both efficiency and appearance [23]. The efficiency ranges from 15% to 22% [24]. In contrast, Polycrystalline PV cells, comprised of various crystal formations, exhibit a unique appearance and characteristics. The efficiency of such panels ranges from 13% to 18% [24]. Thin film PV cells are produced by depositing extremely thin layers of semiconductor materials onto a substrate like glass or a flexible material [23]. The panel can achieve an efficiency of approximately 16% [24].



(c)



(d)

Figure 1. Continued.

In addition to monocrystalline, polycrystalline, and thin film-based PV cell technologies, third-generation solar cells encompass emerging technologies such as organic PV cells and concentrating PV (CPV), necessitating further testing and research. Prominent among established varieties within the third generation are Nano crystal-based solar cells, Polymer-based crystal cells, Dye-sensitized solar cells, and concentrated solar cells [25].

3.4 Selection of inverter

The inverter is a crucial component in a solar PV power plant. Its primary role is to interface the solar panels with

the electrical system [26]. In this study, the Sungrow inverter model SG2500 has been selected. Key characteristics of the inverter are outlined in Table 3 [27–29].

3.5 Energy analysis (1E)

The solar radiation and annual energy output for each airport of the solar PV facility are calculated using PVsyst software. The evaluation criteria include the Reference Yield (RY), Final Yield (FY) or Energy Yield (EY), Energy Loss (EL), Performance Ratio (PR), Capacity Utilization Factor (CUF), and Energy Efficiency (EE) [14, 16]. The mathematical expressions are given as,



(e)

Figure 1. Continued.

Table 1. Monthly GHI and ambient temperature values for the selected cities.

Months	Karachi		Islamabad		Peshawar		Lahore		Quetta	
	GHI	T	GHI	T	GHI	T	GHI	T	GHI	T
	kWh/m ²	°C	kWh/m ²	°C	kWh/m ²	°C	kWh/m ²	°C	kWh/m ²	°C
January	124.9	18.61	83.2	10.29	84.3	8.63	84.2	11.71	108.5	8.76
February	134.6	21.54	83.1	13.22	84.2	11.03	102.9	15.89	121.5	11.23
March	178.6	26.29	140.8	18.93	131.9	17.13	142.8	21.77	158.9	17.05
April	190.2	29.18	165.5	23.92	166	22.43	161.6	26.79	186	22.75
May	201.1	31.31	203.8	29.7	196.3	28.4	184.4	32.64	220.6	28.26
June	180.6	31.57	195.6	31.31	197.7	30.89	179.1	32.53	231.1	29.62
July	145.9	30.7	183.3	30.44	193.9	30.79	163.4	31.08	216.9	29.35
August	139.6	29.4	168.2	29.08	170.4	29.33	157.2	30.35	203.3	28.45
September	158.7	29.14	163.8	27.06	162	26.92	149.4	28.69	193.7	26.24
October	154.5	29.33	140.5	22.94	139	22.28	129.3	25.58	164.1	22.37
November	130.1	24.69	108.6	16.15	104.2	15.04	99.1	18.72	126	15.43
December	116.6	20.1	79.4	11.59	87.1	10.4	83.8	13.69	109.2	10.64
Year	1855.4	26.84	1715.9	22.1	1717	21.16	1637.2	24.16	2039.8	20.9

$$RY = \frac{R_h}{G_o}, \quad (1)$$

$$CUF = \frac{E_{gen}}{P_c \times 24 \times 365}, \quad (5)$$

$$FY = \frac{E_{gen}}{P_c}, \quad (2)$$

$$EE = \frac{E_{gen}}{R_h \times A_{pv}}. \quad (6)$$

$$EL = RY - FY, \quad (3)$$

$$PR = \frac{FY}{RY}, \quad (4)$$

The reference yield represents the expected energy output from a PV system under standard conditions. The final yield or energy yield denotes the actual energy production

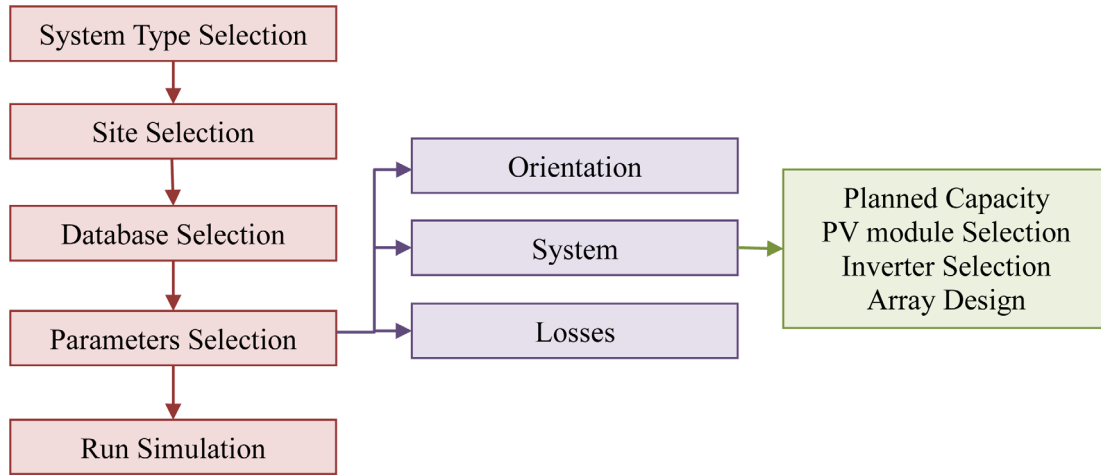


Fig. 2. Steps involved in simulation through PVSyst software.

Table 2. Specific details of considered PV cell technologies.

PV cells technology	Manufacturer	Model	Power rating
Mono-cSi	Canadian solar	CS6U-340M-AG 1500V	340 W _p
	JA solar	JAM60-S10-340-PR	340 W _p
	Trina solar	TSM-DE14A-(II)-340	340 W _p
	LONGI solar	LR6-72 HV 340 M	340 W _p
Poly-cSi	BYD	BYD-340-P6K-36	340 W _p
	Canadian solar	CS3L-340P HE 1500V	340 W _p
	JA solar	JAP72-S10-340-SC	340 W _p
	Trina solar	TSM-PE15H-340	340 W _p
Thin film (CdTe)	First solar	FS-6390A	390 W _p

Table 3. Characteristics of selected inverter.

Main characteristics	
Inverter model	SG2500
Manufacturer	Sungrow
Maximum DC to AC conversion efficiency	98.7
Input side (DC)	
MPPT voltage range	800–1300 V
Maximum voltage	1500V
Output side (AC)	
AC output power	2750 kVA@ 45 °C/2500 kVA@ 50 °C
Output voltage range	10 – 35 kV
Output frequency range	55–65 Hz

achieved by the system in real-world conditions. EL refers to the difference between the reference yield and the final yield. The performance ratio is a metric indicating the overall performance efficiency of the PV system by considering various losses and environmental factors. The capacity

utilization factor (CUF) represents the ratio of the actual energy produced by the system to the maximum possible output under ideal conditions. Energy efficiency is a measure of how effectively the system converts sunlight into usable electricity.

3.6 Exergy analysis (2E)

Exergy analysis in solar PV systems involves assessing the quality and usefulness of energy flows within the system, considering both the quantity and quality of the energy. The amount of solar radiation, the area of PV arrays, and the ambient temperature all play major roles in determining the exergy input of solar radiation (Ex_{in}) and it is evaluated using Petela's relation in equation (7) [30].

$$Ex_{in} = A_{pv} \times R_h \left[1 - \frac{4}{3} \left(\frac{T_a}{T_s} \right) + \frac{1}{3} \left(\frac{T_a}{T_s} \right)^4 \right]. \quad (7)$$

The heat that is radiated from the solar PV module to the surroundings is known as thermal exergy (Ex_{th}) and is calculated by using equation (8).

$$Ex_{th} = U \times A_{pv} \times (T_a - T_m) \left(1 - \frac{T_a}{T_m} \right). \quad (8)$$

Electrical exergy (Ex_{el}) is the term used to describe the electrical power generated by a solar PV system and is estimated using equation (9).

$$Ex_{el} = V_{oc} \times I_{sc} \times FF \quad (9)$$

Exergy output (Ex_{out}) is the algebraic consequence of adding electrical and thermal exergy in equation (10).

$$Ex_{out} = Ex_{el} - Ex_{th}. \quad (10)$$

The ratio of exergy output and exergy input yield exergy input.

$$\eta_{ex} = \frac{Ex_{out}}{Ex_{in}} \times 100. \quad (11)$$

The literature [10, 14, 16] provides comprehensive information on exergy assessment and associated mathematical equations.

3.7 Economic analysis (3E)

Economic viability of the solar PV project can be assessed from the Discounted Payback Period (DPP) and Levelized Cost of Energy (LCOE). The DPP considers the time value of money representing the duration it takes for an investment's cumulative discounted cash flows to reach zero. This metric reflects the time needed to recover the initial investment based on the present value of anticipated future cash flows. The DPP is a more realistic measure of initial investment compared to the simple payback method [31]. The LCOE represents the average cost per unit of electricity generated throughout a project's duration. It involves various expenses such as initial investments, operational and maintenance costs, and any additional charges.

Calculating the DPP involves discounting the cash flows of a project using an appropriate discount rate and then assessing the discounted cumulative cash flows in comparison to the initial investment. The computation of the DPP involves solving the formula expressed in equation (12),

$$\sum_{n=1}^{DPP} \frac{CF_n}{(1+r)^n} - C_{in} = 0, \quad (12)$$

Table 4. Cost break-up for 1MW solar PV facility.

Particulars	Cost (m\$/MW)
PV modules (Crystalline Silicon)	0.23
Capital cost of CdTe panels [32]	0.28
Tracking system	0.048
PV Inverters	0.04
Mounting structure	0.108
Balance of plant (Civil works, cables, transformer, etc.)	0.224
Project development Cost	0.0132
Insurance during construction	0.0026
Financing fee and charges	0.01065
Other cost during construction	0.01325

where CF is the cash inflow and is assumed to be the same throughout the life cycle of the PV system, n is the PV system life considered as 25 years, and r is the discount rate taken as 22%. Equation (13) provides another way of stating the DPP.

DPP = Year before full recovery

$$+ \frac{\text{Uncovered cost at start of the year}}{\text{Discounted cash flow during the year}}. \quad (13)$$

The LCOE can be determined using equation (14)

$$LCOE = \frac{\sum_{t=1}^n \frac{C_{in,t} + C_{m,t}}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}}, \quad (14)$$

where $C_{in,t}$, $C_{m,t}$ and E_t are the investment and expenditures for the year (t), Operational and maintenance expenditures for the year (t), and electricity production for the year (t), respectively.

The price of a 1MW solar PV system includes PV modules, tracking systems, PV inverters, mounting structures, balance of plant (Civil Works, Cables, Transformer, etc.), project development cost, insurance during construction, financing fee and charges, and other cost during construction. The cost breakup (in million dollars per megawatts, m\$/MW) is disclosed in Table 4 [32, 33] and in Figure 3. It is important to note that these cost components were derived from industry-specific documents, ensuring an accurate representation of the financial parameters. However, variations in these costs over time will influence the overall economic outcomes. Similarly, the same amount of electrical energy is supposed to be produced every year throughout the lifetime.

3.8 Environmental analysis

By using solar-generated electricity, the airport indirectly cuts its carbon emissions. The reduction of GreenHouse Gas (GHG) emissions is one of the major advantages of PV systems. The electricity emission factor for Pakistan is 0.473378547 kgCO₂/kWh [35]. This factor represents the amount of carbon dioxide (CO₂) emitted per unit of

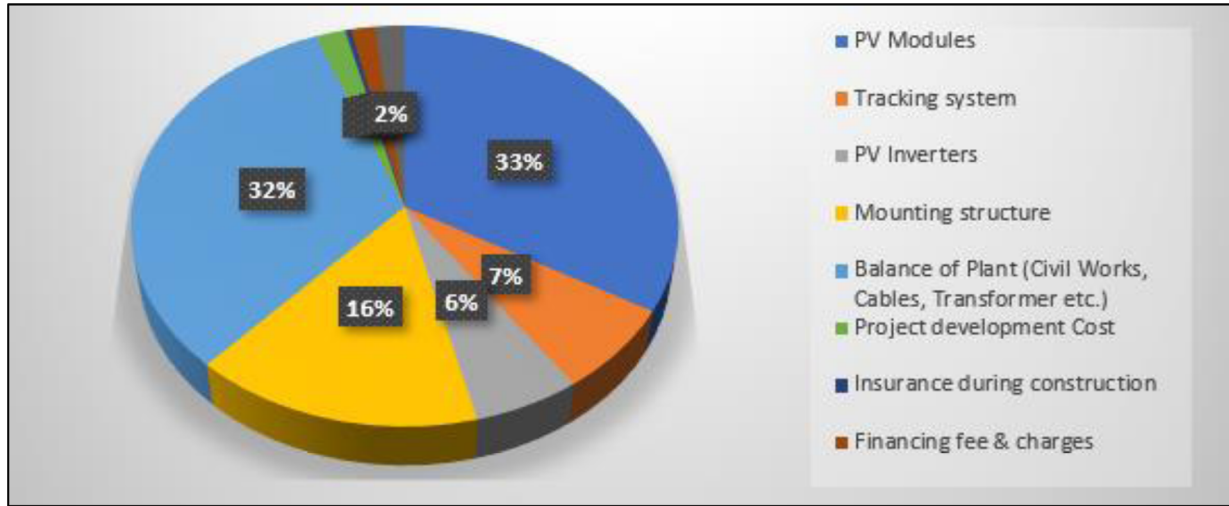


Fig. 3. Chart representation of cost breakup for 1MW solar PV system.

electricity generated in Pakistan. It is a crucial parameter for assessing the environmental impact of electricity production and is often used in calculations related to carbon footprint and emissions associated with energy consumption. At airport premises, the environmental impact of a PV module is examined in this study using a multi-criteria approach.

3.8.1 Energoenvironmental (ENEN) analysis (4E)

Energy-environmental study evaluates the CO₂ and other GHG emissions linked with production and consumption. According to this viewpoint, system analysis is conducted using the following relationship [7, 12]

$$X_{\text{CO}_2} = Y_{\text{CO}_2} \times P_{\text{out}} \times t_{\text{working}} \quad (15)$$

where X_{CO_2} shows how much carbon dioxide was emitted in a specific period of time, Y_{CO_2} reveals the value of carbon dioxide emissions, P_{out} and t_{working} represent the system's power output and operational time, respectively.

3.8.2 Exergoenvironmental (EXEN) analysis (5E)

Assessing the link between exergy and environmental effects is known as exergoenvironmental analysis. The system operational time, carbon emissions, and exergy analysis are the main three components for this analysis [7, 12]

$$X_{\text{ex,CO}_2} = Y_{\text{CO}_2} \times \dot{E}x_{\text{out}} \times t_{\text{working}} \quad (16)$$

where $X_{\text{ex,CO}_2}$ shows how much carbon dioxide was emitted in a specific period of time considering exergetic values and $\dot{E}x_{\text{out}}$ indicates the rate of exergy of the solar energy.

3.8.3 Exergoenvironoeconomic (ENENEC) analysis (6E)

The ENENEC integrates the findings from energy, environmental, and economic analyses to evaluate the trade-offs and synergies among these aspects. This parameter can be evaluated by employing equation (17)

Table 5. Cost of carbon dioxide.

Carbon trading price	78.99	€/tonCO ₂
	85.3092	\$/tonCO ₂

$$C_{\text{CO}_2} = X_{\text{CO}_2} \times c_{\text{CO}_2} \quad (17)$$

where c_{CO_2} indicates the cost of CO₂ and C_{CO_2} shows the energetic price of carbon dioxide. While carbon pricing may vary over time, this study adopts the specific carbon dioxide pricing detailed in Table 5 for the estimation of parameters [36].

3.8.4 Exergoenvironoeconomic (EXENEC) analysis (7E)

Exergy-based environoeconomic analysis closely resembles energy-based environoeconomic analysis, with the key distinction that exergy is employed in calculations instead of energy, as indicated by equation (18)

$$C_{\text{ex,CO}_2} = X_{\text{ex,CO}_2} \times c_{\text{CO}_2} \quad (18)$$

4 Results and discussion

4.1 Initial site appraisal

After an initial assessment of available space, it was determined that all selected airports have sufficient acreage to accommodate the proposed 5 MW solar PV system as seen in Table 6.

4.2 Energy analysis

Energy assessment is conducted using three distinct solar panel technologies: monocrystalline silicon panels (mono-cSi), polycrystalline silicon panels (poly-cSi), and thin film-based panels (CdTe). The analysis considers both fixed tilt and single-axis tracking mounting structures. A detailed spreadsheet comprising 7E assessments for every airport is

Table 6. Available area at airport premises.

Airports	Latitude and Longitude	Sites	Site area (Ac)	Total site area (Ac)	Remarks
Karachi	24.9008°N, 67.1681°E	Site #1	9.86	118.67	✓
		Site #2	17.09		
		Site #3	91.72		
Islamabad	33.5563°N, 72.8341°E	Site #1	30	93.65	✓
		Site #2	14.6		
		Site #3	2.54		
		Site #4	46.51		
Peshawar	33.9898°N, 71.5192°E	Site #1	3.96	29.65	✓
		Site #2	9.98		
		Site #3	5.49		
		Site #4	3.6		
		Site #5	6.62		
Lahore	31.5203°N, 74.4104°E	Site #1	33.76	152.94	✓
		Site #2	19.38		
		Site #3	65.21		
		Site #4	26.19		
		Site #5	8.4		
Quetta	30.2491°N, 66.9488°E	Site #1	6.21	115.99	✓
		Site #2	12.73		
		Site #3	97.05		

1 MW solar PV power system requires 3.5 acres [16].

in the [Supplementary material](#). The major results are discussed in this section. The solar irradiation values and corresponding energy production are obtained through the utilization of PVSyst simulation software.

4.2.1 Monocrystalline silicon technology

Energy analysis is conducted on solar panels from four different manufacturers (Canadian Solar, JA Solar, Trina Solar, and Longi Solar) utilizing monocrystalline silicon technology with the same power rating of 340 W. The selected companies exhibit efficiencies ranging from 17.5% to 20.2%.

Quetta Airport showed the highest reference yield among all chosen technologies due to receiving more solar irradiation. In contrast, Lahore Airport has the lowest reference yield, as it receives the least solar irradiation among the selected airports. The reference yield for Quetta Airport ranges from 2186 kWh/kW to 2205 kWh/kW, while for Lahore Airport, it ranges from 1724 kWh/kW to 1738 kWh/kW for fixed tilt. For single-axis tracking, the reference yield for Quetta Airport ranges from 2739 kWh/kW to 2750 kWh/kW, and for Lahore Airport, it ranges from 1936 kWh/kW to 1947 kWh/kW. Single-axis tracking consistently results in higher yields compared to fixed tilt configurations. It highlights the pivotal role of both technology and configuration choices in determining reference and final yields. The higher final yield at Quetta airport indicates a more effective utilization of solar resources, leading to enhanced energy production.

In contrast, the lower final yield at Lahore Airport raises critical considerations regarding the economic and environmental viability of solar installations.

The final yield of a PV system is closely related to the capacity utilization factor (CUF). For this reason, Quetta Airport emerges as the optimal location, exhibiting the highest values among the selected airports (18.79–21.48% for fixed tilt and 23.26–26.82% for single-axis tracking). In contrast, Lahore Airport is identified with the lowest values (14.86–16.94% for fixed tilt and 16.66–19.06% for single-axis tracking). A higher CUF correlates with a more efficient and effective use of solar energy resources that contributes to a higher final yield.

The analysis highlights significant variations in the performance ratios of the selected airports. Peshawar Airport demonstrates the most favorable ratios whereas Karachi Airport records the lowest values. For Peshawar airport, the performance ratios range from 75.76% to 86.98% for fixed tilt and 75.91% to 87.24% for single-axis tracking. It indicates a high level of efficiency in converting sunlight into usable electricity. Conversely, at Karachi Airport, the performance ratios span from 73.94% to 85.16% for fixed tilt and 74.04% to 85.40% for single-axis tracking.

Energy efficiency and performance ratios are interrelated metrics that reflect the effectiveness of a PV system. For this reason, the energy efficiency of Peshawar Airport stands out as the highest (ranging from 14.966% to 17.586% for fixed tilt and 14.997% to 17.638% for single-axis tracking). In contrast, Karachi Airport exhibits the lowest energy efficiency (ranging from 14.549% to 17.219% for fixed tilt and

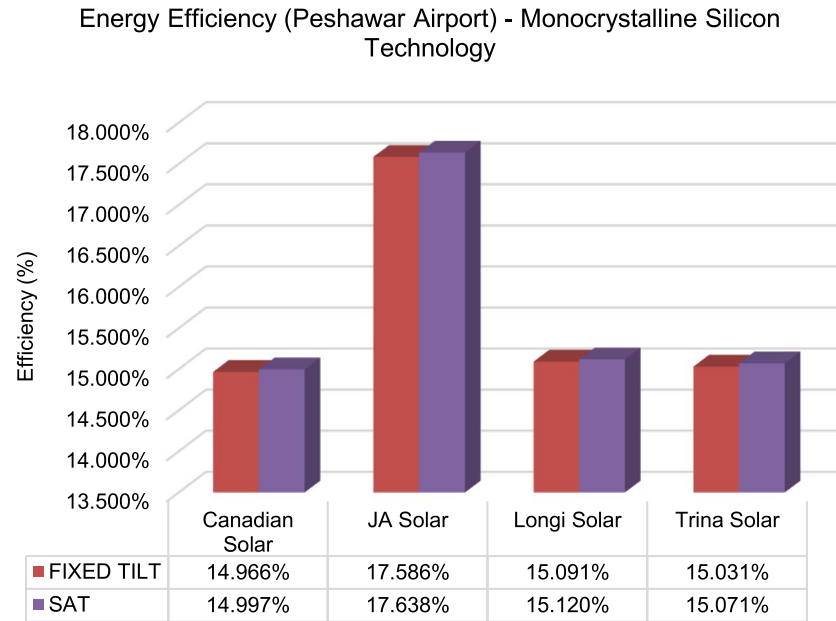


Fig. 4. The energy efficiency comparison for the two mounting structures at Peshawar Airport for mono-cSi technology.

14.537% to 17.267% for single-axis tracking). The energy efficiency comparison for the two mounting structures at Peshawar Airport is illustrated in [Figure 4](#).

4.2.2 Polycrystalline silicon technology

In the analysis of polycrystalline silicon technology, four manufacturers (BYD, Canadian Solar, JA Solar, Trina Solar) were considered revealing the same trend as of monocrystalline technology. For Quetta Airport, the reference yield ranges from 2186 kWh/kW to 2209 kWh/kW for fixed tilt and 2739 kWh/kW to 2749 kWh/kW for single-axis tracking. Meanwhile, Lahore Airport exhibits a range of 1723 kWh/kW to 1740 kWh/kW for fixed tilt and 1936 kWh/kW to 1948 kWh/kW for single-axis tracking. The final yield for Quetta Airport ranges from 1865 kWh/kW to 1887 kWh/kW for fixed tilt and 2327 kWh/kW to 2350 kWh/kW for single-axis tracking, while for Lahore Airport, it varies from 1473 kWh/kW to 1489 kWh/kW for fixed tilt and 1656 kWh/kW to 1672 kWh/kW for single axis tracking.

Peshawar Airport emerges as the most suitable location with the highest performance ratio values among all examined airports (85.17–86.68%, FT, and 85.93–86.95%, SAT). Conversely, Karachi Airport is anticipated to have the lowest performance ratio values (84.04–84.72%, FT, and 84.19–84.75%, SAT). In terms of Capital Utilization Factor (CUF), Quetta Airport stands out as the most favorable location with the highest values among all examined airports (21.29–21.54%, FT, and 26.57–26.83%, SAT), while Lahore Airport is projected to have the lowest CUF values (16.82–17%, FT, and 18.91–19.09%, SAT).

Peshawar Airport displays the highest energy efficiency among the examined airports, with values ranging from 14.398% to 15.76% (FT) and 14.439% to 15.78% (SAT). In contrast, Karachi Airport exhibits the lowest energy

efficiency, ranging from 14.083% to 15.43% (FT) and 14.115% to 15.46% (SAT), owing to its highest EL value in comparison to other airports. Refer to [Figure 5](#) for a visualization of the energy efficiency of the two mounting structures at Peshawar Airport.

4.2.3 Thin film-based technology (CdTe)

First Solar, representing thin film-based (CdTe) technology, was selected for the energy assessment. The results reveal a consistent trend across all airports utilizing thin film-based technology for RY, EY, PR, CUF, and EE. Quetta Airport emerges with the highest values for reference yield (2212 kWh/kW FT and 2752 kWh/kW SAT), final yield (1947 kWh/kW FT and 2420.8 kWh/kW SAT), and CUF (22.22% FT and 27.63% SAT) due to its superior solar irradiation. Conversely, Lahore Airport exhibits the lowest values for reference yield (1743 kWh/kW FT and 1949 kWh/kW SAT), final yield (1532 kWh/kW FT and 1720.4 kWh/kW SAT), and CUF (17.49% FT and 19.64% SAT) as it receives the least solar irradiation among the chosen airports for both mounting structures. Peshawar Airport secures the highest energy efficiency (13.95% FT and 14% SAT) and performance ratio (88.53% FT and 88.90% SAT) owing to its lowest EL value, while Karachi Airport records the lowest energy efficiency (13.681% FT and 13.722% SAT) and performance ratio (86.84% FT and 87.1% SAT) due to the highest EL. Refer to [Figure 6](#) for a visual representation of the energy efficiency variance across the chosen airports.

4.3 Exergy analysis

The three solar panel technologies: mono-cSi, poly-cSi, and CdTe, were employed for exergy evaluation under both fixed tilt and single-axis tracking configurations.

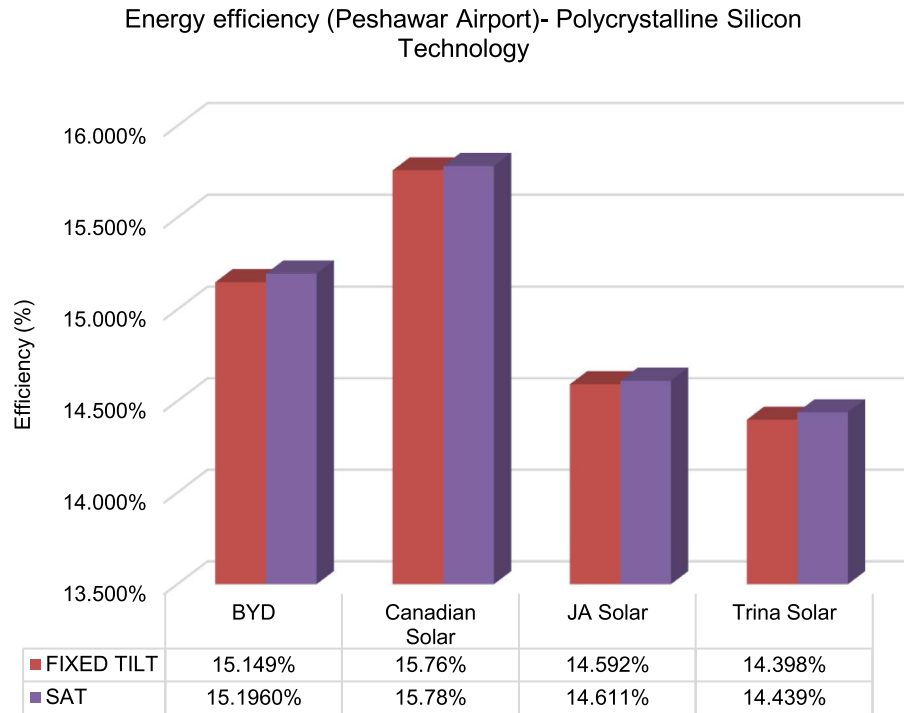


Fig. 5. The energy efficiency comparison for the two mounting structures at Peshawar Airport for Poly-cSi technology.

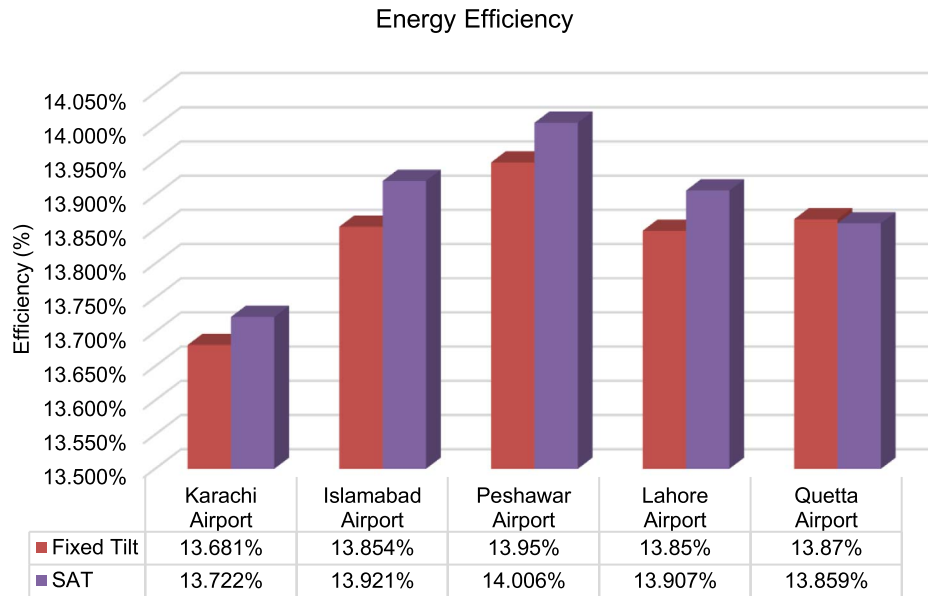


Fig. 6. The energy efficiency comparison for the two mounting structures across all airports for thin film technology.

Quetta Airport demonstrates the highest input exergy values across all technologies, ranging from 51.3 MW to 69.27 MW for mono-cSi, 56.28 MW to 78.89 MW for poly-cSi, and 63.6 MW for CdTe. However, despite the elevated electrical exergy, Quetta records the lowest exergy efficiency ratings. This difference is due to the higher thermal exergy, indicating significant thermal losses.

In contrast, Karachi Airport exhibits a narrower input exergy range, varying from 31.46 MW to 42.7 MW for mono-cSi, 34.67 MW to 44.7 MW for poly-cSi, and 39.17 MW for CdTe. Notably, Karachi displays a higher exergy efficiency range, spanning from 4.15% to 10.05% for mono-cSi, 5.35% to 8.10% for poly-cSi, and 9.35% for CdTe. The superior exergy efficiency at Karachi is

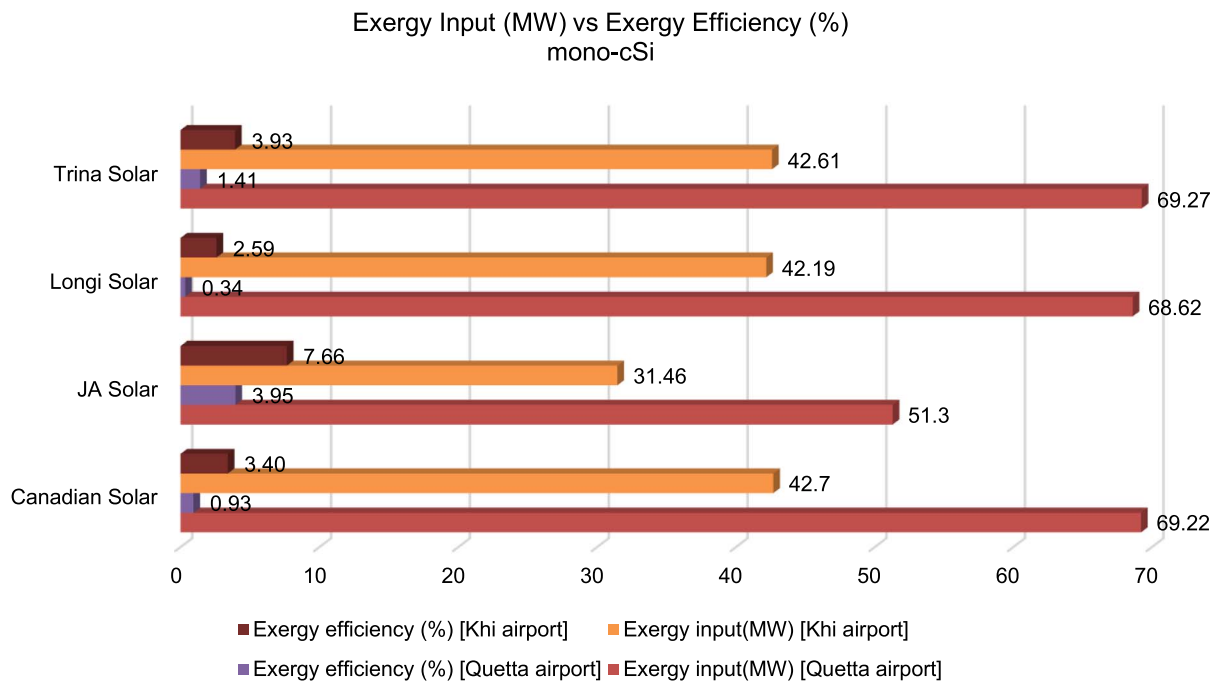


Fig. 7. Comparison of exergy input and exergy efficiency (mono-cSi).

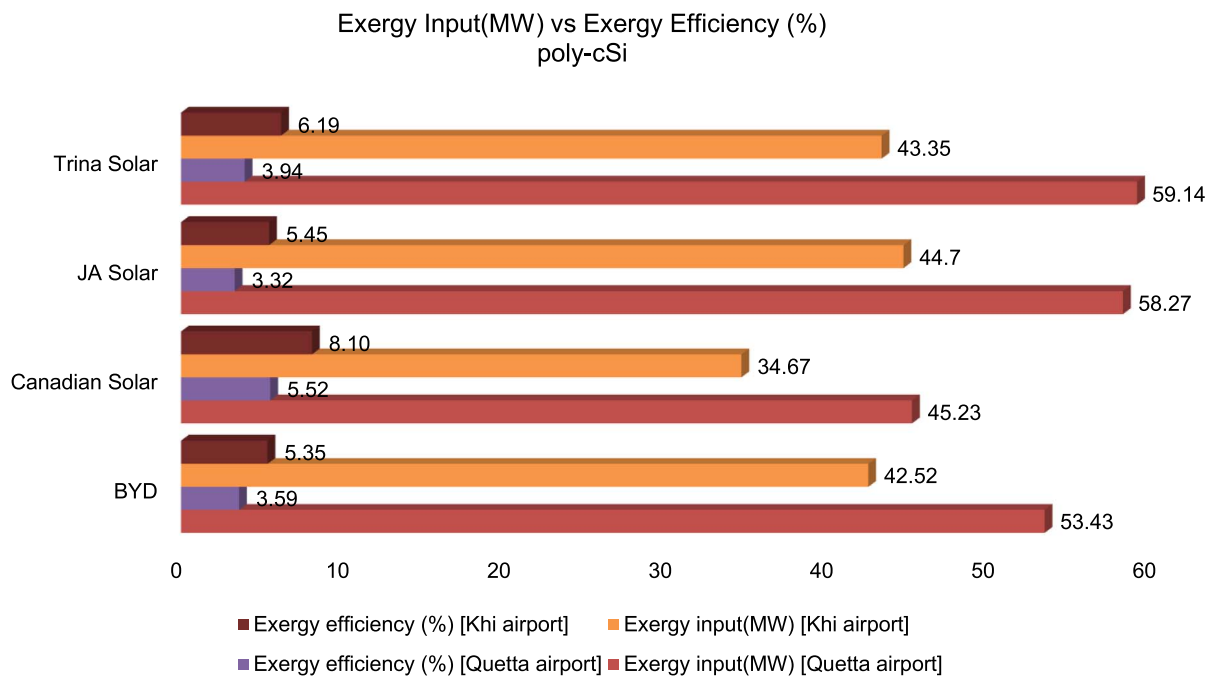


Fig. 8. Comparison of exergy input and exergy efficiency (poly-cSi).

attributed to lower thermal exergy values, suggesting reduced thermal losses.

These findings highlight the impact of solar radiation and ambient temperature on thermal losses and, consequently, exergy efficiency. The visual representations in Figures 7 to 9 show a comparison of exergy input and exergy efficiency between Karachi and Quetta airports for mono, poly, and thin film-based technologies.

4.4 Economic analysis

The economic assessment indicates that Quetta Airport has the lowest values of LCOE and DPP among all selected airports for each technology. Conversely, Lahore Airport displayed the highest values for both LCOE and DPP.

During the period from February 2022 to July 2023, the fluctuating interest rates, ranging from 9.75% to 22%, have

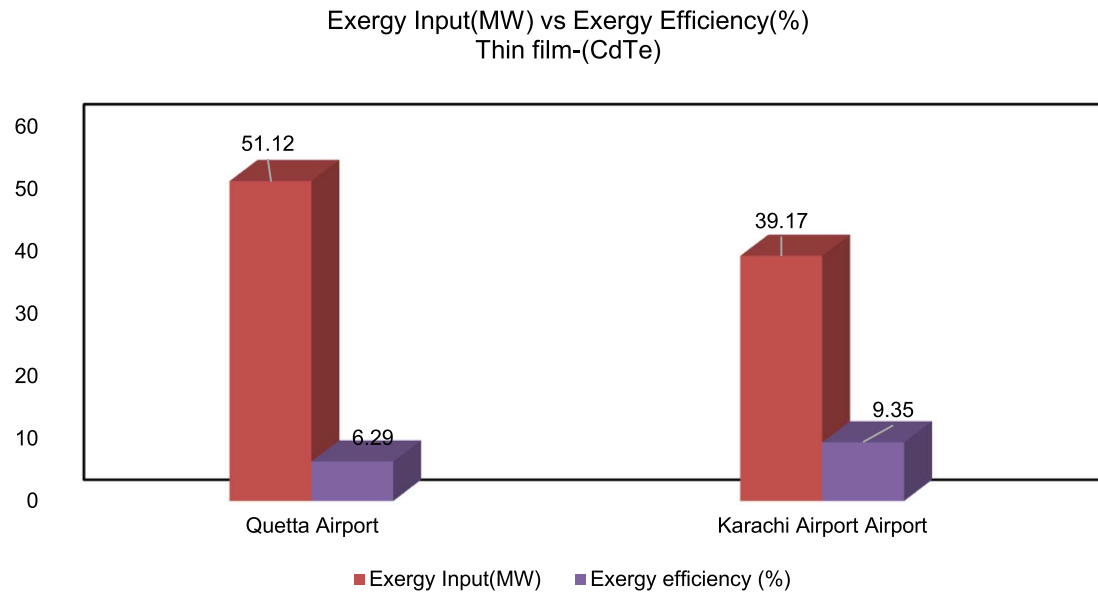


Fig. 9. Comparison of exergy input and exergy efficiency (CdTe).

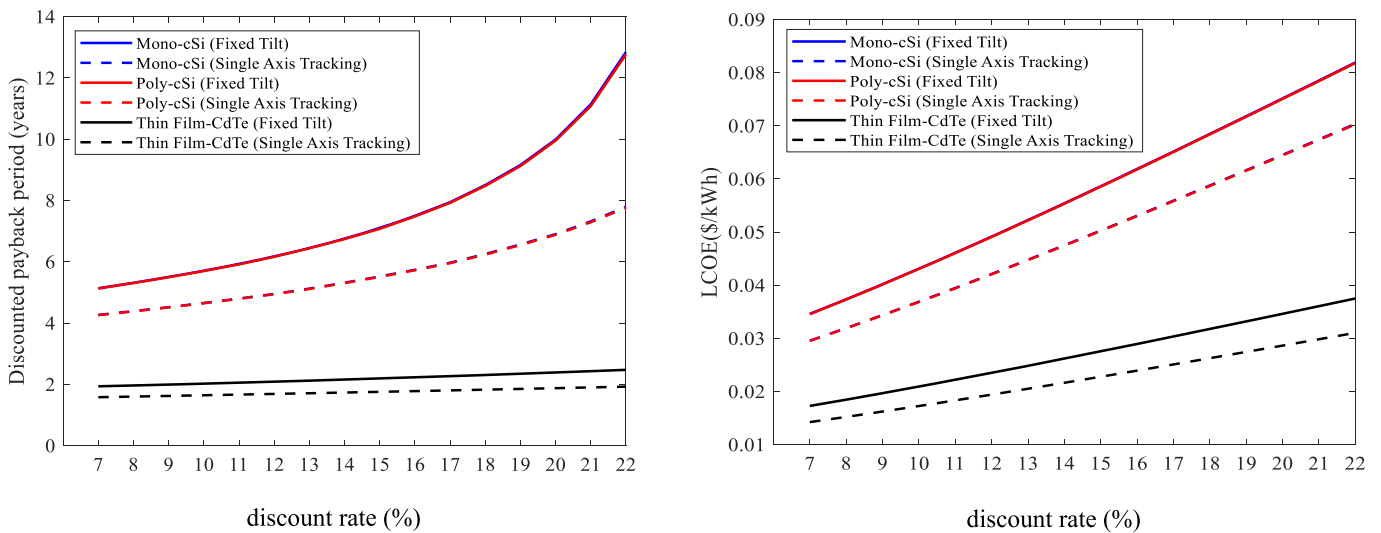


Fig. 10. The effect of discount rate on LCOE and DPP for Quetta airport.

influenced the economic dynamics of solar projects [37]. A detailed analysis in Figure 10 illustrates the impact of these varying interest rates on LCOE and DPP for Quetta Airport, providing insights into the financial implications of different discount rates.

From Figure 10, it is observed that the payback period for poly-cSi (fixed tilt configuration) varies from 5.14 years at a 7% discount rate to a more extended 12.85 years at a 22% discount rate. This aligns with the LCOE, which starts at 0.0346 at a 7% discount rate and gradually rises to 0.0819 at a 22% discount rate.

The poly-cSi (single-axis tracking) configuration displays a payback period that commences at 4.27 years with a 7% discount rate, extending to 7.80 years at a 22% discount rate. Similarly, the LCOE starts at 0.0296 with

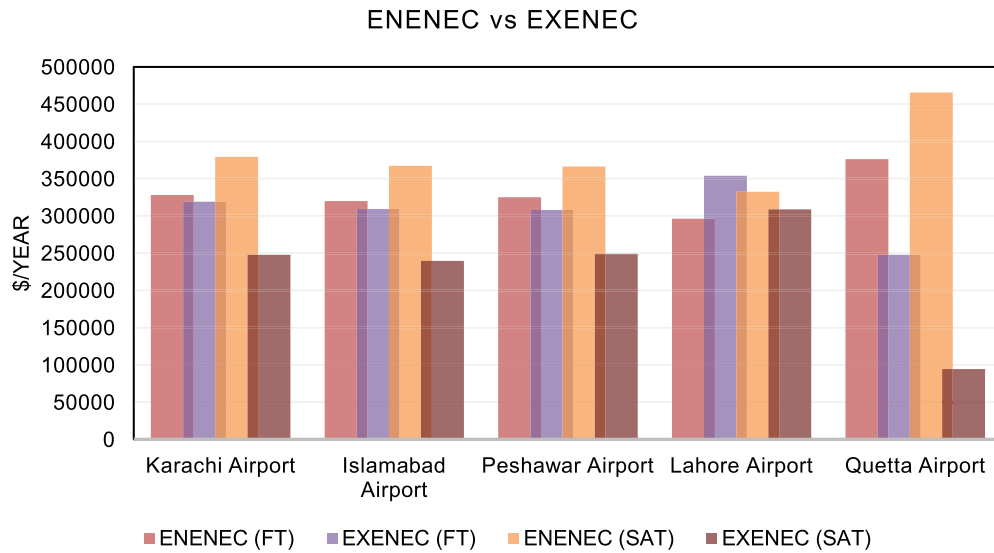
a 7% discount rate and increases to 0.0704 with a 22% discount rate. Both fixed tilt and single-axis tracking configurations of mono-cSi exhibit similar trends, with payback periods and LCOE values escalating as the discount rates rise.

In contrast, the thin film configurations present more cost-effective LCOE values. Overall, single-axis tracking configuration of thin Film stands out with the most favorable across different discount rates ranging from 1.58 years at a 7% discount rate to 1.93 years at a 22% discount rate.

Figure 10 also exhibits the cumulative effect of discount rates and initial investment on payback periods. When dealing with a higher discount rate coupled with a larger initial investment, the impact on the payback period is large and sometimes unprofitable throughout the project's

Table 7. EXEN analysis – Lahore Airport.

Technology	Mitigated CO ₂ (tCO ₂ /year)
Monocrystalline	3414–5766 FT, 2892–5370 SAT
Polycrystalline	4301–5106 FT, 3772–4774 SAT
Thin film (CdTe)	6693 FT, 6213 SAT

**Fig. 11.** Comparison of ENENEC and EXENEC of airports.

lifetime. This is because the increased discount rate speeds up the devaluation of future cash flows, putting significant pressure on recovering the larger initial cost. The dual effect of a higher discount rate and a greater initial investment can lead to an exponential increase in the payback period.

On the other side, when dealing with a higher discount rate alongside a lower initial investment, the effect on the payback period is more restrained. While the heightened discount rate still accelerates the devaluation of future cash flows, the lower initial investment lessens the extent to which capital needs to be recovered. Consequently, the increase in the payback period tends to be more moderate. Hence, the initial investment plays a pivotal role in shaping the financial performance despite the higher discount rates. For this reason, thin-film panels have a more favorable economic outlook. Therefore, optimizing initial costs through efficient procurement will assist in reducing the payback period of the other configurations as well.

4.5 Environmental analysis

4.5.1 Energoenvironmental (ENEN) and Exergoenvironmental (EXEN) analyses

The ENEN analysis highlights that Quetta Airport is the most suitable location for mitigating CO₂ emissions, with the highest values of avoided carbon dioxide ranging from 3895 tCO₂/year to 4453 tCO₂/year for mono-cSi (FT), 4823 tCO₂/year to 5561 tCO₂/year for mono-cSi (SAT),

4414 tCO₂/year to 4466 tCO₂/year for poly-cSi (FT), 5508 tCO₂/year to 5562 tCO₂/year for poly-cSi (SAT), and 4607 tCO₂/year for thin film-CdTe (FT) and 5730 tCO₂/year for thin film-CdTe (SAT). Quetta Airport is favored due to its higher solar irradiation.

Conversely, Lahore Airport exhibits the lowest values for CO₂ mitigation. However, in the ExergoEnviro Economic (EXENEC) assessment, Lahore Airport plays a more significant role in CO₂ mitigation compared to other airports. This is attributed to Lahore Airport having the lowest thermal losses in terms of exergy, while Quetta Airport shows the lowest values of EXEN. These findings are summarized in Table 7.

4.5.2 Energoenviroeconomic (ENENEC) and Exergoenviroeconomic (EXENEC) analyses

The trends observed in the ENENEC and EXENEC studies align with those of the ENEN and EXEN analyses. The graphical representation of the study's findings is illustrated in Figure 11.

4.6 Comparative discussions

A detailed analysis of FS-6390A has been given in Table 8 for both fixed tilt and single-axis tracking. The analysis presented in Table 8 compares solar configurations across all airports, showing variations in performance metrics, economic factors, and environmental impacts. This highlights

Table 8. Detailed analysis of FS-6390A for both fixed tilt and single-axis tracking at all locations.

Parameters	Airports				
	Karachi	Islamabad	Peshawar	Lahore	Quetta
Energy analysis					
Fixed tilt					
Reference yield (kWh/kW)	1960	1875	1889	1743	2212
Final yield (kWh/kW)	1702	1648.8	1672.4	1532	1946.6
Performance ratio (%)	86.84	87.94	88.53	87.89	88.00
Capital utilization factor (%)	19.43	18.82	19.09	17.49	22.22
Energy efficiency (%)	13.68	13.85	13.95	13.85	13.87
Single-axis tracking					
Reference yield (kWh/kW)	2265	2151	2124	1949	2752
Final yield (kWh/kW)	1972.8	1900.6	1888.2	1720.4	2420.8
Performance ratio (%)	87.10	88.36	88.90	88.27	87.97
Capital utilization factor (%)	22.52	21.70	21.55	19.64	27.63
Energy efficiency (%)	13.72	13.92	14.00	13.90	13.86
Exergy analysis					
Fixed tilt					
Exergy input (MW)	39.17	53.07	55.38	44.9	51.12
Thermal exergy (MW)	1.332	1.397	1.4103	1.121	1.78
Electrical exergy (MW)	4.99	4.99	4.99	4.99	4.99
Exergy output (MW)	3.66	3.59	3.58	3.87	3.21
Exergy efficiency (%)	9.35	6.78	6.47	8.63	6.29
Single-axis tracking					
Exergy input (MW)	45.27	60.88	62.27	50.21	63.6
Thermal exergy (MW)	1.771	1.833	1.778	1.398	2.736
Electrical exergy (MW)	4.994	4.995	4.995	4.995	4.995
Exergy output (MW)	3.222	3.161	3.216	3.595	2.258
Exergy efficiency (%)	7.12	5.19	5.17	7.16	3.55
Economic analysis					
Fixed tilt					
LCOE (\$/kWh)	0.0429	0.0443	0.0437	0.0477	0.0375
Discounted payback (years)	2.96	3.11	3.04	3.48	2.47
Single-axis tracking					
LCOE (\$/kWh)	0.0381	0.0395	0.0398	0.0437	0.0310
Discounted payback (years)	2.54	2.67	2.69	3.05	1.93
Environmental analysis					
Fixed tilt					
ENEN (tCO ₂ /year)	4028	3903	3958	3626	4607
EXEN (tCO ₂ /year)	6328	6216	6193	6693	5554
ENENEC (\$/year)	343,628	332,964	337,656	309,334	393,023
EXENEC (\$/year)	539,872	530,291	528,331	570,974	473,836
Single axis tracking					
ENEN (tCO ₂ /year)	4669	4499	4469	4072	5730
EXEN (tCO ₂ /year)	5568	5463	5558	6213	3902
ENENEC (\$/year)	398,312	383,809	381,250	347,382	488,826
EXENEC (\$/year)	474,986	466,024	474,131	530,026	332,920

the importance of adopting a comprehensive and context-specific approach. While fixed tilt configurations demonstrate higher reference yields in specific locations like Karachi and Quetta, the practical advantages often favor single-axis tracking, especially in airports situated in Islamabad, Peshawar, and Lahore. In terms of exergy efficiency, reflecting the quality of the produced energy, Karachi showed the highest values for both fixed tilt and single-axis tracking configurations. This emphasizes the importance of considering not only the quantity of energy produced but also its quality. Economically, single-axis tracking configurations exhibit lower levelized cost of electricity values across all cities, indicating enhanced economic viability compared to fixed tilt configurations. The DPP further supports this, indicating that single-axis tracking systems offer quicker returns on investment. This economic advantage becomes particularly significant in projects where financial considerations are paramount.

In terms of avoided carbon dioxide emissions (ENEN), Quetta Airport consistently exhibits the highest values for both fixed tilt and single-axis tracking, indicating a potential environmental advantage due to higher solar irradiation. However, when considering the combined exergetic and environmental performance (EXEN), Karachi Airport stands out with the lowest values in both configurations, suggesting a more efficient integration of exergy and environmental considerations. Economically, Lahore Airport demonstrates the lowest economic cost associated with environmental benefits (ENENEC) in both scenarios, while Quetta Airport has the highest values. This implies that while Quetta leads in environmental gains, Lahore has a more cost-effective approach to emissions mitigation. The economic cost associated with the combined exergy and environmental performance (EXENEC) follows a similar trend, with Lahore being the most cost-effective among the selected airports. Therefore, the decision will depend on the specific priorities and goals of the project. If prioritizing environmental impact, Quetta could be considered. For a focus on efficient exergy use, Karachi might be preferred. However, for a balanced and cost-effective approach, Lahore stands out as a strong candidate.

5 Conclusion

In conclusion, the comprehensive analysis of various solar PV systems across different airports in Pakistan provides valuable insights into the economic, environmental, and technical aspects of renewable energy integration. The careful evaluation of technology configurations, such as mono-cSi, poly-cSi, and CdTe, under both fixed tilt and single-axis tracking setups, reveals the performance variations.

Quetta Airport stands out as a promising investment with a selection of thin film-based technology with single-axis tracking. The performance metrics collectively demonstrate both economic returns and environmental benefits. More specifically, it includes a reference yield of 2752 kWh/kW, a final yield of 2420.8 kWh/kW, and a capacity utilization factor (CUF) of 27.63%. The short

1.9-year DPP reflects a rapid return on the initial investment. Simultaneously, the substantial carbon dioxide avoidance at 5730 tCO₂ per annum and \$488,826/year in GHG revenue emphasize the positive environmental impact of the system.

Furthermore, the comparative analysis among airports highlights the importance of considering a holistic approach that balances economic efficiency and environmental sustainability. Peshawar Airport stands out with the highest performance ratio and energy efficiency ratings among all airports considered. Lahore Airport exhibits commendable performance in terms of economic costs associated with environmental benefits. Similarly, Karachi Airport demonstrates efficient combined exergetic and environmental performance. Overall, Quetta Airport's thin film-based system with single-axis tracking emerges as a well-rounded solution.

This study contributes to the understanding of optimal solar PV configurations and their implications for diverse airports, providing valuable insights for future renewable energy projects in the region. It highlights the need for a tailored approach, considering specific technological choices and configurations to maximize both economic returns and environmental contributions for sustainable energy solutions.

Although the study provides valuable insights into the performance of solar energy systems, there exist certain limitations. The data constraints and assumptions regarding technological parameters may affect the precision of the analysis. Additionally, the economic variables influenced by local economic conditions and policies, are subject to change that will impact the accuracy of projections. Also, the study did not consider socio-political factors such as space constraints and security measures.

For future research, a more comprehensive analysis is recommended including an exploration of socio-political influences, detailed assessments of available space, security measures, and airport-specific energy demands. Furthermore, investigating the integration of advanced technologies, such as artificial intelligence and machine learning, to optimize real-time performance along with developing dynamic economic impact models will provide a more accurate projection of the long-term economic viability of solar installations in airport environments.

Supplementary material

Supplementary materials are available at <https://doi.org/10.2516/stet/2024007/olm>.

- Results for PV powerplant performance analysis using 7E methodology at selected airports of Pakistan.

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