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Optimising solar: A techno-economic assessment and government facility compensation framework power generation

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Abstract. In light of the necessity to meet growing energy demands while minimising expenses, this article examines two solar power system designs, considering peak and average load situations. The peak system, designed to handle a peak load of 190 MW with 260,568 PV panels installed, generates a significant excess of approximately 49,911 MWh annually. On the other hand, the average load design suggests a little deficit in energy. The monetary analysis reveals considerable capital expenditures for the total installation costs, totalling $58.77 million for an average system and $66.71 million for the peak system. However, the Levelized Cost of Energy (LCOE) rates are relatively competitive, at 0.0835 USD/kWh and 0.0736 USD/kWh respectively. Notably, the study highlights that the environmental impact analysis demonstrates a significant decrease in CO_2 emissions, with the peak system achieving a reduction of up to 3,601,588 tonnes per year. This research has explicitly validated the capabilities of centralised solar power systems in addressing the current and future energy difficulties faced by the Government of Sindh in a sustainable and economically viable manner.

Introduction

On a global scale, the energy industry faces substantial obstacles, such as the exhaustion of natural resources, environmental issues, and rising expenses, which necessitate an urgent transition to sustainable energy alternatives. Pakistan is experiencing a serious energy crisis characterised by severe power shortages, heavy dependence on non-renewable energy sources (61% thermal, 24% hydropower, 12% nuclear as of June 2023), and inadequate infrastructure [1]. Pakistan actively seeks solutions by adopting renewable energy and developing infrastructure to promote economic growth. Crucial organisations facilitate this shift, including Generation Companies (GENCOs), the Water and Power Development Authority (WAPDA), the Private Power Infrastructure Board (PPIB), National Transmission and Dispatch Company (NTDC), Distribution Companies (DISCOs), and National Electric Power Regulatory Authority (NEPRA) [2]. Following the 2010 amendment to the 1973 constitution, provinces were granted the power to generate, transmit, and distribute electricity at the provincial level. The provincial government of Sindh utilised it by implementing the Sindh Transmission and Dispatch Company (STDC) and the 100MW Nooriabad power project [3,4]. These initiatives aim to ease financial burdens by lowering power expenses. Solar and wind energy are more cost-effective than hydropower, making them good options for Pakistan's economic and operating problems. They offer a way to grow the economy and protect the environment [5]. The financial reports covering May 2021 to May 2022 reveal that Sindh's power expenditures amounted to PKR 8,704 million ($ 31.1M) [6]. The Institute for Energy Economics and Financial Analysis (IEEFA) conducted a financial analysis of Sindh's power

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expenditures, revealing that solar and wind energy is the most economically efficient, with photovoltaic power generation being the best renewable option due to affordability and low maintenance costs[7-8].

A feasibility analysis of a 100 MWp solar power facility in Pakistan using PVSOL software was done [9]. A study assessed the facility's financial viability, encompassing revenue, operations, maintenance, interest payments, net profit, and payback period. The facility may generate 180,000 GWh/year and eliminate 90,225 tons/year of CO_2, and the payback period is 3.125 years. Based on feasibility, design, and execution, reference [10] evaluated a grid-tied 150 MW_p solar PV trial project in Karachi, Pakistan, for energy yield. In the PVsyst simulation, the average annual power generation, capacity factor, and performance ratio were 232,518 MWh/year, 17.7%, and 74.73%. Reference [11] evaluated the performance and design of a 20 MW Malaysian airport solar PV system. Power generation, performance ratio, and capacity utilisation factor (CUF) were 26,304 MWh, 76.88%, and 15.22%. A one MW PV grid-tied system in Oman was the subject of a techno-economic analysis by [12], who concluded that the system's annual yield factor was 1875 kWh/kWp. The system indicated a capacity factor of 21.7% and an electricity production cost of roughly USD 0.2258 per kWh.

A 3 MW_p grid-connected solar PV system was tested in Karnataka, India. The annual average performance ratio was 0.7, and the power generation was 1372 kWh/kWp [13]. An Indian grid-connected 10 MW solar PV project was assessed. The annual performance ratio, CUF, and power generation were 86.12%, 17.68%, and 15,798.19 MWh, respectively [14]. However, the techno-economic viability of Ghana's grid-connected 50 MW solar PV was examined [15]. The scientists discovered that monocrystalline, polycrystalline, and thin-film solar cells cost USD 0.124/kWh, USD 0.123/kWh, and USD 0.109/kWh, respectively, to produce power. Mono-Si, poly-Si, and CdTe systems had 75.5%, 75.7%, and 77% performance ratios. Reference [16] investigated a 12 MWp solar-powered airport in Cochin, India. The average annual performance ratio was 86.56%, and CUF was 20.12%. This plant could produce 50,000 kWh per day. During its lifetime, the facility would reduce 12,134.26 metric tons of CO_2.

Previous studies have explored the techno-economic elements of small-scale solar PV systems, but there is a lack of research on expansive systems, especially in government facilities. This study aims to examine the economic and operational benefits of implementing 155 MW average and 190 MW peak grid-connected photovoltaic (PV) systems in Sindh, Pakistan, to address existing shortcomings such as lower energy and operational costs, energy independence, improved safety, and promote sustainability.

Methodology

A well-established technique has been employed to evaluate the feasibility of the proposed centralised solar-powered site, illustrating the sequential procedures involved in conducting the research.

i. Data Collection

The operational zone of Hyderabad Electric Supply Company (HESCO) was analysed. This analysis used HESCO and Sindh's Energy Department's Electricity Monitoring and Reconciliation Cell (EM&RC) data. Field visits to multiple places supplemented the Management Information System (MIS) data accuracy and reliability of HESCO and the energy department's electricity consumption statistics. The study examined power use data from January to December 2022 to determine energy consumption patterns—advanced data processing methods like cleaning, mining, filtering, and estimating ensured data accuracy.

Table 3 shows Sindh government-controlled power use by 75 provincials, affiliated, autonomous, and special institutions.

ii. Climatic conditions of the understudy locations

After analysing the Table 1 parameters, Manjhand, Sindh, is the best place for a solar PV installation. The location meets technical standards and supports the project's clean energy, efficiency, and sustainability goals.

iii. Simulation Tool

Solar energy companies widely use PVsyst for simulations. Solar power plants can be efficiently designed using this software for various climates, different PV modules and inverters, meteorological irradiation data, manual import data from other databases, appropriate sizes, and related components [17].

iv. Design of grid-connected large-scale solar PV system

a) Peak Load Design:

$$P_{annual} = P_{max,monthly} \times 12 \quad (1)$$

P_{annual} represents the solar PV system's projected annual peak load, measured in kilowatt-hours (kWh) and $P_{max,\ monthly}$ represents the highest electricity usage recorded in a month over a year.

b) Average Load Design:

$$L_{avg,monthly} = \frac{E_{total,annual}}{12} \quad (2)$$

$L_{avg,\ monthly}$ represents the average monthly load of the solar PV system, measured in kilowatt-hours (kWh) and $E_{total,\ annual}$ value represents the total yearly electricity consumption of the building (kWh).

v. Panel Generation Factor

$$\text{PGF} = \frac{\text{daily solar radiation at } the \text{ site per day}}{\text{STC irradiance}} \quad (3)$$

The PGF values for Hyderabad, Thatta, Nawabshah, Manjhand, and Tharparkar are calculated as 5.69, 5.558, 5.65, 5.668 and 5.53, respectively, using the solar irradiance values.

vi. PV *module* selection

AE Solar's 132-AE solar modules are ideal for average and peak PV systems, offering a typical panel efficiency of 22.56% and a power rating of 700 W_p. These modules are resistant to extreme weather conditions and elevated temperatures. Table 2 of the Monocrystalline 132-AE Solar PV Module shows the technical specifications [18].

vii. Inverter Size Optimisation

It is a crucial optimisation strategy in PV systems, determining the optimal size of a solar inverter by dividing the installed DC power capacity by the AC power output rating [19]. P_{inv} represents the power rating of the inverter's AC output.

$$\text{ILR} = \frac{W_{T,peak}}{P_{inv}} \quad (4)$$

viii. Inverter selection

The chosen PVS800 ABB central inverter has a maximum system voltage rating of 1100 V_{dc}, which precisely matches the maximum input voltage rating of the inverter. The selected inverters have a frequency range of 50/60 Hz and a rated maximum power output of 1200 kW_{ac} [20].

Table 1 Site selection parameters

Location	Annual Global Irradiation [kWh/m^2]	Annual PV output [kWh/kWp]	Grid Connectivity [distance, existing/new]	Annual Climatic Conditions	Infrastructure and Access
Nawabshah	2,251.4	1737.9	Approx. 250 km, new grid	**35.6 [°C]**	It needs to be built.
Hyderabad	2,266.5	1,754	Approx. 62 km, new grid	**35 [°C]**	Road access, utilities, and proximity to resources.
Tharparkar	2,217	1642.1	Approx. 270 km, new grid	**35 [°C]**	It needs to be built.
Thatta	2221.7	1724.6	Approx. 110 km, new grid	**31 [°C]**	It needs to be built.
Manjhand	2100	1744.9	Approx. 80 km, existing grid	**35.1 [°C]**	Road access, utilities, and proximity to resources.

Table 2 Technical specifications of solar PV module

Parameters	Value (unit)
Manufacturer	AE Solar Germany
Model	AE700TME-132BDS
Rated maximum power capacity	700 [W]
Max voltage (V_{mp})	42.10 [V]
Max power current (I_{mp})	16.63 [A]
Open circuit voltage (V_{oc})	50.13 [V]
Short circuit current I_{sc}	17.43 [A]
Efficiency	22.56 [%]

Performance parameters for PVsyst software

In PVsyst, the required input data is reduced, calculation times are sped up, and accuracy is maintained.

1. Technical Parameters

Table 3 Performance technical parameters for PVsyst software

Parameter	Description	Equation	Unit	Reference
PV Array Yield	The array yield is the ratio of the energy output from a photovoltaic (PV) array for a specific time (such as a day, month, or year) divided by its rated power.	$Y_a = \frac{E_{DC,array}}{P_{PV,rated}}$	[kWh/kW/day]	[21]
Reference Yield	Reference yield is the ratio of solar radiation H_t (kWh/m^2) absorbed by the solar module plane to G_o (1kW/m^2). It represents a solar plant's daily peak sun hours in any location.	$Y_r = \frac{H_t}{G_o}$	[kWh/kW/day]	[21]
Specific Production	Annual energy production per kW_p is "specific production". It evaluates the plant's financial value and compares technologies and systems' operational performance.	$\text{Specific production} = \frac{\text{produced energy}}{P_o}$	[kWh/kW$_p$]	[21]
Performance Ratio	The ratio between the final and reference yields represents the performance ratio (PR). The PR compares installed PV systems at different places by percentage.	$PR = \frac{Y_f}{Y_r} * 100$	[%]	[21]
System Losses	The system loss L_s corresponds to the dissipation of energy on the AC side, which includes the irregular functioning of the inverter, AC transformer, and wiring.	$L_S = Y_a - Y_f$	[hour/day]	[21]
Final Yield	The final yield Y_f is the total system useable AC energy E_{grid} (kWh) over a specified period divided by the installed plant's nominal power P_o (kW_p).	$Y_f = \frac{E_{grid}}{P_o}$	[kWh/kW/day]	[21]

PV Module Efficiency (η_{PV})	The solar module's energy conversion as a percentage of available radiation is called module efficiency.	$\eta_{PV} = \frac{E_{AC}}{E_{DC}} * 100$	[%]	[21]
Inverter Efficiency (η_{inv})	The inverter generates the AC power P_{ac} fed into the grid, while the PV array produces the DC power P_{dc}.	$\eta_{inv} = S * \frac{E_{DC}}{H_t} * 100$	[%]	[21]
PV System Efficiency	The instantaneous efficiency of a photovoltaic (PV) system is determined by multiplying the efficiency of its PV module efficiency (η_{PV}) by the efficiency of the inverter efficiency (η_{inv}).	$\eta_{sys} = \eta_{PV} * \eta_{inv}$	[%]	[21]
Capacity Utilisation factor	The ratio between a PV plant's actual annual energy output and the amount of energy it would generate at nominal capacity for one year. The capacity utilisation factor of a solar PV power plant is determined by three main factors: the size of the inverter, the tracking ability, and the quality of the resource.	$CF = \frac{Y_f}{8760}$	[%]	[21]

2. Key Economics Parameters

Table 4 Key Economics Parameters for the PV Systems

Parameter	Description	Equation	Reference
Net Present Value	A project's net present value (NPV) is the difference between the present value of cash flows over the project's lifetime and the initial capital investment cost.	$NPV = \sum_{n=0}^{N} \frac{Revenue}{(1+r)^n} - \text{initial cost}$	[22]
Internal rate of return	In financial terms, the internal rate of return (IRR) is the discount rate at which a project's net present value (NPV) becomes zero.	$NPV = \sum_{n=0}^{N} \frac{C_n}{(1+IRR)^n}$	[22]
Simple Payback Period	The simple payback period is the duration, measured in years, required for the cash flow (minus loan payments) to equal the total investment, including debt and equity.	$SPB = \frac{\text{initial investment}}{\text{annual savings}}$	[23]
Levelised cost of energy	The levelised cost of electricity, also known as energy production cost, is the cost per unit of electricity required to achieve zero net present value.	$LCOE = \frac{\text{yearly cost} + O\&M}{\text{yearly energy system produces}}$	[24]

3. Environmental Analysis

Greenhouse gases, primarily absorbed by infrared light, are a significant contributor to global warming, causing distress to millions worldwide [25]—equation (5), which is considered to be consistent for the chosen site.

$$Produced\ emissions = Annual\ generation * CO_2/kWh \quad (5)$$

Results and Discussion

I. Technical viability under peak and average load scenario

Both peak and average simulation results reveal the techno-economics of solar PV systems. The peak system with 260,568 PV modules produces 339,721 MWh annually, or 1,863 kWh/kWp. The average system with 221,430 PV modules generates 155 MW and 288,687 MWh yearly. For both suggested systems, the performance ratio is 0.872, with an inverter output of 87.2% and a PV array

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output loss of 11.3%. Calculations used a 30/180° tilt angle. The peak system's excess units may be cheaper for the facility's 289,809 MWh yearly energy needs.

Table 5 shows that PVsyst software provides the facility with the required and generated units from the average and peak PV systems. Compared to the needed units, the average solar PV system produces 1,122 MWh less yearly. During the same period, the peak solar system produced 49,911 MWh, exceeding the facility's energy needs. The analysis shows how well the solar systems perform over time and meet the facility's energy needs. Additionally, Table 6 shows the technical specifications calculated by the PVsyst software.

II. Financial analysis

Table 7 shows the average and peak PV solar system financial performance. The average PV system installation costs are 58,770,750 USD, with annual operating costs of 21,066,800 USD. The system has a 4.8-year Simple Payback Period and an LCOE of 0.0835 USD/kWh. This yields 211.3% ROI. Its IRR is 17.17%. On the other hand, Peak PV solar systems cost 66,714,400 USD to install and 21,485,900 USD to operate. Its Levelized Cost of Energy (LCOE) is 0.0736 USD/kWh and has a shorter Simple Payback Period of 6.5 years. NPV for the peak system yields 320.6% ROI and 26.10% IRR. Peak PV solar systems offer a longer payback period, higher returns, and a more favourable electricity cost than average PV systems. This study provides valuable insights for decision-makers involved in large-scale solar PV systems.

I. Environmental Analysis

Energy from solar PV facilities is not emission-free. Tables 8 and 9 break down the life cycle emissions for the system's primary components to compute a solar plant's CO_2 emissions. The average and peak PV solar systems are assessed for greenhouse gas (GHG) emissions. An average PV solar system produces 288,687.29 MWh annually, lowering CO_2 emissions by 3,853,975.3 tons. This shows its significant carbon emission reduction. Meanwhile, the system generates 333,511.75 tonnes of CO_2, totalling 3,010,449.3 tons.

In contrast, the peak PV solar system, which generates 339,720.83 MWh of electricity annually, effectively offsets 535,273.1 tonnes of CO_2. Although the system produces 333,511.75 tonnes of CO_2, it achieves a net reduction, resulting in a total CO_2 balance of 3,601,588. These findings highlight the complex interaction between emissions reduction and generation within each system, offering essential insights for sustainable energy decisions.

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Table 5 Comparison of generated and required units (MWh) for government facilities

Month	Units required [MWh] by the government sites	Units generated [MWh] by the average solar system	Units generated [MWh] by peak solar system
January	19,018	24,026	28,274
February	18,533	22,478	26,452
March	19,694	27,052	31,836
April	24,213	24,182	28,456
May	29,954	24,420	28,736
June	29,215	24,413	28,729
July	25,685	22,748	26,768
August	24,013	22,345	26,294
September	22,203	24,309	28,606
October	23,992	25,548	30,065
November	29,395	25,231	29,694
December	23,895	21,935	25,812
Total	289,809	288,687	339,721

Table 6 Technical specifications of the simulation's PV panels and inverters

Sr no.	Parameters	Calculated values (Average)	Calculated values (Peak)
1	Unit Nominal Power	700 [W_p]	700[W_p]
2	No. of PV modules	221,430 units	260,568 units
3	Cell area	644,494 [m^2]	758,409 [m^2]
4	Module area	687,023 [m^2]	808,455 [m^2]
5	No. of inverters	150 units	182 units
6	Operating Voltage	700-1500 []V	700-1500 [V]
7	Nominal Power (STC)	155 [MW_p]	182.4 [MW_p]
8	Modules	10,065 string x 22 In series	10,857 string x 24 In series
9	Inverter rating	1,000 [kWac] (150 units)	1,000 [kWac] (182 units)
10	Inverter power	1,000 [kW_{ac}]	1,000 [kW_{ac}]
11	CO_2 emissions cut	3,010,449.323 [tCO_2/year]	3601580.433 [tCO_2/year]

Table 7 Financial parameters of the proposed PV solar systems

System parameters	Average PV Solar System	Peak PV Solar System
Total Installation	$58.8 M	$66.7 M
Operating Cost	$21.1M [$/year]	$21.5 M [$/year]
Energy Generated	288,687 [MWh/year]	339,721 [MWh/year]
LCOE	0.0835 [$/kWh]	0.0736 [$/kWh]
Payback Period	4.8 [years]	6.5 [years]
NPV	$ 124.0 M	$213.5 M
ROI	211.3 [%]	320.6 [%]
IRR	17.17 [%]	26.10 [%]

Table 8 Peak PV Systems' Lifecycle Emissions

Item	LCE	Quantity	Subtotal [$kgCO_2$]
Modules	1713 [$kgCO_2/kW_p$]	189,998 [kW_p]	325,412,518
Supports	2.97 [$kgCO_2/kg$]	2,714,250 [kg]	8,056,301
Inverters	294 [$kgCO_2$/Units]	182 units	53,508

Table 9 Average PV Systems' Lifecycle Emissions

Item	LCE	Quantity	Subtotal [$kgCO_2$]
Modules	1713 [$kgCO_2/kW_p$]	144,999 [kW_p]	248,383,287
Supports	2.97 [$kgCO_2/kg$]	2,714,250 [kg]	8,056,301
Inverters	294 [$kgCO_2$/Units]	146 units	42,924

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