DESIGN, MODELLING AND PERFORMANCE ANALYSIS OF A RESIDENTIAL GRID-TIED AND OFF-GRID SOLAR SYSTEM

WRITTEN BY

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BACKGROUND OF STUDY

- Pakistan's Sunbelt region offers high solar irradiance and nearly 280 to 300 sunny days annually.
- The country's energy sector is dominated by fossil fuels, leading to volatile fuel import costs, large-scale carbon emissions, and frequent power outages.
- The government has introduced policies like the Alternative and Renewable Energy (ARE) Policy 2019, feed-in tariffs, and net metering regulations to encourage solar installations.
- High initial capital costs, lack of financing options, limited public awareness, and inadequate grid infrastructure limit grassroots solar PV deployment.
- Lahore, the capital of Punjab, presents both a promising and challenging environment for solar energy development.
- High ambient temperatures in the region can adversely affect PV module efficiency due to thermal losses.
- Urban challenges such as building shadows, dust accumulation, limited rooftop space, and lack of knowledge regarding system design hinder optimal solar PV performance.

- The cost of solar photovoltaic (PV) systems in Pakistan has significantly declined over the past decade.
- Residential setups typically fall between USD 2,000 and 3,000, while a standard 10 kW installation is priced between USD 6,000 and 8,000.
- Policy incentives such as zero-rated sales tax, customs duty exemptions, and net metering frameworks contribute to lowering the financial burden for adopters.
- High upfront investment and limited access to long-term financing remain key barriers for many households.
- Despite challenges, the overall price trajectory of solar energy technologies continues to decline, reinforcing solar PV as a viable solution to Pakistan's growing energy deficit and rising electricity tariffs.

SOLAR PV MARKET IN PAKISTAN (2024)

System Size(kW)	Price Range (USD)	Key Components Included
3 kW	2,000 – 3,000	Solar panels, inverter, Hardware, mounting structure, installation Cost
5 kW	3,500 – 5,000	Solar panels, inverter, Hardware, mounting structure, installation Cost
10 kW	6,000 – 8,000	Solar panels, inverter, Hardware, mounting structure, installation Cost
20 kW	10,000 – 14,000	Solar panels, inverter, Hardware, mounting structure, installation Cost
50 kW	25,000 – 35,000	Solar panels, inverter, Hardware, mounting structure, installation Cost
100 kW	50,000 – 70,000	Solar panels, inverter, Hardware, mounting structure, installation Cost
Utility Scale (per watt)	0.60 – 0.80	Solar panels, inverter, Hardware, mounting structure, installation Cost

RESEARCH OBJECTIVES

- Design optimized grid-tied and off-grid PV systems for a residential property in Lahore.
- Simulate system performance under real-world conditions using MATLAB/Simulink and HOMER Pro.
- Assess energy output, efficiency, and losses for both configurations.
- Conduct a techno-economic analysis including capital costs, LCOE, and payback periods.
- Evaluate environmental benefits, including CO emission reductions and sustainability metrics.
- Compare the performance and viability of grid-tied versus off-grid systems.
- Provide policy and technical recommendations for improved PV adoption in Pakistan.

Literature review

- Muhammad Umair Akhtar, M. Tariq Iqbal "Modeling and Simulation of Grid-Tied Three-Phase PV System in Lahore, Pakistan". European Journal of Electrical Engineering and Computer Science. 8, 1 (Feb. 2024), 23–32. DOI:https://doi.org/10.24018/ejece.2024.8.1.603.
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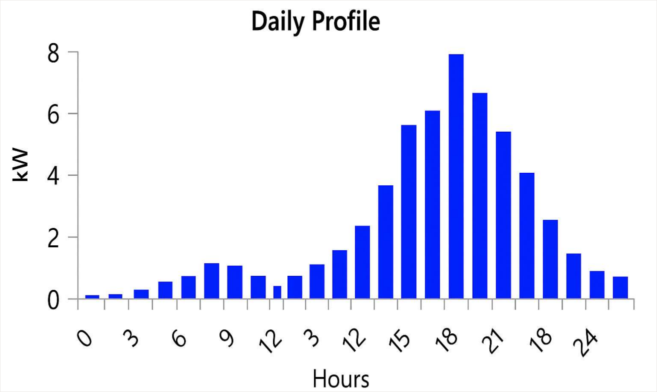
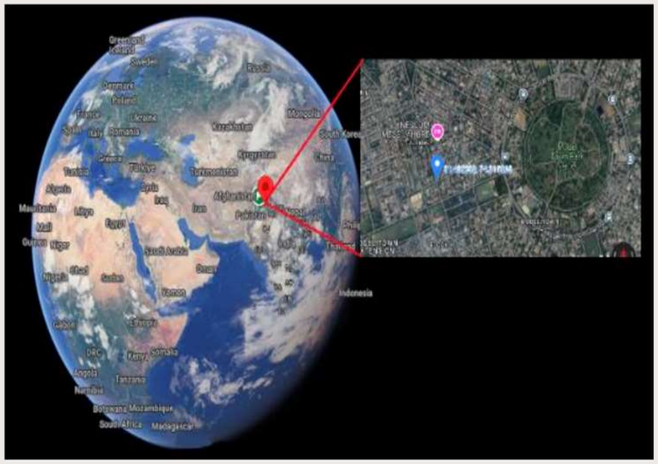
DESIGN AND ANALYSIS OF PHOTOVOLTIC SYSTEM FOR A HOUSE IN MODEL TOWN LAHORE USING HOMER PRO

- The study evaluates the economic viability of an 11 kW photovoltaic (PV) system in Model Town, Lahore.
- The system, using Jinko Solar 540Wp panels, was compared to a grid-only model based on local electricity tariffs.
- The PV system, despite its higher initial cost (USD 18,995), significantly reduces long-term energy expenses and reliance on the grid.
- The PV system also reduces the carbon footprint associated with grid electricity generated from fossil fuels.
- The study concludes that the PV system is economically and environmentally feasible. Future work will explore battery storage to enhance energy autonomy.

GRID-TIED PV SYSTEM DESIGN (HOMER PRO)

- The site is a residential house with a population of approximately 22 million.
- The house's coordinates are longitude 31.4829 and latitude 74.3156.
- The average load of the house is around 58 kWh, peaking at 7.6 kW during summer.
- Air conditioning units are used to maintain indoor temperature.





SYSTEM'S COMPONENTS

The system has two main components.

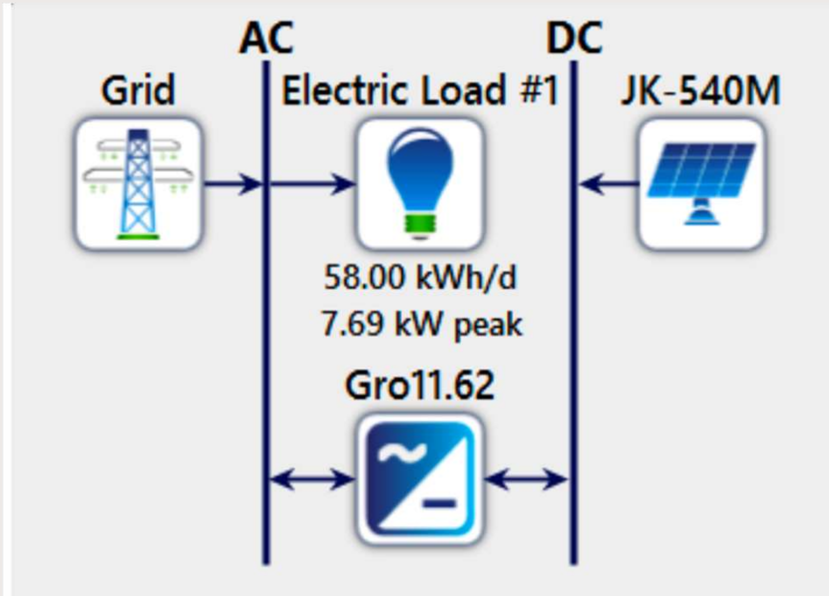
1. Solar Panels (Jinko).
2. Grid-Tied Hybrid Inverter (Growatt)

Solar Panels (Jinko)

- Higher power output
- Better performance in high temperatures
- Reduced shading impact
- Stronger mechanical resistance

Grid-Tied Hybrid Inverter (Growatt)

- Converting DC from the panels into AC for home appliances.
- Synchronizing the power with utility voltage and frequency.
- Exporting excess power back to the grid during high production hours.
- Auto Switching of load between Solar and Utility.



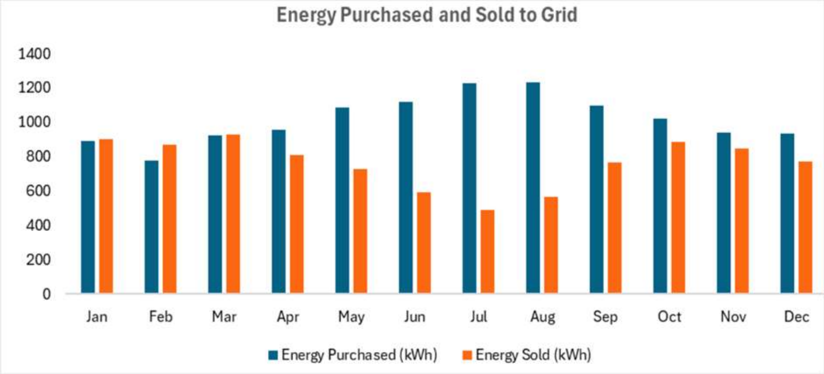
ELECTRICAL SPECIFICATION OF SOLAR SYSTEM

Parameter	Value
Rated Output Power	12100 VA / 1100 W
Rated Voltage	230 / 400 VAC
Frequency Range	50 Hz / 60 Hz
PV Voltage Range	140–1000 dc V
PV Isc	16 dc A× 2
Maximum Input Current	13 dc A× 2
Maximum Output Current	18.3 ac A
Operating Temperature	−25°C to +60°C

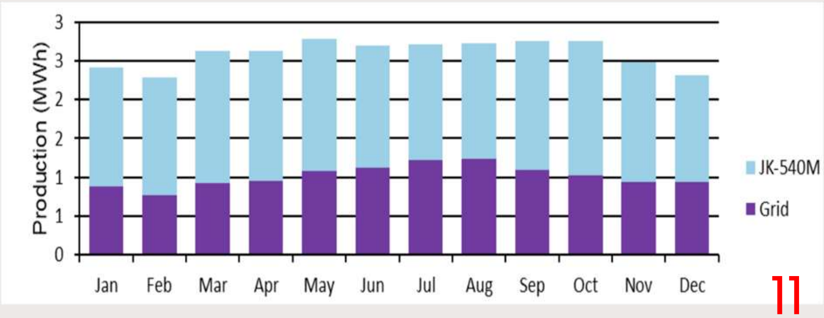
Parameter	Value
Maximum Power (Pmax)	540 W
Open Circuit Voltage (Voc)	49.2 V
Short Circuit Current (Isc)	13.85 A
Maximum Power Voltage (Vmp)	40.7 V
Maximum Power Current (Imp)	13.27 A
Module Efficiency	20.94%
Power Tolerance	0 – 3%
Maximum System Voltage	1500 V DC
Operating Temperature Range	-40°C to 85°C
Maximum Series Fuse Rating	25 A

KEY RESULTS

- Current grid-supplied energy costs of $3,129 reduce to $1,086 per year with the addition of an 11 kW PV system.
- Annual savings of $2,043 are achieved due to a 65% decrease in energy expenses.
- The PV system has a favourable payback period of 1.97 years and an internal rate of return (IRR) of 50.7%.
- The Jinko PV system installed at the site has a nominal capacity of 11.0 kW and an annual energy production of 18,978 kWh.
- The system achieves a penetration level of 89.6%, ensuring nearly 90% of the site's energy demand can be supplied by solar power.
- The LCOE for the PV system is extremely low at $0.0208 per kWh, indicating the long-term cost-effectiveness of the solar installation.
- The system is expected to operate for approximately 4,384 hours per year, with an average power output of 2.07 kW.
- Annual energy losses are calculated to be 854 kWh, confirming the system's operational reliability and performance.



Parameter	Base System	Proposed System
Net Present Cost (USD)	$40,452	$18,097
CAPEX (USD)	$0.00	$4,059
OPEX (USD/year)	$3,129	$1,086
LCOE (per kWh)	$0.148	$0.0462
CO_2 Emitted (kg/year)	13,379	7,704
Fuel Consumption (L/year)	0	0



DYNAMIC MODELLING (MATLAB/SIMULINK)

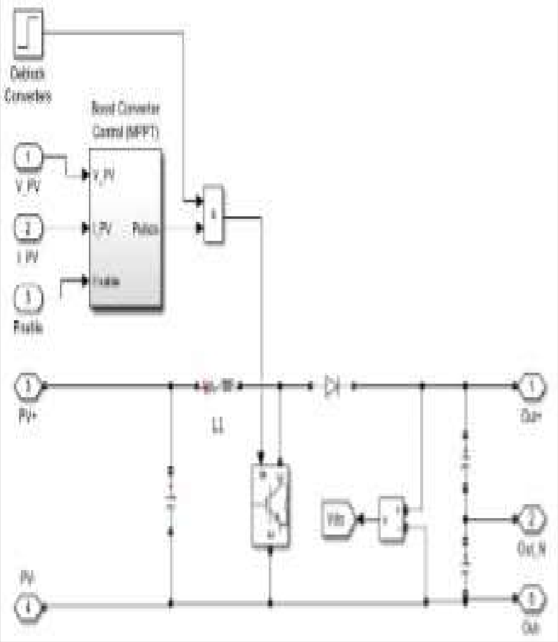
- The study presents a dynamic simulation of a grid-connected photovoltaic system, modeled in MATLAB/Simulink, tailored to the urban environmental conditions of Lahore.
- The system utilizes high-efficiency Jinko Solar panels, a DC-DC boost converter, and a Growatt inverter, resulting in a stable 12 kW output with Incremental Conductance Maximum Power Point Tracking (MPPT) control.
- The study utilizes a system dynamics model and simulation in Simulink, with all solar-produced power sent to the connected load and the local grid.

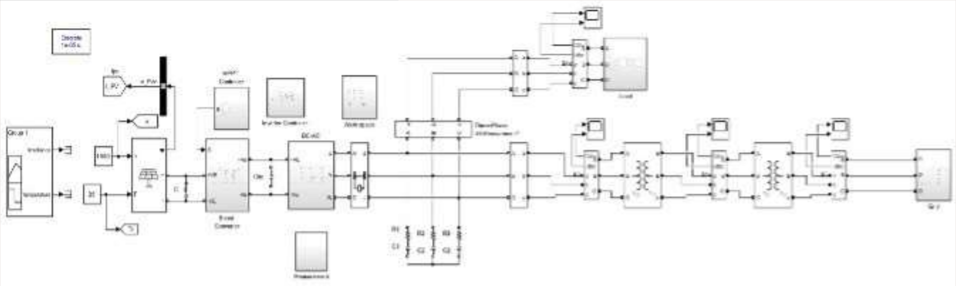
SITE DETAIL

- The research site is a residential house with ample rooftop space and ideal project conditions.
- The location offers high solar insolation year-round, enhancing the efficiency and output of the PV system.
- The model is tailored to the specific environmental conditions of Lahore, incorporating climate-related parameters.
- The Simulink model has been implemented on a house under study.
- The grid-tied photovoltaic (PV) system developed for this study incorporates Jinko Solar panels for efficient solar energy conversion.
- The PV array operates at an optimized voltage of 48 V, regulated by a Maximum Power Point Tracking (MPPT) controller.
- The system employs a Growatt MOD 11KTL3-X, an 11 kW pure sine wave hybrid inverter, for seamless integration with the electrical grid.
- The system operates without battery storage, directly feeding the generated power into the grid.

PV ARRAY AND DC-DC CONVERTER IN SIMULATION

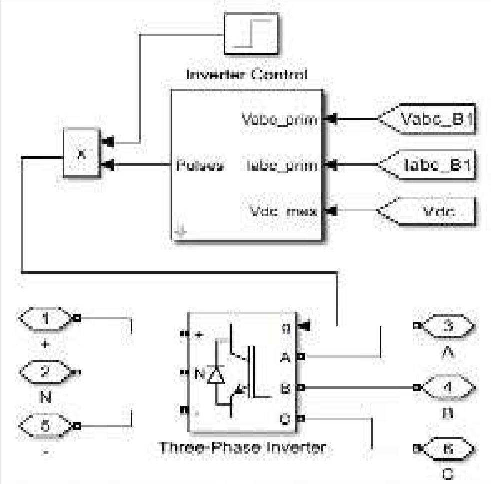
- Jinko solar, a high-efficiency monocrystalline solar panel, is used in the study.
- The panels have a rated output of 540 watts and a module efficiency of 20.94%.
- Key electrical specifications include an open-circuit voltage (Voc) of 49.2 V, a short-circuit current (Isc) of 13.85 A, a maximum power voltage (Vmp) of 40.7 V, and a maximum power current (Imp) of 13.27 A.
- The PV system has a module efficiency of 20.94%, power tolerance of 0 – 3%, and a temperature coefficient of Isc (αIsc) of 0.048%/°C, βIsc of -0.28%/°C, and γIsc of -0.35%/°C.
- A Boost Converter model is used in Simulink to replicate the real system's functionality and dynamics.
- The Boost Converter optimizes power flow from the PV array to the inverter at an output voltage of 476 V.
- Maximum Power Point Tracking (MPPT) control is implemented to optimize the DC-DC converter's performance in the PV system.





PV ARRAY AND DC-DC CONVERTER IN SIMULATION

- The Integral Regulator is incorporated into the MPPT control to minimize steady-state errors during tracking and ensure the system remains at the maximum power point.
- The proposed system uses a Growatt pure sine wave hybrid inverter, specifically designed for residential and small commercial PV systems.
- The inverter supports three modes of operation: stand-alone, grid-tied, or hybrid.
- It has dual outputs for smart load management and can be automatically turned off to conserve battery during nighttime.

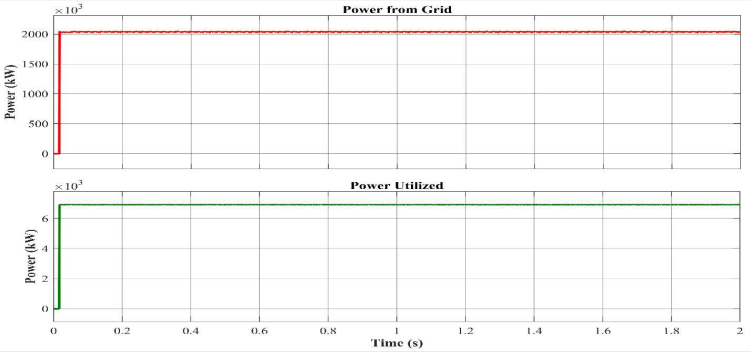


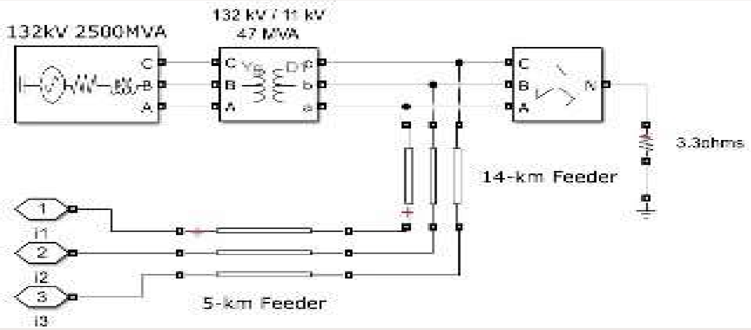
Type	Rating
Rated Output Power	12100 VA / 1100 W
Rated Voltage	230/400 VAC
Frequency Range	50 Hz / 60 Hz
PV Voltage Range	140–1000 VDC
PV Isc	16 A × 2 (DC)
Maximum Input Current	13 A × 2 (DC)
Maximum Output Current	18.3 A (AC)
Operating Temperature	−25 °C to +60 °C

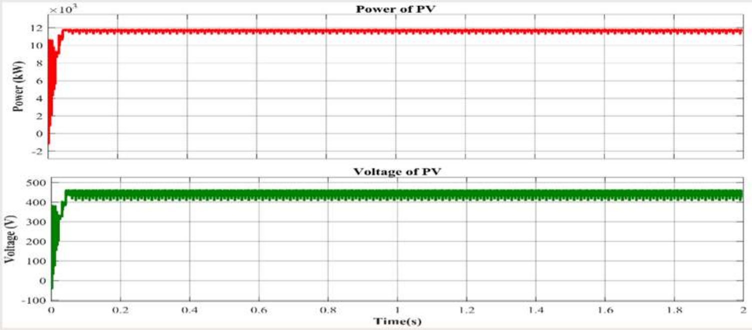
Type	Rating
Maximum Power (Pmax)	540 W
Open Circuit Voltage (Voc)	49.2 VDC
Maximum Power Voltage (Vmp)	40.70 VDC
Short Circuit Current (Isc)	13.85 A
Maximum Power Current (Imp)	13.27 A
Module Efficiency	20.94%
Power Tolerance	0 – 3%
Temperature Coefficient of Isc (α_{Isc})	0.048%/°C
Temperature Coefficient of Voc (β_{Isc})	-0.28%/°C
Temperature Coefficient of Pmax (γ_{Isc})	-0.35%/°C

SIMULATION RESULTS

- System components include Jinko Solar JKM540M-72HL4-V panels and Growatt PV Grid Inverter MOD 11KTL3-X.
- Solar panels showed optimal power output of approximately 11 kW under peak sunlight conditions, with an efficiency of around 17.37%.
- The panels maintained efficiency even under partial shading and cloud cover.
- Advanced cell technology and anti-reflective coating optimized light absorption.
- PV input voltage of 48 V and MPPT voltage set at 48 V for maximum efficiency.
- DC-DC boost converter elevated DC voltage to 350 V, converted to a 220 V AC supply through the inverter for grid integration.
- The inverter's rapid response to grid voltage and frequency fluctuations maintained a stable output of up to 12 kW.
- PV power output was closely linked to solar irradiance levels, demonstrating efficient energy harvesting.
- The integration of PV generation and grid connection facilitated smooth energy management.
- The system met high demand while optimizing power flow between the PV array and the grid.





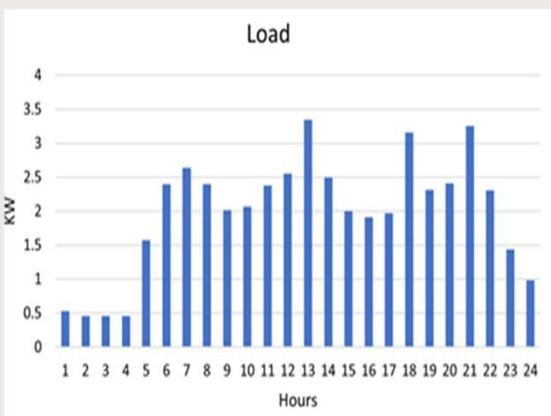


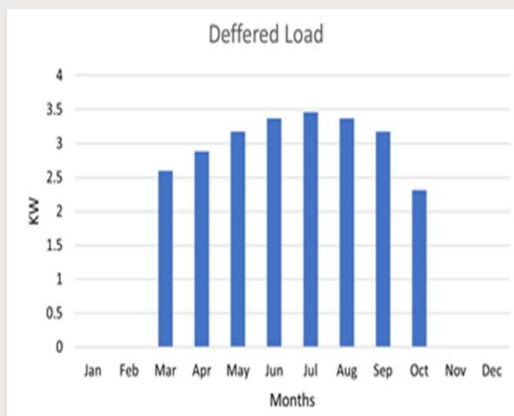
FEASIBILITY STUDY OF AN OFF-GRID SOLAR PV SYSTEM FOR A RESIDENTIAL APPLICATION IN MODEL TOWN, LAHORE

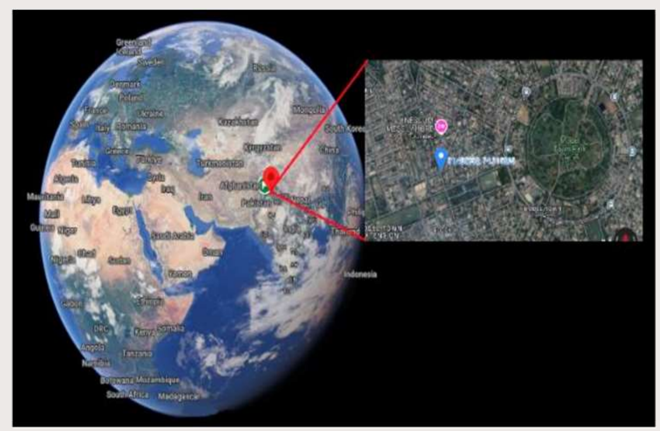
- The study focuses on the design and feasibility of an off-grid solar photovoltaic system for residential use in Model Town, Lahore, Pakistan.
- The primary author was involved in all stages of the research process, including literature review, system design, simulation modelling, and performance analysis.
- The study demonstrates the technical and economic viability of an off-grid hybrid PV system that integrates a 12.6 kW PV array, 89 kWh battery storage, and an 11-kW inverter.
- The system achieves an internal rate of return (IRR) of 228%, a payback period under 0.5 years, and significant carbon emission reductions.
- The system is environmentally friendly, with zero CO emissions and almost no energy disruptions, making it suitable for regions facing frequent power outages and high energy costs.

SITE LOCATION AND LOAD PROFILE

- The study is conducted at a building in Lahore, a metropolitan division with a population of around 22 million.
- The location is located at 74.3156 degrees of latitude and 31.482982 degrees of longitude.
- The house's typical electric load diagram shows an average daily electricity consumption of 25.06 kWh, with a significant increase during summer.
- The maximum electricity consumption is about 7.0 kW, combining the house load and the AC load (Deferrable load) used in summer.

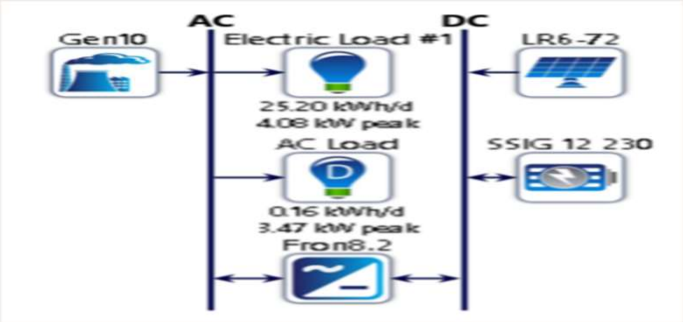






RESOURCES

- Utilizes Jinko Solar's JKM540M-72HL4-V solar panels with a rated capacity of 585 watts.
- Features a half-cut cell configuration for increased power output, improved efficiency, and enhanced mechanical load tolerance.
- Incorporates a Growatt MOD 11KTL3-X, an 11kW pure sine wave hybrid inverter.
- rated for operation on 230 VAC, 50 Hz systems.
- Supports both battery-backed and battery-less configurations.
- Simulation of the storage system using the Kinetic Battery Model.
- The battery rated voltage is 12 V and has a rated energy capacity of 2.78 kWh.
- Features include nominal voltage (V), nominal capacity (kWh), maximum capacity (Ah), capacity ratio (0.486), rate constant (1/hr), roundtrip efficiency (%), maximum charge current (A), maximum discharge current (A), and maximum charge rate (A/Ah).

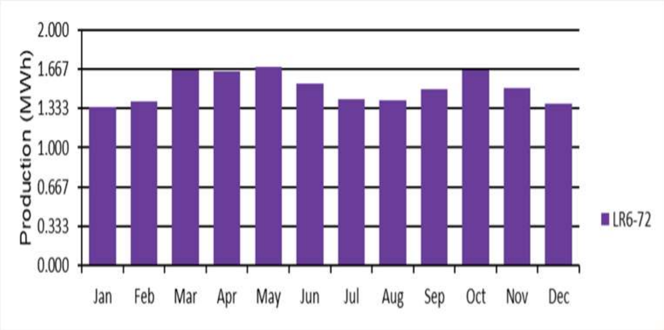


Parameter	Value
Nominal Voltage (V)	12
Nominal Capacity (kWh)	2.78
Maximum Capacity (Ah)	232
Capacity Ratio	0.486
Rate Constant (1/hr)	0.409
Roundtrip Efficiency (%)	80
Maximum Charge Current (A)	41
Maximum Discharge Current (A)	300
Maximum Charge Rate (A/Ah)	1

Type	Rating
Nominal Output Power	585 W
Voltage (No Load)	49.2 VDC
Voltage at Peak Power	40.70 VDC
Current (Short Circuit)	13.85 A
Current at Peak Output	13.27 A
Conversion Efficiency	20.94%
Output Deviation Range	0 – 3%
Temp. Effect on Short Circuit Current	0.048%/°C
Temp. Effect on Open Circuit Voltage	-0.28%/°C
Temp. Effect on Power Output	-0.35%/°C
Maximum System Voltage	1500 VDC
Operating Temperature Range	-40°C to 85°C
Maximum Series Fuse Rating	25 A

RESULTS

- The hybrid microgrid system comprises a 12.6 kW Jinko Solar PV array, 89.0 kWh of Trojan SSIG 12 230 battery storage, and an 11.0 kW Growatt inverter.
- The simulated load is 25.2 kWh/day with a peak demand of 3.35 kW.
- Annual PV production reached 18,120 kWh with a specific yield of 1,439 kWh/kW and a capacity factor of 16.4%.
- The system achieved 197% PV penetration and operated 4,384 hours/year.
- Battery autonomy was calculated at 67.4 hours with 5,566 kWh/year throughput and 1,243 kWh/year losses.
- The net present cost of the hybrid system was estimated at $14,713, a 91% cost reduction over the system's 25-year lifetime.
- The Levelized Cost of Energy dropped from $1.38/kWh (diesel) to $0.123/kWh (hybrid).
- The capital cost increased from $4,867 to $9,534 but was offset by an initial operating cost savings of over $11,998
- The investment yielded an Internal Rate of Return (IRR) of 228% with a simple payback period of just 0.491 years.



Parameter	Value
Nominal Capacity	12.6 kW
Total Output	18,120 kWh/year
Capital Investment	$2,540
Maintenance Cost	$86.1 per year
Specific Output	1,439 kWh/kW
LCOE	$0.0165 per kWh
PV Input to the System	197%

Parameter	Value
Nominal Capacity	89.0 kWh
Expected Life	13.1 years
Annual Throughput	5,566 kWh/year
Capital Costs	$5,888
Maintenance Cost	$96.0 per year
Losses	1,243 kWh/year
Autonomy	67.4 hours

RESULTS

Component	Parameter	Value	Unit
PV	Total Production	18,120	kWh/year
PV	Capacity Factor	16.4	%
Battery	Usable Capacity	71.2	kWh
Battery	Annual Throughput	5,566	kWh
Battery	Autonomy	67.4	hr
Inverter	Energy Out	9,252	kWh/year
Inverter	Losses	336	kWh/year

Parameter	Value
Capacity	11.0 kW
Hours of Operation	8,756 hours/year
Mean Output	1.06 kW
Energy Out	9,252 kWh/year
Min Output	0 kW
Energy In	9,588 kWh/year
Max Output	3.35 kW
Losses	336 kWh/year
Capacity Factor	9.60%

Metric	Diesel System	Hybrid System	Change (%)
Net Present Cost	$165,157	$14,713	-91.1
Capital Cost (CAPEX)	$4,867	$9,534	+95.9
Operating Cost (OPEX)	$12,399	$400.56	-96.8
LCOE	$1.38	$0.123	-91.1
IRR	N/A	228%	N/A
Simple Payback	N/A	0.491	Fast ROI

CONCLUSION & RECOMMENDATIONS

- Examines design, modelling, and performance analysis of grid-tied and off-grid residential solar PV systems.
- Grid-tied PV systems are cost-effective and environmentally sustainable, with lower Net Present Cost (NPC) compared to grid-only models.
- Grid-connected PV systems are financially viable for urban residences in Pakistan with proper system sizing and optimization.
- A high-resolution model of a grid-connected system was developed to assess its performance under dynamic environmental conditions.
- The system maintained a consistent output of 12 kW under variable irradiance and temperature levels, proving the practical reliability of grid-tied solar solutions.
- An off-grid solar PV configuration with battery backup was explored, achieving an internal rate of return of 228%, a payback period of 0.491 years, and a 91% reduction in net present cost compared to traditional diesel-based systems.
- The system achieved complete elimination of carbon emissions while ensuring reliability and independence from grid interruptions.

POLICY RECOMMENDATIONS

- Grid-tied and off-grid solar PV systems are cost-effective, requiring targeted government support.
- Financial instruments like soft loans, leasing schemes, and targeted subsidies can enhance affordability.
- Consistent and transparent implementation of net metering policies is crucial.
- The HOMER-based grid-tied model assumes accurate feed-in tariff compensation and grid stability, but inconsistent policy enforcement can undermine benefits.
- Off-grid systems are ideal for sustainable electrification strategies due to near-zero emissions and operational resilience.

FUTURE WORK

- Integration of hybrid energy systems: Combining solar PV with other renewable resources for more balanced solutions.
- Battery storage optimization: Using advanced optimization techniques for efficient sizing and scheduling.
- Economic modelling: Based on current costs and static tariff structures.
- Sensitivity analysis: Consideration of inflation, panel degradation, battery lifecycle costs, and evolving net metering policies.
- Lifecycle assessments: Quantifying embedded energy and total emissions footprint.

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LIST OF PUBLICATIONS

1. Hassan, Asad Mehmood and Iqbal, Tariq (2024) Design and Analysis of Photovoltic System for a House in Model Town Lahore Using Homer Pro. In: 33rd Annual Newfoundland Electrical and Computer Engineering Conference (NECEC), November 14, 2024, St. John's, Newfoundland and Labrador.
2. "The Dynamic Modeling of a Grid-Connected Photovoltaic Setup Using MATLAB/Simulink". *European Journal of Energy Research*, vol. 5, no. 4, July 2025, pp. 1-6, https://doi.org/10.24018/ejenergy.2025.5.4.167.
3. "Feasibility Study of an Off-Grid Solar PV System for a Residential Application in Model Town, Lahore". *European Journal of Energy Research* 5, no. 5 (October 23, 2025): 1–5. Accessed October 29, 2025. https://www.ej-energy.org/index.php/ejenergy/article/view/171.


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QUESTIONS