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Comparative Techno-Economic Evaluation of a Standalone Solar Power System for Scaled Implementation in Off-Grid Areas

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Abstract: The increasing environmental concerns and dependence on fossil fuel-based energy sectors necessitate a shift towards renewable energy. Off-grid communities can particularly benefit from standalone, scaled renewable power plants. This study developed a comprehensive techno-economic framework, analyzed the objective metrics, and assessed the influence of economies of scale in solar PV power plants to electrify off-grid communities, taking Baluchistan, Pakistan, as a pilot case. Simulations and analyses were performed using the System Advisor Model (SAM). The results indicate a noteworthy reduction in the levelized cost of energy (LCOE) with increased power generation capacity. It was observed that utilizing bi-facial modules with single-axis tracking leads to a more cost-effective LCOE compared to the relatively expensive dual-axis trackers. The main cost factors identified in the analysis were capital costs, installed balance of plant (BOP), mechanical, and electrical costs. Notably, the disparity between the highest and lowest LCOE values across the six different power generation pathways amounted to approximately 38.5%. The average LCOE was determined to be 2.14 USD/kWh for fixed-mounted plants, 1.79 USD/kWh for single-axis plants, and 1.74 USD/kWh for dual-axis plants across the examined power generation capacity range. The findings can serve as a valuable benchmark, specifically for regional key stakeholders, in making informed investment decisions, formulating effective policies, and devising appropriate strategies for off-grid electrification and the development of renewable energy value chains.

Keywords: solar PV; techno-economic analysis; economy of scale; off-grid electrification

Citation: Sadiq, M.; Kokchang, P.; Kittipongvises, S. Comparative Techno-Economic Evaluation of a Standalone Solar Power System for Scaled Implementation in Off-Grid Areas. *Energies* **2023**, *16*, 6262. https://doi.org/10.3390/en16176262

Academic Editors: Konstantinos Aravossis and Eleni Strantzali

Received: 29 July 2023
Revised: 23 August 2023
Accepted: 24 August 2023
Published: 28 August 2023

1. Introduction

The renewable energy sector is continuously evolving, with technological advancements improving the efficiency and cost-effectiveness of renewable energy systems (RES) [1]. As technology progresses, off-grid communities can benefit from more affordable and improved renewable energy solutions [2]. Reliance on centralized power grids can be challenging in remote or off-grid areas where infrastructure development is limited. The adoption of RES would enable these communities to achieve self-sufficiency and reduce dependence on external energy sources.

Like many other developing nations, Pakistan faces significant electricity challenges access, affordability, and shortfall. Around 40% of the population lacks access to reliable electricity, while even those with access encounter issues such as electricity shortages and high prices [3]. Moreover, 37.2% of Pakistan's population live in extreme poverty in 2023, earning an average of USD 3.65 per day [4]. This means that they may struggle to afford its usage even if they have access to the national electricity grid. As of August 2022, the electricity deficit in Pakistan has escalated to 7461 MW [5]. Considering an anticipated surge in electricity demand, this deficit is anticipated to escalate significantly, reaching a staggering 40,000 MW by the year 2030 [6]. These statistics highlight the need for Pakistan to address the electricity shortfall issues while considering the accessibility and affordability challenges faced by a significant portion of the population.

Baluchistan is the largest province in terms of area in Pakistan [7], and approximately 85% of its total population (13.16 million) resides in rural areas, leading this province to be known as the "powerless province" [8]. The electrification rate in this province stands at around 23%, significantly lower than the average national electrification rate of 72% [9]. As of 2023, the electricity demand is 1650 MW, but only 400–600 MW are supplied, resulting in persistent and regular load shedding (power/grid outages) of 12–18 h/day in main towns, excluding the capital city of Quetta, regardless of the season [10]. The situation in rural areas of this province is even worse, with electricity available for only 4 h/day, and significant areas still are beyond the jurisdiction of the national or regional grid systems [11]. Consequently, this province suffers greatly in terms of agricultural, industrial, and trade activities, in addition to civic problems, making it the least-developed province. The National Transmission and Despatch Company (NTDC) has a total electric transmission line of ~27 km in the province, capable of transmitting a maximum of around 600 MW [9]. Therefore, even when the government issues orders to reduce load shedding across the country, it does not provide any relief to consumers in Baluchistan due to the inadequate and insufficient transmission and distribution network.

The energy needs in Baluchistan Province are predominantly fulfilled through biomass energy sources such as firewood, animal dung, and agricultural waste [12]. However, electricity consumption is increasing at a rate of 17% per year [13]. The province has significant potential for solar, wind, geothermal, and micro-hydro power. Around 40% of its land receives solar energy at 6 kWh/m^2 per day, which adds up to a power generation potential of approximately 1.2 million MW [14]. The government of Pakistan, specifically the Ministry of Planning and Development, has recently shown its endorsement for investigating localized and off-grid alternatives to deliver electricity in the remote regions of Baluchistan [15]. Harnessing solar power for off-grid communities in this province would contribute to improvements in healthcare, education, communication, and water supply, leading to overall socio-economic development and well-being. A detailed survey conducted for the adoption of solar power in rural Baluchistan revealed that 89.2% of the rural population is willing to install solar power systems. However, due to their poor financial condition, they have been unable to install these systems and are awaiting support from the government or international donors [16]. In 2016, the provincial government of Baluchistan allocated USD 4.6 million for solar and wind power to attract private sector investment [17]. However, the private sector has shown reluctance to invest due to several factors, including the poor law and order situation, the remote location of the area, inadequate communications and infrastructure, and a low return on investment [18]. Another potential hurdle associated with emerging technologies is that financial institutions and large-scale investors tend to be risk-averse, often requiring realistic techno-economic information and a pilot plan before providing financing.

As of 2022, the global utility-scale solar sector has witnessed significant growth, with approximately 37,000 MW of operating projects and an additional 112,000 MW in development [19]. The 2030 target of achieving an unsubsidized levelized cost of energy (LCOE) of USD 0.02/kWh for utility-scale solar PV projects was set by the Department of Energy (DOE), USA [20]. However, several challenges hinder the widespread adoption of solar power, including inefficient solar panels and LS and high capital and operational expenditures contributing to a higher LCOE in comparison to power tariffs. To promote the adoption of large-scale solar PV systems in areas with favorable solar energy potential, it is crucial to assess the techno-economic metrics based on local conditions and specific components.

In addition to the continuous research focused on reducing costs in solar systems, it is imperative to address concerns regarding inefficient infrastructure and the development of a proper value chain. Furthermore, to attract private sector investment, make wellinformed investment decisions, and gain a comprehensive understanding of the potential and challenges involved, it is of utmost importance to possess detailed techno-economic information about scaled solar power plants in specific geographical locations. Providing this information would greatly contribute to instilling confidence in investors and financial institutions.

The reviewed set of recent studies in Table 1 reveals a disparity in the clarity of the literature concerning the techno-economic metrics of scaled solar power plants. These studies demonstrate variations in technical assumptions and cost estimates and exhibit limitations in scope and procedural deficiencies. Furthermore, they overlook multiple parameters essential for determining the LCOE beyond capital expenditure (CAPEX) and operational expenditure (OPEX). The key deficiencies, as summarized below, underscore the importance of evaluating detailed techno-economic metrics in this field:

- Several significant cost-contributing parameters were either overlooked or arbitrarily selected. For example, Niaz et al. (2022) [21] examined the LCOE considering CAPEX and OPEX over ten years but did not include factors such as power generation scale, salvage value, degradation rate, loss factors, or replacement cost. Similarly, Nadaleti et al. (2020) [22] only considered CAPEX and OPEX. Yates et al. (2020) [23] calculated LCOE using a range of CAPEX and OPEX costs but did not address the impact of economies of scale. Ahshan et al. (2022) [24] investigated the LCOE of wind power, primarily focusing on CAPEX and OPEX. Shehabi et al. (2022) [25] used income tax rate, CAPEX, OPEX, balance of system (BOS) cost, equity, and replacement cost to determine LCOE but did not consider salvage value or the impact of economies of scale.
- The lack of a standardized approach for accounting CAPEX is noted. The direct CAPEX should encompass the costs of PV modules, current balancing devices, installation expenses, and contingency costs when calculating the net present value (NPV). However, it is taken generically, considering CAPEX as the cost/unit-power while excluding the other three cost variables, e.g., by Assowe et al. [26], Alessandro et al. [27], Jang et al. [28], and Burdack et al. [29].
- Furthermore, in the USA as of 2021, out of a total of 1125 proposed photovoltaic (PV) projects, 90% were based on single-axis tracking systems as opposed to fixed tilt systems, and mono-crystalline silicon (mono-c-Si) modules accounted for 69% of installations compared to thin-film modules [30]. Additionally, policy measures in the USA, such as extending the exemption from the 15% import duty through 2026, have encouraged the installation of bi-facial modules. This divergence in plant setup and module specifications in large-scale deployment highlights the need for research to understand how these factors impact energy output and cost.

To facilitate informed decision making regarding the implementation of scaled solar power for electrifying off-grid communities, this study provides a comprehensive techno-economic assessment.

Given the existing knowledge gap and the projected growth in renewable electricity demand, the contribution of this study mainly includes:

- Development of a robust framework for scaled solar PV plants that incorporates all relevant technological, financial, and benefit considerations. This approach enabled the accurate determination of techno-economic metrics, allowing for a fair comparison with fossil fuel-based power generation.
- Incorporate the essential macro- and micro-cost and technical parameters (Table 2) that are integral to the analysis and that must be considered when developing a techno-economic analysis model. Neglecting any of these parameters can lead to underestimation or overestimation of techno-economic metrics, rendering them unreliable. While certain parameters may have specific ranges, completely excluding them may result in misleading conclusions.
- Evaluation of economies of scale impact on techno-economic metrics of a scaled renewable power plant.

- By examining these factors, the primary objective of the study is to generate valuable insights into the feasibility and viability of implementing scaled solar power plants in the region.

Table 1. Key parameters of LCOE (non-exhaustive).

Study (Year Published, Ref.)	2022, [21]	2022, [24]	2022, [25]	2020, [22]	2020, [31]	2020, [23]	2016, [32]	2015, [33]
System lifetime	√	√	√	√	√	√	√	×
Degradation rate	×	√	×	×	×	×	×	×
Technical loss factor	×	×	×	×	√	×	×	×
Carbon trading price	×	√	×	×	×	×	×	×
Residual value	×	×	×	×	×	×	×	×
CAPEX	√	√	√	√	√	√	√	√
OPEX	√	√	√	√	√	√	√	√
Discount rate	×	×	×	√	×	√	√	×
Inflation rate	×	×	×	×	×	×	√	×
BOS and installation cost	×	×	×	×	×	×	×	×
Foundation (land preparation)	×	×	×	×	×	×	×	×
Engineering and developer overhead	×	×	×	×	×	×	×	×
Contingency	×	×	×	×	×	×	×	×

Table 2. Parametric framework of techno-economic assessment.

Category	Parameter	Notes
Site selection	Geographical location	DNI and financial factors, e.g., utility tariffs, tax rate, inflation and discount rate, carbon credits, etc., vary with location/country of interest.
Energy generation	Capacity	The economy of scale has an impact on net technical and cost parameters.
Performance and cost	System lifetime	Various renewable power-generation systems have different life spans and replacement costs.
Feasibility	Energy harvesting system	Solar PV, solar-thermal, wind, and biomass have different energy potentials concerning net output power.
System performance	Efficiency	Module type in the case of PV, turbine class in the case of wind, and Biomass's energy-to-power-conversion technique affect the power generated.
System performance	Loss factor	In practice, at the industrial level of power generation systems, specific energy and exergy losses typically exist, e.g., DC/AC losses in PV plants.
Net output power	Degradation rate	The performance of the power generator degrades with time, reducing the net output power.
System cost	CAPEX	The cost of components related to renewable energy system changes due to ongoing increases in global installed capacity and product improvements; more realistic CAPEX based on a well-defined system's design impacts the net cost.
	Lifetime cost	Power generation systems and BOS have different lifetimes; hence during the specific analysis period, these should be accounted for separately.
	OPEX	Logistics, labor wages, and insurance costs, and other soft costs are often country-specific, hence have a pronounced impact in the long run as OPEX mainly affects annual equivalent costs.
Project finance	Equity	The equity with a specific interest rate through a reasonable estimate must be accounted for in the life cycle costing of the renewable power generation to encourage private sector investment.
Net present value	Residual value	The residual value is a significant cost factor, specifically when the analysis period is shorter than plant life.
	Discount rate	Discount and inflation rates directly affect the LCOE, neglecting or assuming it leads to unrealistic results.
	Inflation rate	
	IRR	To attract private sector investment, IRR with a reasonable estimate should be declared, and its effect should be reflected in net cost.

Table 2. *Cont.*

Category	Parameter	Notes
Annualized cost	Carbon credit	The penalty charges avoided from reducing CO_2 emitting to the atmosphere are accounted for in LCC while evaluating the LCOE.
	Replacement cost	If the analysis period is different than the system life, then replacement cost needs to be accounted for in annualized cost.
Capital cost	Foundation	Renewable power plant requires a considerable land area for installation, which has a significant impact on CAPEX if leased or purchased. The CAPEX must account for land purchase and preparation costs where applicable.
	Engineering and developer overhead	Overhead costs, e.g., computer programming, communication, and encoding, are specifically crucial in setting central control systems in scale enactment.
	Contingency	In LCOE estimation over the 25–35 years period of the power generation system, the cost associated with uncertain and unpredictable risk should be considered.
	BOS and installation cost	BOS equipment and installation cost is a significant direct cost component, and it should be accounted for separately from the CAPEX.

2. Methods and Materials

2.1. Geographical Location

Several factors impact the site selection for a scaled solar power plant, such as the country's economic condition, commitment to the green energy transition, resource constraints, and renewable energy targets [34]. Additional considerations include wind speed, direct normal irradiance (DNI), water resources, transportation, and existing infrastructure such as industrial zones. Yang et al. [35] recommend a cumulative irradiation value of >2000 kWh/m^2/year while cautioning against exposure to less than 1600 kWh/m^2/year of DNI. High wind speeds can have adverse effects on solar PV plant performance, leading to increased thermal losses and structural instability [34]. Given that around 83% of the population in District Chagai, Balochistan, in Table 3 resides in the off-grid area [36], and considering the region's favorable solar energy potential, this study selects this area as a pilot case (Figure 1).

Table 3. Characteristics of selected solar PV plant site.

Production Site (Pakistan)	Co-Ordinates (°N, °E)	DNI (kWh/m^2/d)	Avg. GHI (kWh/m^2/d)	Avg. Wind Speed (m/s)	Avg. T (°C)
Chagai, Baluchistan	29.3058, 64.6945	5.94	5.93	3.1	28.6

2.2. Metrological Data

The metrological data was obtained from the National Solar Radiation Database at the NREL database [37]. By employing these site-specific data, it is believed that the assessment of solar power will yield more precise results compared to relying on average solar irradiation statistics for a given location.

2.3. Power Generation Pathways

The simulation encompasses a range of pathways derived from the combination of three different module configurations and two module types. Through comprehensive enumeration, a total of six pathways were examined in Figure 2. The findings were obtained through open-access simulation tools, the System Advisor Model (SAM.V22.11.21) [38] and a spreadsheet analyzer.

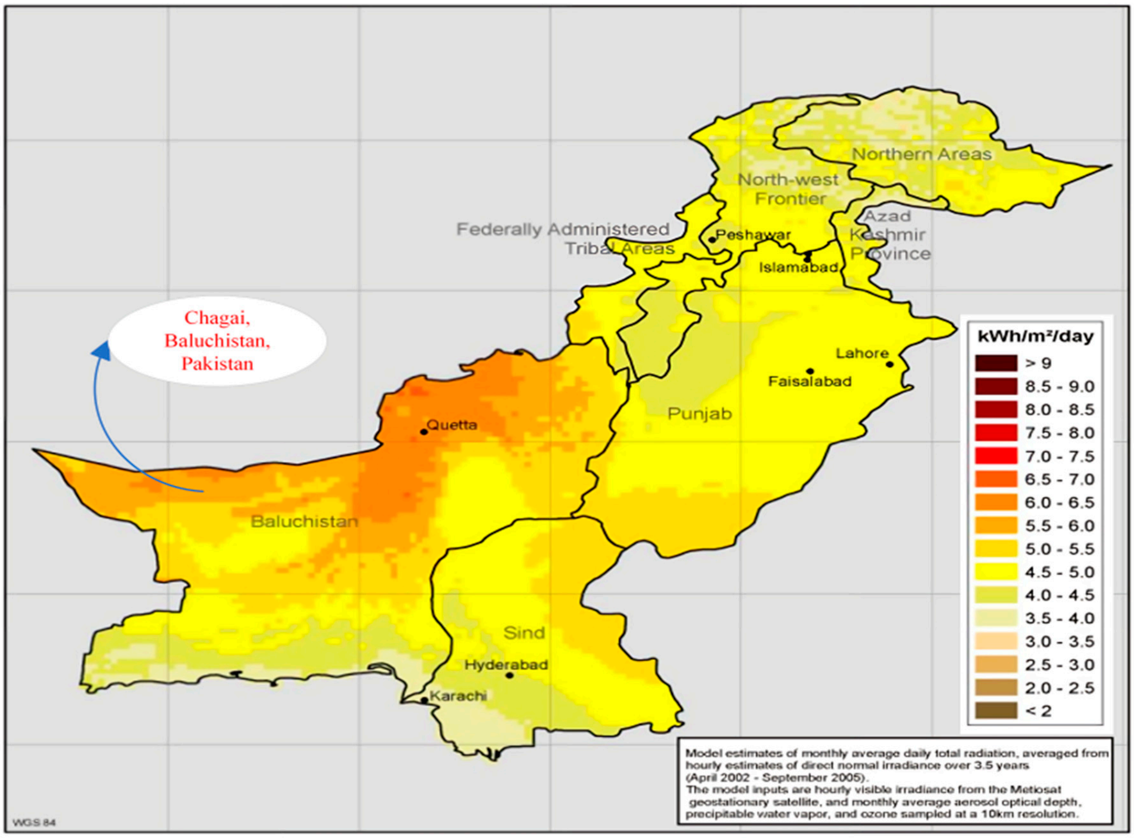

Figure 1. Geographical location of the selected site.

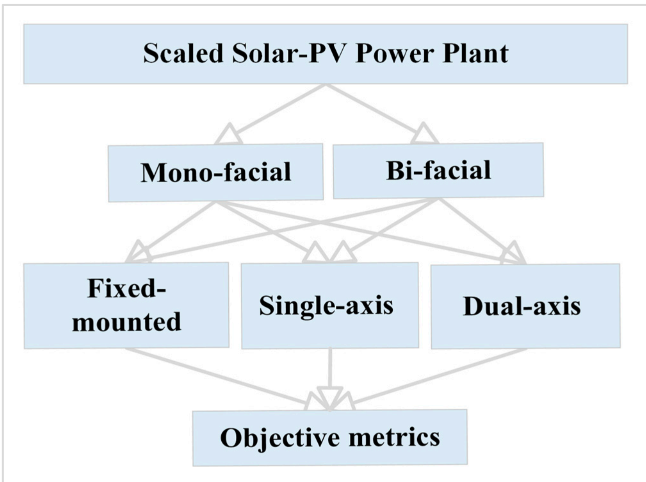

Figure 2. Roadmap of solar PV plant.

2.4. Simulation Algorithm

The algorithm presented in Figure 3 is employed to assess the key objective metrics: The LCOE, capacity factor (CF), total annual energy generated, and energy yield (EY). The technical specifications of the modules, as outlined in Table 4, along with the air-mass modifier polynomial ratio described in Ref. [39], are taken into account to address the effects of the solar spectrum on net power. Additionally, losses resulting from optical lenses, alignment errors, tracker errors, and wind flutter are considered in the loss factor.

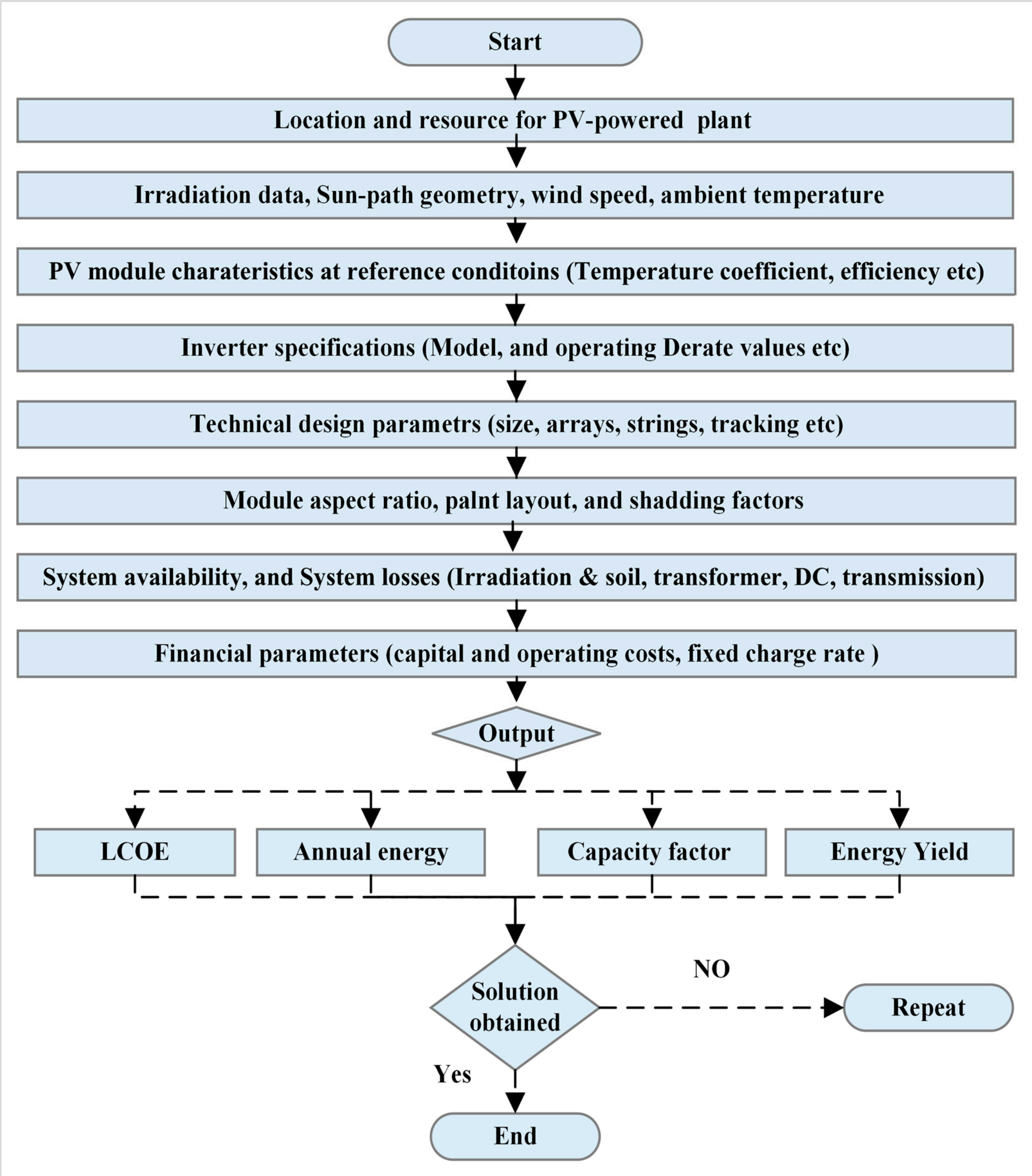

Figure 3. Simulation algorithm of power plant.

Table 4. Specification of solar PV module.

Parameters	Unit	Value	
		Bi-Facial [40]	Mono-Facial [41]
Efficiency	%	21.79	20.88
Power capacity	W_{dc}	671.055	540.696
Performance degradation	%/y	0.45	0.55
Voltage (maximum)	V_{dc}	38.5	31.2
Current (maximum)	A_{dc}	17.4	17.3
Temperature coefficient	W/°C	−0.303	−0.371
Cells	Nos	66	55
Area	m^2	3.080	2.59
Unit mass	kg/m^2	11.092	11.092
Length	m	3.08	2.59

The model incorporates factors such as efficiency, loss factors, thermochemical characteristics, variation in cell efficiency, and the impact of azimuth angle. The performance and cost of the converters, trackers, and voltage optimizers significantly influence the net output of the system. The critical technical characteristics of the modules, along with the application of air-mass modifier polynomial ratios explained in Ref. [39], effectively account for the spectrum effects on net power. The model also considers losses attributed to the visual lens, placement error, tracker error, and wind flap, which are encompassed within the overall loss factors.

The economic model incorporates various input parameters such as module cost, inverter cost, BOS mechanical and electrical costs, installation cost, and non-labor soft costs including approval, procurement, and developer overhead (Table 5). Estimated expenses within the literature typically fall within a specific price range. For instance, predictions for the total installed cost of a solar PV system with single-axis tracking range from 1.3 USD/Wac to 1.14 USD/Wdc for a 100 MW capacity [42,43]. The Solar Energy Industries Association (SEIA) [19] reported that the global average cost of commercial solar PV plants installed in 2021 was 0.77 USD/Wdc for fixed-tilt systems and 0.89 USD/Wdc for single-axis systems. The NREL [44] reports the median cost of 25 different utility-scale solar PV plants as 1.2 USD/Wac and 0.97 USD/Wdc. These costs represent global averages, and the net output is significantly influenced by module scale, location, type, brand, and the presence of clean energy credits. Dedvar et al. [45] examined the scaled impact on the minimum sustainable price (MSP) of solar PV modules in a practical manufacturing plant setting. They observed a progressive decline in MSP with increasing capacity, with reductions of 9%, 8%, and 6% for capacities of 600 MW, 1.2 GW, and 2.4 GW, respectively.

Certain fixed expenditures, such as general administration, vegetation care, and module cleaning, are shared among various plant components, resulting in decreased OPEX with increasing plant capacity. Around a 50% decline in OPEX has been noted in thirteen years, i.e., from 35 USD/kWdc/year in 2007 to 17 USD/kWdc/year in 2019 [46]. Similarly, a report from Berkeley Lab [47] highlights a 51.4% reduction in OPEX over the past 12 years. The Trina-Solar modules examined in this study claim a 6.32% reduction in BOS costs when bi-facial 600+ W modules are installed compared to mono-facial modules [48].

Table 5. Economic parameters.

Parameters	Unit	Value	Reference
Installer margin and overhead	USD/W_{dc}	0.05	[49]
WACC	%	6	Typical value
Installation cost	USD/W_{dc}	0.11	[49]
BOP (mechanical)	USD/W_{dc}	0.10	[50]
BOP (electrical)	USD/W_{dc}	0.09	[50]
Sun-tracker (single-axis)	USD/W_{dc}	0.1	[30]
Sun-tracker (dual-axis)	USD/W_{dc}	0.15	[30]
Engineering and developer overhead	USD/W_{dc}	0.08	[49]
PII	USD/W_{dc}	0.04	[50]
Contingency	% CAPEX	2	Typical value
Fixed-mounted OPEX	USD/kW_{dc}/y	13	[51]
Single-axis OPEX	USD/kW_{dc}/y	14	[52]
Dual-axis OPEX	USD/kW_{dc}/y	16.26	[52]
Depreciation	%/y	MACRS Standards (Industries)	[53]
DC/DC power optimizer	USD/W_{dc}	0.15	[54]
PV Module Performance degradation	%/y	0.5	[50]
Residual value	% CAPEX	20	Typical value
Inflation	%	2.6	[55]

AC: alternate current; DC: direct current; CAPEX: capital expenditures; OPEX: operating expenditures; MARCS: modified accelerated cost recovery system; BOP: balance of plant; PV: photovoltaic; PII: permitting, inspection, and interconnection; WACC: weighted average cost of capital.

The LCOE serves as an economic metric for comparing renewable power generation systems from various sources. Equation (1) defines the LCOE [39], and in this study, modified and detailed relationships are employed as presented in Equations (2) and (3). These equations are solved using the standard life cycle cost (LCC) concept, as illustrated in Figure 4, to determine the NPV. By adopting this approach, a thorough evaluation of the economic feasibility of the solar power plant system can be achieved.

$$\text{LCOE (USD/kWh)} = \frac{\textit{Total life cycle cost of the energy generation system } (\$)}{\textit{Total electricity generated } (\text{kWh})} \quad (1)$$

$$\text{LCOE (USD/kWh)} = \frac{\text{CAPEX} + C_{o\&m} - {r_{deg}}^{n} - R_{value}}{E_n} \quad (2)$$

where:

CAPEX is the capital expenditure (USD)
$C_{o\&m}$ is the operation and maintenance cost (USD)
r_{deg} is the degradation rate (%)
n is the plant's lifetime
R_{value} is the residual value (USD)
E_n is the electricity generated

$$\text{LCOE (USD/kWh)} = \frac{\text{CAPEX} + C_{ins} + \frac{C_{rep}}{(1+d)^n} + \sum_{i=1}^{n} \frac{C_{o\&m}}{(1+d)^i} - \sum_{i=1}^{n} \frac{(r_{dep} \times r_{tax})^i}{(1+d)^i} - \frac{R_{value}}{(1+d)^n}}{\sum_{i=1}^{n} \frac{E_i \times (1-r_{deg})^i}{(1+d)^i}} \quad (3)$$

where:

C_{ins} is the installation cost (power plant) (USD)
C_{rep} is the replacement cost (USD)
I_i is the Year "i"
kW is the Kilowatt
n is the plant's lifetime
USD is the dollar (United States)
r_{dep} is the depreciation rate (%)
r_{tax} is the federal capital tax on investment

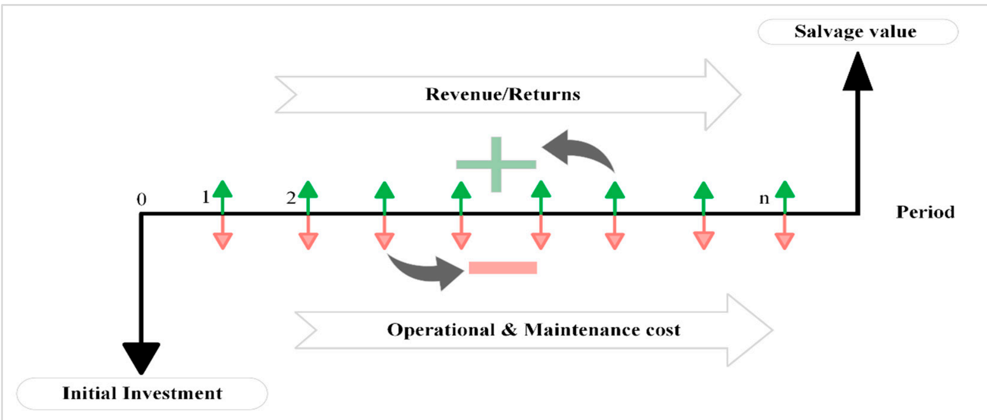

Figure 4. Life cycle cost.

2.5. Assumptions and Exclusions

- The economic model focused on cost analysis without an energy storage system.
- Power transmission and distribution costs were not taken into account.

- The cost of land acquisition or lease was not included and was assumed to be covered by the public development budget.
- Incentives for investment, green power generation, or capacity build-up are not accounted for in the NPV.

3. Results and Discussion

Techno-economic metrics are analyzed across four different generation capacities: 1000 MW, 3000 MW, 5000 MW, and 7000 MW, and six various pathways. The reason for considering different capacities is to evaluate the influence of economies of scale on the overall impact. The chosen range of installed capacity aligns with the requirements of the region's first solar PV plant [56], designed to meet the annual energy demands of an off-grid community. To ensure an equitable comparison across various renewable energy technologies and geographical sites in a global context, the power plant is considered connected directly to the consumer's facility, eliminating the need for an energy storage system. It is worth noting that the irradiation potential varies throughout the year, such that during the winter solstice it is ~44.3% lower compared to the summer solstice in Figure 5. As a result, the monthly energy generation at the selected plant location exhibits significant variability, particularly during the spring and fall equinoxes (Figure 6).

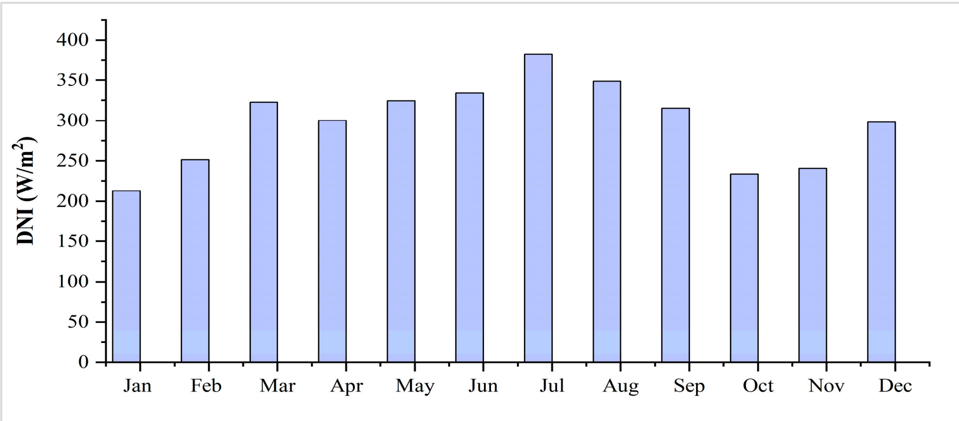

Figure 5. Average direct of normal radiation per month in Pakistan.

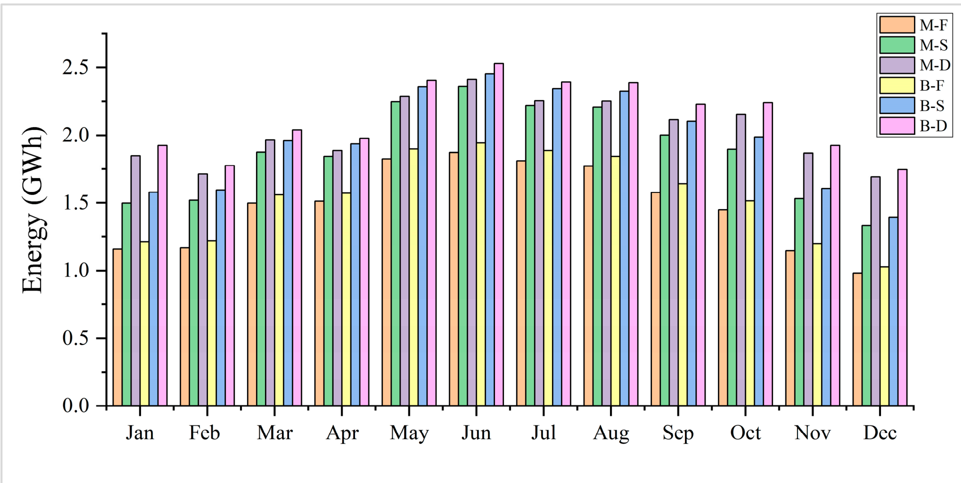

Figure 6. Monthly energy generated from various generation pathways, (M; mono-facial, B; bi-facial, F; fixed-mounted, S; single-axis, D; dual-axis).

Given the variation in the energy received, the size of a power plant required to meet a particular electricity load at this study site is found ~38.4% smaller during the summer solstice compared to the winter solstice. The comparative assessment of current market prices reveals that the cost of bi-facial modules is ~38% higher than mono-facial modules. Additionally, transitioning from a fixed-mounted configuration of the sun-tracking system to a single-axis configuration increases the cost by ~47%, while the cost difference in transitioning from a single-axis to a dual-axis configuration is ~40%. Considering these discrepancies, an evaluation of the energy generation and plant performance in Table 6 is conducted to determine the optimal plant setup using either mono-facial or bi-facial modules for scaled implementation in a standalone position.

Table 6. Plant performance metrics.

Metric	Fixed-Mounted		Single-Axis		Dual-Axis	
	Mono-Facial	Bi-Facial	Mono-Facial	Bi-Facial	Mono-Facial	Bi-Facial
Annual energy (GWh)	17.76	18.52	22.53	23.64	24.45	25.56
CF (%)	22.9	22.1	28.3	29.5	31.1	32.2
Energy yield (kWh/kW)	1777	1852	2255	2363	2446	2558

The analysis reveals that transitioning from mono-facial to bi-facial modules with a single-axis configuration results in a net power output change of ~5%. Similarly, changing the plant setup from mono-facial to bi-facial modules using the dual-axis configuration leads to a net power output change of ~4.6%. Based on this comparative assessment, the use of bi-facial modules in a single-axis configuration is preferred over the mono-facial configuration due to the higher difference observed in net power output.

The model evaluated the installation of two distinct module types presently accessible on the market, along with three potential mounting structures. Comparable meteorological data and economic and technical input parameters are used to evaluate the influence of module types on BOS costs and LCOE. Six distinct designs are assessed, encompassing two module types and three module orientations, yielding varying optimized LCOE values in Figure 7. The LCOE experiences a decrease of ~12% when shifting from a fixed-mounting to a single-axis configuration, regardless of whether mono-facial or bi-facial modules are used. However, the difference in LCOE when transitioning from a single-axis to a dual-axis configuration is ~2%, which is not considered significant. Considering the higher cost associated with installing dual-axis sun-trackers and the relatively lower increase in energy generation, the LCOE assessment suggests that single-axis tracking is more economically favorable until dual-axis systems become more developed and economically feasible in the future.

Comparing the outcomes of this study with other studies proves challenging due to variations in solar energy potential across different worldwide geographical locations, differences in plant installed capacity, and diverse technical and cost assumptions and limitations. Nonetheless, the results obtained from this study can be compared to recently bid utility-scale regional solar PV projects conducted in areas with similar solar irradiance levels in Table 7. The observed decrease in costs with increasing plant capacity in this study aligns with the awarded prices of the power purchase agreement (PPA) for recent projects. For example, the LCOE for a 2000 MW plant in the UAE is ~55% lower than that of a 1200 MW project. Similarly, the LCOE in Qatar and Oman, which are reported as 1.57 USD/kWh and 1.78 USD/kWh respectively, are also comparable to the findings of this study, with slight variations attributed to differences in solar irradiance due to different geographical locations. Furthermore, the resulting LCOE from this study is comparable to the reported values of 1.67 USD/kWh (PV-battery storage system) and 1.45 USD/kWh (PV-battery storage system-diesel generator) for the geographical location in District Dera Ismail Khan, Pakistan [57]. Similarly, another study by ARENA in Australia [58] reported 1.14 USD/kWh, with the slight difference attributed to ~11% more sunshine hours available for a full load at the selected site of this study as compared to the location in Australia.

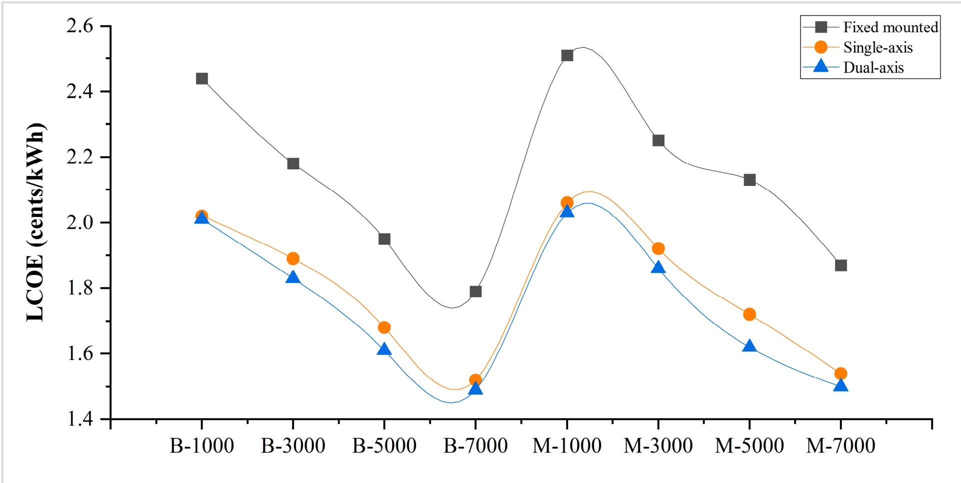

Figure 7. Economy of scale impact of solar PV electricity cost at the selected site (M; mono-facial, B; bi-facial).

Based on a qualitative assessment, the integration of concentrated solar power with conventional plants in Pakistan resulted in a reduced levelized cost of electricity (LCOE) [59]. An evaluation encompassing technical, economic, and environmental considerations advocated for an independent standalone solar PV system in Ref. [60], exhibiting a payback period of 3.125 years and facilitating a substantial reduction of 90,225 tons per annum in CO_2 emissions within the Pakistani context.

Drawing from an inquiry into a hybrid energy system combining wind, PV, and biomass components in Pakistan, an LCOE of 5.744 USD/kWh was ascertained [61]. Moreover, a comparative analysis of the technical and economic dimensions of scaled solar PV installations across five diverse locations, detailed in Ref. [62], identified the Baluchistan Province as the most suitable locale, distinguished by a diminished LCOE of approximately 2.6 USD/kWh. When juxtaposed with the established LCOE of 5.6 USD/kWh attributed to a wind power system as appraised in Ref. [63], the present study's findings—specifically, LCOE values of 2.14 USD/kWh (fixed-mounted PV systems), 1.79 USD/kWh (single-axis tracking systems), and 1.74 USD/kWh (dual-axis tracking systems)—underscore the viability of solar PV plants within the prevailing market dynamics.

Table 7. PPA of recently tendered regional projects.

Country	Plant Capacity (MW)	Awarded PPA (USD/kWh)	Year	Reference
UAE	1200	2.951	2019	[64]
	2000	1.351	2022	[65]
Qatar	800	1.572	2020	[66]
Oman	500	1.781	2019	[67]

PPA: power purchase agreement.

4. Conclusions and Policy Recommendations

The techno-economic analysis conducted on scaled solar PV plants with a power capacity range of 1000–7000 MW has yielded several significant findings. The transition from mono-facial to bi-facial modules, combined with a single-axis configuration, resulted in a noticeable increase in net power output of ~5%. Similarly, the shift from mono-facial to bi-facial modules with a dual-axis configuration led to a net power output increase of around 4.6%. The findings indicate that a power plant utilizing bi-facial modules with a single-axis configuration offers greater feasibility compared to one employing mono-facial modules in a fixed-mount arrangement. In terms of cost factors, the BOS cost and the OPEX, primarily attributed to cleaning and vegetation management, emerged as the most significant after considering the CAPEX. The selected site demonstrated substantial power generation potential, making it well-suited for large-scale commercial solar PV plants. The average LCOE was determined to be 2.14 USD/kWh for fixed-mounted plants, 1.79 USD/kWh for single-axis plants, and 1.74 USD/kWh for dual-axis plants across the examined power generation capacity range. The anticipated economies of scale, driven by the expanding global market for solar PV plants and renewable energy, are expected to further contribute to overall cost reductions. Given the lower cost of green power, as evidenced by the LCOE, particularly in Pakistan and specifically in the Balochistan Province, the region's extensive land area, and high solar energy yield (with 7–13 h of sunshine per day) position it as a compelling leader in the renewable power sector. The comprehensive techno-economic framework developed in this study has yielded a meticulously crafted solar PV system design that is scalable for implementation in off-grid rural settings. This design is a product of rigorous exploration of pertinent techno-economic variables. In forthcoming research endeavors, this framework is positioned for augmentation to encompass the assessment of additional sustainable power systems, including wind and biomass alternatives. This envisioned extension bears the promise of providing invaluable insights to inform the energy system design within off-grid regions.

To foster investment decisions and formulate effective policies to promote off-grid electrification and the development of renewable energy value chains, the following policy recommendations are proposed:

- The active involvement of the private sector is crucial in fostering a resilient renewable energy value chain, especially in regions with limited existing energy infrastructure. It would be helpful to mobilize financial resources from non-budgetary sources and to provide the technical and managerial expertise required for building scaled solar PV plants in off-grid areas.
- The formulation of specialized policies and regulatory frameworks related to solar power generation is required. These initiatives are essential to attract and facilitate investors and to overcome the challenges associated with the renewable energy value chain.
- The BOS cost is the major contributing factor in the LCOE; therefore, solar PV module manufacturers should focus on improving module density within a string to reduce expenses for accessories such as electric cables and racks. Additionally, the production of large-sized and high-power solar PV modules is recommended to decrease the construction time and lower the overall cost of the system.
- Although the LCOE using bi-facial modules is ~7–10% lower, a careful comparison of sun-tracker costs is necessary before deciding. A dual-axis tracking system generates around 19.87% more power than a fixed-mounted system, but it comes with a net installed cost difference of ~15.45%. Therefore, when dealing with limited space, a cost-benefit analysis of installing sun trackers and types of modules is critical.

Author Contributions: Conceptualization, M.S. and P.K.; methodology, M.S.; software, M.S.; validation, P.K. and S.K.; formal analysis, M.S.; investigation, P.K.; resources, M.S.; data curation, M.S. and P.K.; writing—original draft preparation, M.S.; writing—review and editing, M.S. and P.K.; supervision, P.K. and S.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Graduate Scholarship Programme, Chulalongkorn University for ASEAN or Non-ASEAN countries, and the APC was partly funded by Energy Research Institute, Chulalongkorn University.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

BOS	Balance of system
CCUS	Carbon capture utilization and storage
CAPEX	Capital expenditures
CF	Capacity factor
DNI	Direct normal irradiance
FCEV	Fuel cell electric vehicle
GHG	Greenhouse gas
GHI	Global horizontal irradiance
IPCC	Intergovernmental Panel on climate change
IRENA	International renewable energy agency
LCOE	Levelized cost of energy
LCC	Life cycle cost
MOE	Ministry of Energy United States of America
MOU	Memorandum of understanding
MT	Million tones
NPV	Net present value
NREL	National Renewable Energy Laboratory
OPEX	Operational expenditures
PV	Photovoltaic
PPA	Power purchase agreement
R&D	Research and development
RES	Renewable energy systems
SAM	System Advisor Model
TWh	Terawatt hours
USD	United States dollar
WACC	Weighted average cost of capital

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