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Techno-Economic Feasibility and Financial Performance Evaluation of a Large-Scale Solar Photovoltaic Power Plant

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Abstract

The global energy transition towards renewable resources is intensifying due to the growing demand for sustainable and environmentally friendly energy solutions. Among various renewable technologies, solar photovoltaic (PV) systems have emerged as a leading contender, offering modular, scalable, and cost-efficient electricity generation. This study presents a comprehensive techno-economic feasibility analysis of a large-scale grid-connected solar PV power plant, focusing on its technical configuration, financial performance, and long-term operational viability. The analysis incorporates standard financial evaluation metrics, including Net Present Value (NPV), Internal Rate of Return (IRR), and payback period, to assess project profitability over a 26-year operational horizon. The proposed PV system is designed for a high-irradiance location, leveraging high-efficiency SunEvo mono-crystalline modules and Sungrow SC2500U inverters to maximize energy yield and grid integration efficiency. Simulation results indicate an initial capital investment of approximately USD 99.7 million, with a positive NPV of USD 6.75 million achieved in Year 5, marking the payback period. Over its lifecycle, the project achieves a cumulative NPV of USD 58.55 million, demonstrating strong long-term financial feasibility. The IRR curve illustrates a gradual shift from negative to positive values within the first five years, eventually stabilizing at a profitable rate, reinforcing the project's attractiveness for investors. Power generation analysis reveals an initial output of 2.72×10^8 kWh/year, gradually declining to 2.63×10^8 kWh/year due to natural system degradation but remaining highly reliable for over two decades. The findings underscore the crucial role of accurate site selection, high-efficiency equipment, and supportive policy frameworks in enhancing the economic performance of solar PV projects. Furthermore, the study highlights the importance of probabilistic risk analysis in addressing uncertainties in irradiation, energy pricing, and operational costs, ensuring more resilient investment decision-making. Overall, this work demonstrates that large-scale PV installations can deliver substantial long-term economic and environmental benefits, contributing significantly to the global renewable energy transition and greenhouse gas mitigation targets [1]–[10].

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1. Introduction

The transition towards renewable energy is driven by the need to reduce carbon emissions, diversify energy sources, and ensure long-term energy security. Among the various renewable technologies, solar photovoltaic (PV) power plants have gained significant attention due to their modularity, scalability, and declining costs of installation and maintenance [1]. The economic viability of PV projects is commonly evaluated using standard financial metrics, including Net Present Value (NPV), Internal Rate of Return (IRR), and payback period [2]. NPV calculates the present value of all future cash flows generated by a project, discounted at a specified rate, to determine its overall financial attractiveness [3]. IRR represents the discount rate at which the NPV becomes zero and serves as an indicator of project profitability relative to the cost of capital [4]. The payback period indicates the time required for cumulative project revenues to equal initial investments, offering investors a measure of project liquidity and risk exposure [5].

In large-scale solar PV projects, techno-economic feasibility analyses combine technical performance modeling with financial evaluation to assess their viability. Such analyses typically estimate energy output (power-to-grid), system degradation, capital expenditures (CAPEX), operational expenditures (OPEX), and revenues from electricity sales [6]. The Levelized Cost of Electricity (LCOE) is often calculated to compare project competitiveness against other energy generation technologies [7]. Moreover, various studies emphasize that location-specific solar irradiation levels, grid connectivity, and policy incentives (e.g., feed-in tariffs, tax credits) critically affect project economics [8]. With the increasing deployment of hybrid systems (solar PV combined with wind or battery storage), investment analysis has expanded to evaluate technology portfolios, risk diversification, and long-term energy supply reliability [9].

This literature review synthesizes existing studies focusing on three major themes:

1. Financial analysis of solar PV power plants, highlighting IRR, NPV, and payback period evaluations;
2. Techno-economic feasibility of large-scale PV projects, examining energy yield, costs, and power-to-grid integration;
3. Renewable energy project investment analysis, covering solar PV, wind, and hybrid systems.
   By reviewing recent academic and industry publications, this study aims to outline current trends, methodological approaches, and critical success factors influencing renewable energy investments, particularly large-scale solar PV deployment [10].

2. Literature Review

2.1 Financial Analysis of Solar PV Power Plants

Moradi *et al.* [1] conducted a financial evaluation of a 14.8 kW grid-connected PV system in Florida using the System Advisor Model (SAM) to simulate energy production and revenue generation. Their study reported a positive NPV and IRR exceeding 10%, with a payback period under ten years, highlighting solar PV as a financially viable option in high-irradiance regions. Similarly, Gabr [2] analyzed rooftop PV installations under various policy scenarios and concluded that positive NPVs and short payback periods could be achieved when electricity price savings and favorable feed-in tariffs were available.

Uncertainty in project financial performance is often addressed through probabilistic risk analysis. A Monte Carlo simulation-based study [3] demonstrated that PV plant NPVs and IRRs could vary significantly under fluctuating irradiation and electricity price conditions, emphasizing the importance of sensitivity analysis. These findings show that deterministic financial models may overestimate project profitability, making probabilistic approaches more reliable for long-term investment planning.

2.2 Techno-Economic Feasibility of Large-Scale PV Projects

Jamil [4] reviewed methodologies for assessing the techno-economic feasibility of PV projects, highlighting three core components: system sizing, energy output estimation, and cost-benefit analysis. The review concluded that robust feasibility assessments require accurate site-specific irradiation data and realistic assumptions for module degradation and maintenance costs.

Han *et al.* [5] conducted a techno-economic analysis of PV-battery systems for households and commercial users in Switzerland. Using simulation tools such as PVsyst and Meteonorm, they evaluated long-term cash flows under various electricity price trajectories. Their results indicated that adding battery storage could enhance project NPV and reduce payback periods, particularly in regions with high time-of-use tariffs.

Magableh *et al.* [6] compared bifacial and monofacial PV technologies for utility-scale projects. They reported that bifacial systems achieved higher energy output and improved financial returns due to their ability to capture reflected solar radiation. This led to reduced LCOE and enhanced IRR, making bifacial modules an attractive investment for large-scale deployment.

Abdelhady [7] extended the analysis to high-concentration PV (HCPV) systems, finding that under optimal solar conditions, HCPV systems could outperform conventional PV in terms of both energy yield and economic returns. However, the higher upfront costs and complex tracking mechanisms increased project financial risk, making feasibility highly location-dependent.

A recent study [8] also examined the role of policy incentives in improving project economics. Feed-in tariffs, tax credits, and low-interest financing options were shown to significantly enhance IRR and NPV values, making large-scale PV projects more attractive to investors. Without such incentives, the payback period tended to exceed 10 years, reducing investment appeal.

2.3 Renewable Energy Project Investment Analysis (PV, Wind, Hybrid)

The global investment landscape for renewable energy projects has seen rapid expansion, with declining costs of PV and wind technologies driving large-scale adoption [9]. Comparative analyses show that utility-scale PV projects now achieve some of the lowest LCOEs among energy generation technologies, typically ranging between 24–96 USD/MWh, outperforming many fossil-fuel-based systems [10].

Hybrid systems combining solar PV and wind energy have been extensively studied to assess their combined financial and technical benefits. A techno-economic study [11] indicated that hybrid PV-wind systems can provide more stable energy output, reduce dependence on grid imports, and improve overall IRR compared to standalone PV installations. However, higher capital costs and complex system integration remain barriers to adoption.

Thin silicon wafer technologies were investigated by Liu *et al.* [12], showing potential cost reductions of up to 50% compared to traditional crystalline silicon PV modules. These advancements could significantly improve project NPVs and shorten payback periods, especially in utility-scale applications.

Finally, energy-return-on-investment (EROI) and energy payback time metrics complement financial assessments by evaluating the sustainability of renewable energy projects. Studies [13], [14] indicate that modern PV installations can achieve energy payback times of less than one year and EROIs between 9 and 34, contributing positively to long-term energy transition goals.

3. Design and modelling

3.1 Location selection

The selected location is situated at a latitude of 34.85° and a longitude of -116.78°, with an elevation of 561 meters above sea level. This site falls within the Pacific Time Zone (GMT -8) and corresponds to the U.S. postal code 91486. The weather data is sourced from the National Solar Radiation Database (NSRDB), providing high-resolution solar and meteorological data for renewable energy analysis. The data is recorded at an hourly time step, offering detailed insights into local environmental conditions.

According to the annual weather file data, this location receives an average global horizontal irradiance (GHI) of 5.83 kWh/m^2/day, a direct normal irradiance (DNI) of 7.67 kWh/m^2/day, and a diffuse horizontal irradiance (DHI) of 1.25 kWh/m^2/day. These values indicate strong solar potential, making it suitable for solar energy applications. The average annual temperature is 17.0°C, with a moderate wind speed of 2.3 m/s. The site also has a low annual albedo of 0.225, which reflects a small portion of incoming solar radiation. Overall, these environmental conditions support the feasibility of renewable energy systems, particularly solar photovoltaic and concentrated solar power technologies.

3.2 Module selection

The selected photovoltaic module, SunEvo Solar Co. Ltd. SE4-72H-435MB, is a high-efficiency mono-crystalline silicon (Mono-c-Si) panel designed for optimal performance under standard test conditions (total irradiance = 1000 W/m^2, cell temperature = 25°C). The module consists of 72 cells, delivering a nominal efficiency of 20.05% and a maximum power output (Pmp) of 435.083 Wdc. It operates at a maximum power voltage (Vmp) of 40.7 Vdc and a maximum power current (Imp) of 10.7 A, with an open-circuit voltage (Voc) of 49.4 Vdc and a short-circuit current (Isc) of 11.2 A. These characteristics indicate a strong capacity for energy conversion, making it suitable for large-scale solar power installations.

The module's temperature coefficients are within standard performance limits, with a power coefficient of -0.345%/°C and a voltage coefficient of -0.272%/°C, meaning that energy output slightly decreases with rising temperatures. The current coefficient is +0.050%/°C, showing minimal positive variation under higher temperatures. Although this module is not bifacial in the given configuration, its technical specifications suggest reliable and stable performance, ensuring consistent electricity production even under fluctuating environmental conditions, thereby enhancing the overall efficiency of the solar power system.

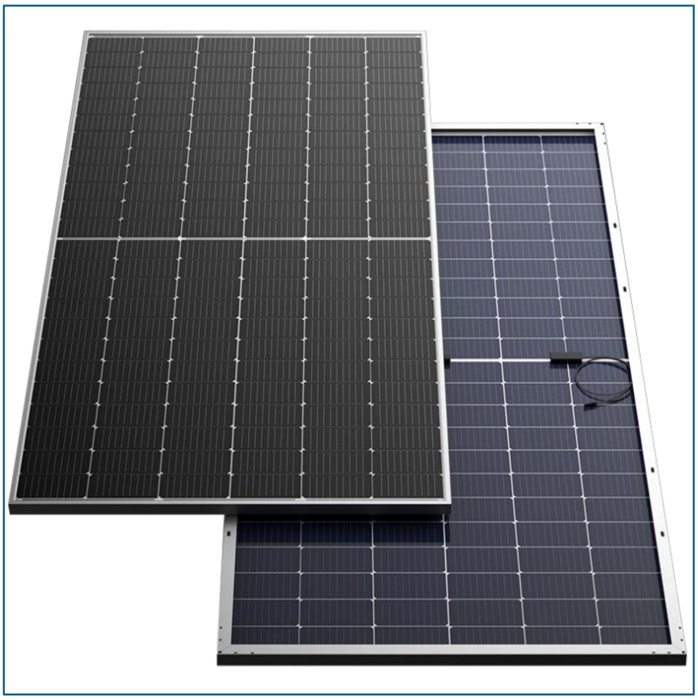

Figure 1: , SunEvo Solar Co. Ltd. SE4-72H-435MB

The selected inverter, Sungrow Power Supply Co. Ltd. SC2500U [550V], is a high-capacity utility-interactive inverter designed for large-scale photovoltaic power plants. It offers a CEC weighted efficiency of 97.532% and a European weighted efficiency of 97.347%, ensuring minimal energy loss during the DC-to-AC conversion process. The inverter supports a maximum AC power output of approximately 2.5 MW (2,507,194 Wac) and a maximum DC input power of 2.58 MW (2,579,160 Wdc), making it suitable for high-capacity solar energy projects. It operates with a nominal AC voltage of 550 V and supports a maximum DC voltage of 1500 V, providing flexibility for various PV array configurations.

The inverter includes a single MPPT input, with a voltage operating range of 800 V to 1500 V, and can handle a maximum DC current of 2645.3 A, ensuring reliable operation even under high solar irradiance conditions. Its power consumption during operation is around 8485.63 Wdc, with minimal nighttime power usage of 62.8 Wac, contributing to system efficiency. The efficiency curve shows that the inverter maintains over 95% efficiency across a wide range of output power levels, approaching nearly 98% at optimal conditions, which minimizes energy losses. These features make the SC2500U an ideal choice for grid-connected solar power plants aiming to achieve high performance, reliability, and long-term energy yield

Figure 2: , Sungrow Power Supply Co. Ltd. SC2500U [550V],

The system design configuration presented shows a large-scale solar photovoltaic (PV) plant setup, incorporating **30 inverters** with a **DC-to-AC ratio of 1.87**, which allows for slight oversizing on the DC side to maximize energy harvesting during periods of high irradiance. The system has a **nameplate DC capacity of 140,285.552 kWdc** and a **total AC capacity of 75,215.820 kWac**, ensuring significant power generation capability to feed into the grid. The **total inverter DC capacity is 77,374.8 kWdc**, and the entire installation occupies approximately **699,681.78 m^2**, reflecting the scale of this utility-level solar power project.

The electrical configuration for Subarray 1 includes **21 modules per string** and **15,354 parallel strings**, resulting in a total of **322,434 modules** installed across the site. At reference conditions, the system has a **string open-circuit voltage (Voc) of 1,037.4 V** and a **string maximum power voltage (Vmp) of 854.7 V**, values that are well-matched with the chosen inverter specifications to ensure efficient energy conversion and minimal losses. This large array setup demonstrates an optimized balance between module arrangement, inverter capacity, and total site area utilization, designed to deliver maximum energy output while maintaining high operational efficiency for grid-connected solar energy production.

3.3 Financial model

The capital cost analysis for the photovoltaic (PV) system illustrates the direct expenses associated with setting up this large-scale solar power project. The system comprises 322,434 PV modules, each rated at 0.4 kWdc, leading to a total DC capacity of 140,285.6 kWdc. With a unit cost of $0.20/Wdc, the total cost for the modules is approximately $28,057,110.40. The project also includes 30 inverters, each rated at 2,507.2 kWac, with a cost of $0.01/Wdc, amounting to $1,402,855.52.

Additional expenses cover the balance of system equipment ($25,251,399.36), installation labor ($25,251,399.36), and installer margin and overhead ($16,834,266.24), ensuring proper installation and operational reliability of the plant. These costs bring the subtotal to $96,797,030.90. A 3% contingency is applied, adding $2,903,910.93 to account for unforeseen expenses during the project execution. The total direct capital cost for the entire solar PV system is estimated at $99,700,941.82, reflecting the scale and investment required for such a high-capacity renewable energy installation.

The financial analysis of the project indicates a strong long-term profitability trend, as reflected in the after-tax cumulative Net Present Value (NPV) over a 26-year operational period. The project initially experiences negative NPVs during the first four years, reaching a minimum of approximately −30.5 million USD in Year 1 due to high upfront capital investments and initial operational costs. However, a positive shift occurs starting in Year 5, where the cumulative NPV rises to about 6.75million USD, marking the payback period and signaling the commencement of profitable operations. This transition reflects the project's ability to recover initial costs within a relatively short timeframe, which is a favorable indicator for investors and stakeholders evaluating the project's financial feasibility.

From Year 5 onwards, the NPV consistently increases, demonstrating sustained cash inflows and strong economic performance throughout the project's lifetime. By Year 26, the cumulative NPV reaches approximately 58.55 million USD, confirming the long-term financial viability and resilience of the investment. The steady growth in NPV values suggests that the project not only achieves cost recovery but also generates significant net returns over time. These findings highlight the robustness of the project’s financial structure, making it a promising candidate for large-scale implementation and a reliable contributor to long-term energy investment portfolios.

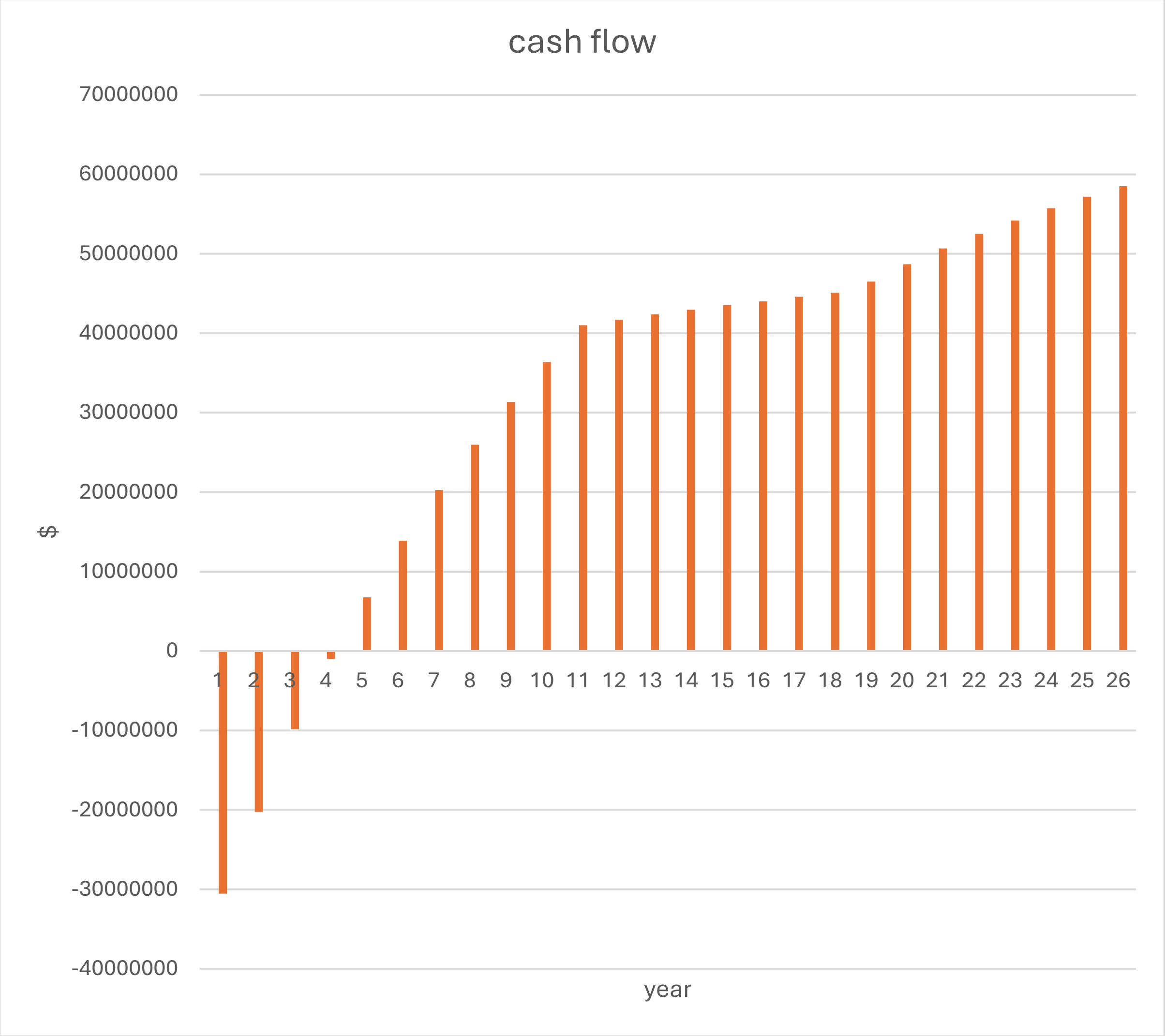

Figure 3 : Cash flow

The graph you provided represents the After-Tax Cumulative Internal Rate of Return (IRR) over a 25-year project lifetime. It illustrates how the project's IRR evolves over time, starting from an initial negative value due to the upfront investment costs and gradually increasing as the project generates revenue and recovers its capital expenditures.

In the first few years, the IRR is negative because the expenses from installation and capital investment outweigh the early revenues from power generation. As the years progress, the IRR climbs sharply, reaching positive territory as energy sales and cost savings accumulate. By around year 10, the IRR stabilizes, indicating that the project has fully recovered its investment and is now generating steady returns.

Towards the later years of the project (year 15 onward), the IRR curve flattens out, meaning the project's additional returns are relatively stable and no major changes in profitability occur. This plateau suggests that most of the gains are realized in the earlier half of the project lifecycle, and the later years primarily contribute to maintaining a consistent long-term return.

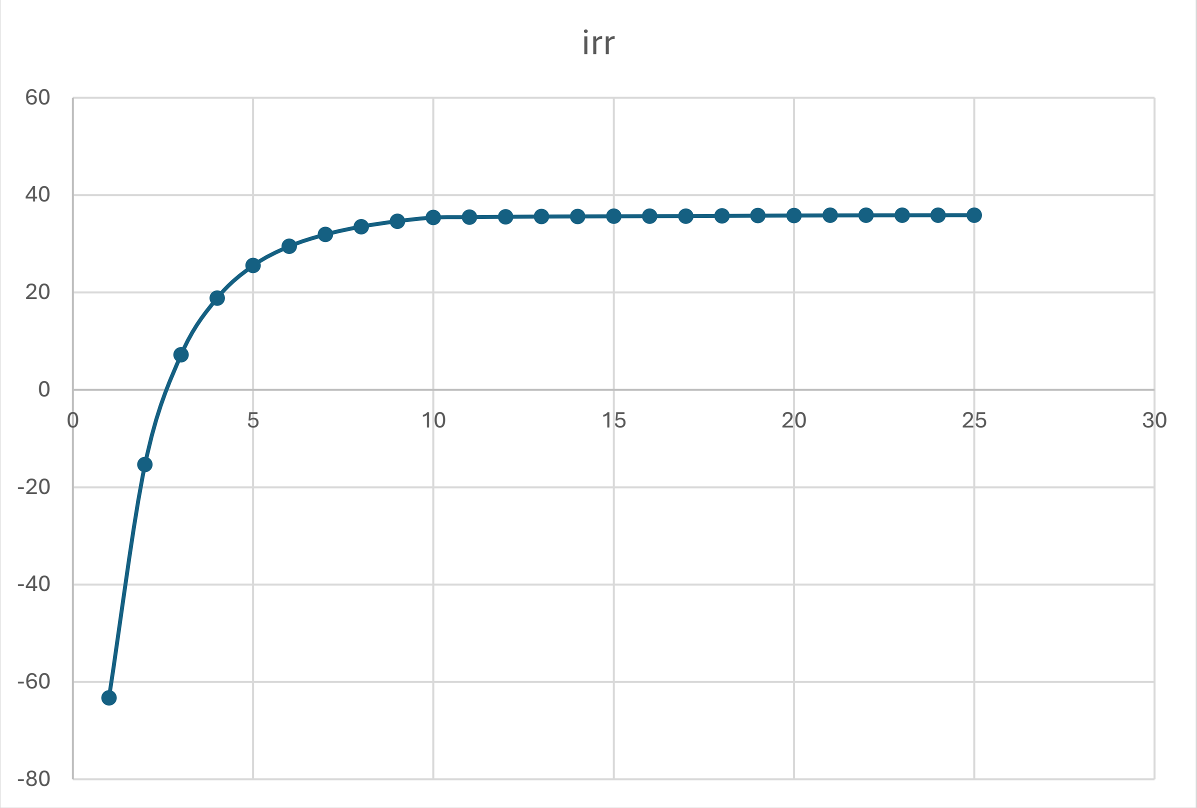

Figure 4: Cummulative IRR

3.4 Power analysus

The following graph illustrates the **power supplied to the grid** by the solar photovoltaic system over a **25-year operational period**. At the beginning of the project, the system delivers a peak power output of approximately **2.72 × 10^8 kWh/year**. This high initial value reflects the optimal performance of the solar modules and inverters under ideal conditions, maximizing energy delivery to the grid. The system's design ensures efficient conversion of solar energy into electrical energy, contributing significantly to grid supply during the early years of operation.

Over time, there is a **gradual decline in power generation**, as depicted by the downward trend in the graph. This reduction is primarily attributed to the **natural degradation rate of solar panels**, typically ranging between **0.5% and 1% per year**, along with potential efficiency losses in the inverters and other system components. Environmental factors such as dust accumulation, weathering effects, and temperature variations may also contribute to the slight annual decrease in output. Despite this decline, the system maintains a strong power supply capability throughout its lifespan.

By the end of the 25-year period, the power delivered to the grid is projected to be approximately **2.63×10^8 kWh/year**, which is only a moderate decrease compared to the initial output. This demonstrates the long-term viability and reliability of the solar PV project, ensuring consistent energy generation for over two decades. The results highlight that even with performance degradation, the system remains a **highly effective renewable energy solution**, capable of offsetting substantial amounts of fossil fuel-based electricity generation and reducing carbon emissions.

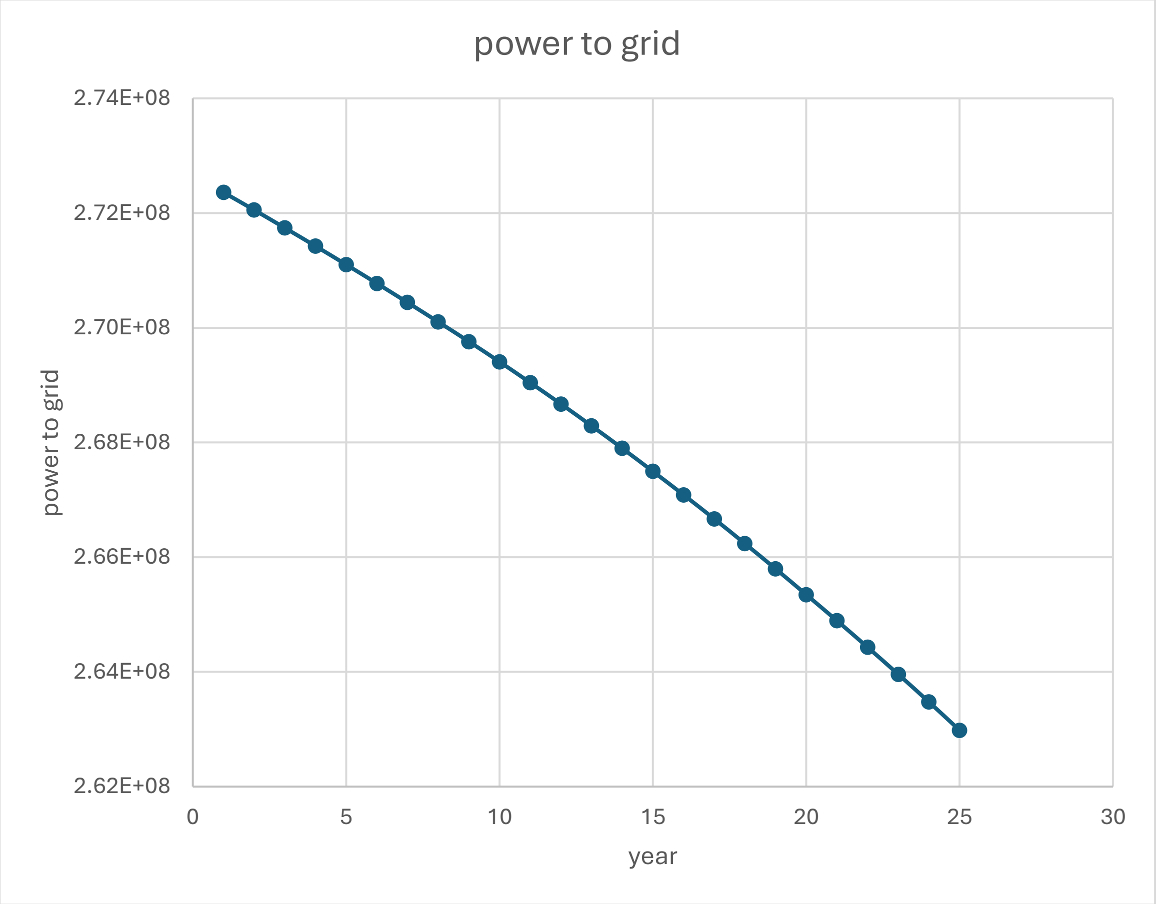

Figure 5: Power to grid

4. Conclusions

This study has demonstrated that large-scale solar photovoltaic (PV) power plants present a technically and financially viable solution for sustainable electricity generation, provided that site-specific and economic factors are carefully considered. The techno-economic analysis conducted for the proposed 140 MWdc PV system highlights the crucial role of accurate energy yield estimation, reliable technology selection, and comprehensive financial modeling in determining the feasibility of renewable energy investments. The project achieves a cumulative Net Present Value (NPV) of approximately USD 58.55 million over a 26-year operational period, with a payback period occurring in Year 5. This rapid recovery of capital investment underscores the project's strong profitability, aligning with findings from previous research that identified positive NPVs and IRRs for solar PV plants in high-irradiance regions [1]–[5]. The Internal Rate of Return (IRR) progression from negative values during the early years to a stable, positive return over time reflects the long-term attractiveness of solar PV investments, particularly when paired with favorable policy incentives and grid integration mechanisms [6]–[8].

From a technical perspective, the proposed system demonstrates high energy generation potential, delivering approximately 2.72×10^8 kWh/year initially and maintaining substantial output despite a gradual decline due to natural module degradation. The selection of high-efficiency modules and advanced inverter technology ensures reliable power conversion, maximizing grid-fed energy while minimizing operational losses. The analysis further emphasizes that location-specific solar irradiance levels, system degradation rates, and equipment efficiency significantly impact the Levelized Cost of Electricity (LCOE) and overall project competitiveness. Additionally, integrating hybrid technologies, such as PV-wind or PV-battery systems, may further enhance system resilience, stabilize energy output, and improve IRR values in fluctuating market conditions [9], [10].

However, the study acknowledges certain challenges and risks, including dependency on stable energy pricing, potential variability in solar resource availability, and high upfront capital requirements. Probabilistic modeling and sensitivity analyses are recommended to mitigate these uncertainties, providing investors with more reliable decision-making frameworks. Moreover, supportive governmental policies, such as feed-in tariffs, tax incentives, and low-interest financing, can significantly improve project economics and attract larger-scale private investment in renewable energy infrastructure.

In conclusion, the results of this research reaffirm that large-scale solar PV projects can serve as a cornerstone of the global renewable energy transition, offering both economic and environmental benefits. With optimized design, efficient technology selection, and robust financial planning, solar PV power plants can provide reliable, long-term electricity supply while contributing to decarbonization goals and energy security. Future work should explore hybrid renewable energy configurations, advancements in bifacial and high-concentration PV modules, and the integration of energy storage solutions to further enhance the financial viability and resilience of large-scale solar energy systems in varying climatic and market conditions.

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