Economic Analysis of a 1 MW Rooftop Grid-Connected Solar Photovoltaic System under Indian Climatic Conditions

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***Abstract*—The increasing demand for electrical energy and the environmental impacts associated with fossil-fuel-based power generation have accelerated the adoption of renewable energy technologies. Among these, rooftop solar photovoltaic (PV) systems have emerged as an effective solution for sustainable electricity generation. This paper presents the technical and economic analysis of a 1 MW grid-connected rooftop solar photovoltaic system designed for Indian climatic conditions. The study evaluates system design, expected energy generation, financial feasibility, and environmental benefits using simulation-based analysis. The proposed system is estimated to generate approximately 1,758 MWh of electricity during its first year of operation with a performance ratio ranging from 73% to 86.4%. The financial assessment indicates a Levelized Cost of Electricity (LCOE) of approximately ₹2.4/kWh, demonstrating the long-term economic viability of the project. In addition to significant savings in electricity costs, the system contributes substantially to carbon emission reduction, supporting India's transition toward sustainable energy development. The results indicate that large-scale rooftop PV systems can provide reliable, clean, and cost-effective electricity for institutional and commercial applications while reducing dependence on conventional energy sources.**

***Index Terms*—Rooftop Solar Photovoltaic, Grid-Connected PV System, Renewable Energy, Economic Analysis, Performance Ratio, Levelized Cost of Electricity (LCOE), MATLAB/Simulink, Sustainable Energy.**

I.INTRODUCTION

The rapid growth in electricity demand, coupled with concerns regarding climate change and depletion of fossil fuel resources, has increased the importance of renewable energy technologies worldwide. Solar photovoltaic (PV) technology has become one of the most promising renewable energy solutions because of its environmental sustainability, low operating cost, and abundant solar resource availability.

India possesses excellent solar potential, receiving approximately 300 sunny days annually with average solar radiation of around 4.7 kWh/m²/day. These favorable climatic conditions make rooftop solar PV systems an attractive option for meeting growing electricity demand while reducing greenhouse gas emissions. Government initiatives, supportive policies, and continuous improvements in PV module efficiency have further accelerated the deployment of grid-connected rooftop solar installations across the country.

This study focuses on the economic and technical analysis of a 1 MW rooftop grid-connected solar photovoltaic system. The research evaluates system performance, energy generation, financial feasibility, and environmental impact to demonstrate the practicality of large-scale rooftop solar deployment under Indian climatic conditions.

II. LITERATURE REVIEW

The rapid advancement of rooftop solar photovoltaic (PV) technology has attracted considerable attention from researchers due to its technical, economic, and environmental benefits. Numerous studies have investigated system performance, energy generation, financial feasibility, and grid integration of rooftop PV installations.

Previous studies have shown that grid-connected rooftop PV systems significantly reduce electricity costs while improving energy security. Performance indicators such as Performance Ratio (PR), Capacity Utilization Factor (CUF), and annual energy yield are commonly used to evaluate plant efficiency. Research indicates that system performance is influenced by solar irradiance, ambient temperature, module orientation, shading effects, inverter efficiency, and maintenance practices.

Several researchers have emphasized the importance of operation and maintenance in maintaining long-term system efficiency. Dust accumulation (soiling), partial shading, and module degradation can considerably reduce power output if regular cleaning and monitoring are not performed. Modern monitoring systems and preventive maintenance strategies help improve plant availability and reduce operational losses.

Economic studies have demonstrated that the declining cost of photovoltaic modules and supportive government policies have made rooftop solar systems financially attractive.

Parameters such as Capital Cost (CAPEX), Operation and Maintenance Cost (OPEX), Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period, and Levelized Cost of Electricity (LCOE) are widely adopted for evaluating investment feasibility. Studies consistently report that properly designed rooftop PV systems provide attractive long-term financial returns while reducing dependence on conventional electricity generation.

Environmental assessments further indicate that rooftop solar photovoltaic systems play a significant role in reducing greenhouse gas emissions, conserving fossil fuel resources, and supporting sustainable development. Large-scale deployment of rooftop PV technology contributes to India's renewable energy targets while improving energy reliability and reducing transmission losses.

Based on the available literature, it is evident that technical optimization, proper economic planning, and efficient operation and maintenance are essential for maximizing the performance and financial viability of large-scale rooftop solar photovoltaic systems.

Therefore, this research focuses on the comprehensive technical and economic evaluation of a 1 MW grid-connected rooftop solar photovoltaic system operating under Indian climatic conditions.

III. METHODOLOGY

Project Planning and Site Selection

The proposed study evaluates a 1 MW grid-connected rooftop solar photovoltaic (PV) system under Indian climatic conditions. The methodology begins with the selection of a suitable rooftop site based on structural strength, available installation area, shading conditions, solar irradiance, roof orientation, and accessibility for operation and maintenance. The design assumes that the selected rooftop receives adequate solar radiation throughout the year with minimal shading losses.

System Design

The PV system consists of high-efficiency photovoltaic modules connected in series and parallel to achieve the required DC capacity. The generated DC power is converted into AC power using grid-connected inverters and supplied to the utility grid through a net-metering arrangement. The complete system includes PV modules, mounting structures, DC and AC cables, protection devices, inverters, and monitoring equipment.

Energy Yield Estimation

The annual energy generation is estimated using location-specific solar radiation and climatic data. The analysis considers major system losses such as module temperature effects, inverter losses, cable losses, mismatch losses, and system availability. Key performance indicators, including Performance Ratio (PR) and Capacity Factor (CF), are used to evaluate the operational efficiency of the proposed plant.

Financial and Economic Analysis

The economic feasibility of the project is assessed using standard financial indicators, including:

- Capital Expenditure (CAPEX)
- Operation and Maintenance Cost (OPEX)
- Levelized Cost of Electricity (LCOE)
- Payback Period
- Return on Investment (ROI)

These parameters are used to determine the long-term financial viability of the 1 MW rooftop PV system and to evaluate the cost of electricity generation over the system's operational lifetime.

Grid Integration and Safety

The proposed PV system is designed for grid-connected operation with appropriate protection mechanisms, including anti-islanding protection, over-voltage protection, grounding, and circuit protection devices. The system complies with relevant grid-interconnection and electrical safety requirements to ensure reliable and secure operation.

Environmental Assessment

The environmental impact of the proposed system is evaluated by estimating the reduction in carbon dioxide emissions and the contribution of renewable energy generation toward sustainable development. The analysis also considers the conservation of fossil fuels and the reduction of greenhouse gas emissions achieved through solar energy utilization.

IV. RESULTS AND DISCUSSION

System Performance

The simulation results indicate that the proposed 1 MW grid-connected rooftop solar photovoltaic system performs efficiently under Indian climatic conditions. The system is designed to maximize energy generation while maintaining stable grid operation. The PV array configuration and inverter sizing ensure effective utilization of available solar radiation throughout the year.

The estimated annual electricity generation during the first year of operation is approximately 1,758 MWh, with an average capacity factor of 19.83%. The Performance Ratio (PR) varies between 73% and 86.4%, indicating satisfactory system efficiency after accounting for practical losses such as temperature effects, inverter losses, wiring losses, and module mismatch.

Financial Performance

The economic assessment demonstrates that the proposed rooftop PV system is financially viable for long-term operation. Based on the estimated installation cost, operation and maintenance expenses, and lifetime energy generation, the Levelized Cost of Electricity (LCOE) is approximately ₹2.4 per kWh. This value is significantly lower than the average commercial electricity tariff, making the project economically attractive for institutional and commercial consumers.

Environmental Benefits

The environmental analysis shows that the proposed system contributes significantly to reducing greenhouse gas emissions. Over its operational lifetime, the plant is expected to generate approximately 40,445 MWh of clean electricity and offset nearly 27,794 metric tonnes of carbon dioxide (CO_2) emissions. These results demonstrate the important role of rooftop solar PV systems in supporting sustainable development and reducing dependence on fossil-fuel-based electricity generation.

V. DISCUSSION

The results confirm that a 1 MW rooftop grid-connected solar PV system is both technically and economically feasible under Indian climatic conditions. High solar irradiance availability, combined with efficient PV modules and grid-connected operation, enables reliable electricity generation with low operating costs.

Although the actual performance of the system may vary due to seasonal weather conditions, dust accumulation, shading, and equipment aging, regular operation and maintenance can minimize these effects and maintain high system efficiency throughout the project lifetime.
The study therefore demonstrates that large-scale rooftop solar installations can play a vital role in meeting future energy demands while supporting India's renewable energy and carbon reduction goals.

VI. CONCLUSION

This study presented the technical and economic analysis of a 1 MW grid-connected rooftop solar photovoltaic (PV) system under Indian climatic conditions. The findings demonstrate that rooftop solar technology is a reliable, environmentally sustainable, and economically viable solution for large-scale electricity generation.

The proposed system is capable of generating approximately 1,758 MWh of electricity during its first year of operation and about 40,445 MWh over its expected lifetime. The analysis indicates a Performance Ratio (PR) ranging from 73% to 86.4%, reflecting efficient system operation under practical conditions. Furthermore, the estimated Levelized Cost of Electricity (LCOE) of approximately ₹2.4/kWh confirms the long-term economic feasibility of the project. The environmental assessment also highlights the potential to reduce nearly 27,794 metric tonnes of CO_2 emissions, supporting India's renewable energy targets and sustainable development objectives.

The study concludes that grid-connected rooftop photovoltaic systems can significantly reduce dependence on conventional fossil-fuel-based electricity while lowering operating costs and improving energy security. Their successful implementation requires careful system design, appropriate site selection, regular operation and maintenance, and effective grid integration.

Future work may focus on integrating battery energy storage systems, artificial intelligence-based performance monitoring, Internet of Things (IoT)-enabled fault diagnosis, advanced Maximum Power Point Tracking (MPPT) techniques, and real-time optimization methods to further improve the efficiency, reliability, and economic performance of rooftop solar photovoltaic systems.

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