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Enhancing Solar PV System Performance in Bangladesh: A Comprehensive Analysis of the Sarishabari Solar Plant and Strategic Recommendations

Riad Mollik Babu[1*], Md Shahidul Islam[1], Enamul Basher[1], Md Hasibur Rahman[2]

[1] Department of Electrical and Electronic Engineering, University of Asia Pacific, Dhaka 1205, Bangladesh
[2] Department of Electrical and Electronic Engineering, Bangabandhu Sheikh Mujibur Rahman Science and Technology University, Gopalganj 8100, Bangladesh

Corresponding Author Email: riadmallickbabu@gmail.com

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ABSTRACT

This study evaluates the Sarishabari Solar Plant, a 3.3 MW grid-connected photovoltaic (PV) system in Bangladesh, to identify operational, economic, and strategic improvements aligned with national renewable energy goals. Combining empirical data from plant officials with simulation results, we assessed performance metrics, proposed optimization strategies, and explored hybrid integration for enhanced sustainability and efficiency. Utilizing PVsyst for performance simulations, HOMER Pro for hybrid solar-wind configurations, and MATLAB Simulink for grid stability assessments, we analyzed energy yield, levelized cost of energy (LCOE), performance ratio, and the impacts of battery storage. The plant's performance ratio of 70.06% indicates potential for optimization. Implementing a fixed 24° tilt angle reduces the payback period to 9.5 years, surpassing current seasonal adjustments. Integrating a Battery Energy Storage System (BESS) stabilizes grid performance during irradiance drops, achieving a 0.8% improvement in return on investment (ROI). Additionally, incorporating 100 kW wind turbines in a hybrid setup optimizes the net present cost and capacity factor, contributing to sustainable energy development. Over a 30-year lifecycle, the plant is estimated to save approximately 50,000 tons of CO_2, underscoring its alignment with Bangladesh's greenhouse gas (GHG) emissions reduction targets. By uniquely combining performance, economic, and environmental assessments through an integrated simulation framework, this study provides actionable insights for renewable energy stakeholders in Bangladesh.

1. INTRODUCTION

The global energy landscape is undergoing a profound transformation as nations grapple with the twin challenges of meeting rising energy demands and addressing climate change. Renewable energy sources, particularly solar photovoltaics (PV), are increasingly viewed as pivotal to achieving sustainability goals. For developing nations like Bangladesh, the transition to renewable energy is not merely an environmental imperative but also an economic and social necessity. With a population exceeding 170 million and a rapidly growing economy, Bangladesh faces significant energy challenges, including a heavy reliance on fossil fuels, frequent power shortages, and the adverse impacts of greenhouse gas (GHG) emissions on its vulnerable ecosystems.

Renewable energy currently constitutes 4.44 percent of the total installed power capacity in Bangladesh, with 1378.62 MW out of 31077 MW coming from renewable sources, predominantly solar power [1]. The government has set an ambitious target to increase this share to 40% by 2041, leveraging the country's ample solar irradiance [2]. However, achieving this target requires addressing critical barriers, such as suboptimal system efficiencies, land scarcity, high initial costs, and challenges in integrating intermittent renewable energy into the national grid [3]. These barriers highlight the need for innovative solutions to optimize performance and economic feasibility while ensuring environmental sustainability.

The Sarishabari Solar Plant epitomizes the opportunities and challenges inherent in large-scale solar PV deployment. As the first grid-connected solar PV power plant in Bangladesh, the plant underscores the potential of solar energy to meet growing electricity demands. While the plant contributes significantly to the national grid, a performance ratio of 70.06% suggests room for improvement, especially in comparison to benchmarks in neighboring regions. A performance ratio (PR) of 83.72% was observed for a 2 MW solar PV system in India [4, 5]. In Pakistan, the PR was identified as 81.4% [6], while in Nepal, the average PR across solar PV installations stands at 83.5% [7]. This disparity underscores the need for targeted interventions to enhance operational efficiency and economic viability.

This research conducts a thorough examination of the Sarishabari Solar Plant, proposing strategies for optimizing its efficiency and ensuring sustainable operations. The investigation includes determining an optimal fixed tilt angle to enhance energy generation, streamline maintenance, and improve economic viability. It also assesses the role of BESS in stabilizing power output, managing peak loads, and maintaining grid reliability amidst solar irradiance variability. The feasibility of hybrid configurations combining solar and wind energy is further explored to mitigate intermittency and bolster system resilience. Advanced simulation tools such as PVsyst, MATLAB Simulink, and HOMER Pro are central to this analysis, providing insights specific to the Sarishabari plant's conditions and offering scalable recommendations for similar installations in Bangladesh.

This study underscores the transformative potential of combining advanced technologies, such as energy storage and hybrid systems, with strategic policy support to accelerate Bangladesh's transition toward a sustainable energy future. By proposing actionable recommendations for performance enhancement, it aims to optimize existing solar PV systems and guide the development of future renewable energy projects, thereby supporting the nation's energy security and environmental goals. Bangladesh, with a relatively compact area of 148,460 km², experiences a fairly uniform distribution of wind and solar irradiance across its entire region. This geographic consistency enhances the relevance and impact of studies on renewable energy integration, as findings are more widely applicable throughout the country.

2. LITERATURE REVIEW

The global shift towards renewable energy has accelerated advancements in solar photovoltaic (PV) technology, yet optimizing the performance and economic viability of PV systems remains a central focus, particularly in regions with high solar irradiance but variable energy demands [8]. This literature review examines methods for enhancing PV performance, including hybrid system integration, tilt angle optimization, and energy storage solutions, emphasizing their relevance for Bangladesh.

2.1 Solar PV system efficiency and benchmark performance ratios

Studies provide performance ratio (PR) benchmarks across various climatic conditions, highlighting opportunities for efficiency gains. For instance, evaluations of PV systems in tropical regions found optimized systems achieving PRs above 80% [9]. Comparisons of PV installations in South Asia reported average PRs around 81.02%, demonstrating both challenges and opportunities for performance improvement in the region [10]. In Bangladesh, where solar resources are ample, but PRs remain lower than in neighboring countries, tailored solutions are essential to maximize energy output and economic returns [11].

2.2 Hybrid solar-wind energy systems for stability and cost efficiency

Hybridizing solar PV with other renewable sources, particularly wind, has proven effective in addressing the intermittency of solar energy. Research in Southeast Asia showed that hybrid configurations reduce power variability and enhance grid stability, especially in regions with complementary seasonal or diurnal wind and solar patterns [12]. Studies also highlighted economic benefits, noting significant reductions in levelized cost of energy due to shared infrastructure and increased energy output [13]. For Bangladesh, hybrid systems combining solar and wind resources could ensure a reliable power supply during the monsoon season when wind speeds are higher, complementing reduced solar output [14].

2.3 Optimization of tilt angle for enhanced solar irradiance capture

Optimizing the tilt angle of solar panels is essential for maximizing energy yield, and research indicates that while daily or seasonal adjustments can yield higher gains, a fixed tilt angle can offer a practical balance between efficiency and simplicity, especially in regions with consistent sunlight. Studies show that a fixed tilt angle aligned with the latitude of the installation site often performs well, providing substantial energy capture without the need for adjustments. For example, optimal fixed angles in locations such as Karachi (25.5°) and Suez (28°) closely match their latitudes, with only a marginal decrease in energy yield compared to adjustable systems, as seen in Suez, where fixed angles produced 7.77% less solar radiation than a biannual adjustment [15, 16]. Similarly, research in Albania found that the best fixed angles for cities like Tirana, Kuksi, and Vlora align closely with their latitudes, supporting the case for fixed tilt angles as a viable solution where maintenance simplicity and cost-effectiveness are prioritized [17]. Thus, while adjustable systems offer higher efficiency, fixed tilt angles can provide robust performance, especially in areas where practical constraints make them an economically sound choice.

2.4 Integration of energy storage systems for reliability and peak shaving

Battery Energy Storage Systems (BESS) play a critical role in enhancing grid reliability, supporting peak shaving, and enabling the integration of renewable energy sources. As highlighted in study by Dunn et al. [18], selecting the appropriate battery technology is key to achieving efficient grid storage solutions. Research shows that BESS can lower average electricity costs and increase system flexibility, thus facilitating renewable integration [19]. Collaborative research by the National Renewable Energy Laboratory (NREL) and SunPower advances storage testing to further clean energy deployment on the grid [20]. BESS integrated with PV systems has also been proposed to improve demand curves in power systems [21], while different operation models for wind-integrated systems are evaluated for adequacy [22]. BESS applications extend to grid regulation as well, with studies demonstrating its impact on primary frequency response [23]. Optimization algorithms have been developed to determine the optimal BESS size for peak shaving and valley filling in microgrids, minimizing operational costs [24]. Furthermore, energy management strategies have been introduced for EV charging stations that account for battery aging and distributed energy resources (DERs) [25]. Recent work has focused on optimal scheduling methods that integrate BESS with combined heat and power (CHP) and other renewable sources, effectively reducing power curtailment rates and operational costs [26, 27]. These studies collectively underscore the transformative role of BESS in modernizing grids and advancing renewable energy integration.

3. METHODOLOGY

This study utilizes a comprehensive methodology to assess the operational performance, economic viability, and grid reliability of the Sarishabari Solar Plant. By integrating PVsyst simulations for energy production and economic metrics, MATLAB Simulink for grid reliability and fault response, and HOMER Pro for hybrid solar-wind optimization, we evaluate the plant's efficiency and resilience under varied conditions. This approach provides a thorough analysis of system performance, explores the role of energy storage in stabilizing power output, and investigates hybrid configurations for enhanced sustainability.

3.1 PV site location and system design

The Sarishabari Solar Plant, located in Sarishabari, Bangladesh. The project, situated on an 8-acre site leased from the Bangladesh Power Development Board (BPDB), indicates the country's commitment to harnessing renewable energy sources. With GPS coordinates at 24°46'19" NL & 89°50'37" EL (Figure 1).

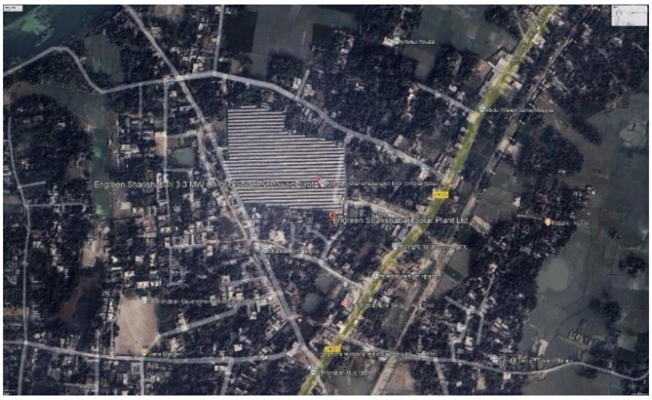

Figure 1. Satellite overview of Sarishabari Solar Power Plant (Source: Google Earth Pro)

3.2 System design and specification

This section provides an in-depth overview of the system's design elements and specifications, detailing the configuration and characteristics of the solar PV components, including the array orientation, and key equipment specifications that drive the plant's operational performance and energy yield.

3.2.1 System components and layout

Table 1 provides information on the orientation of the PV array. A manual solar tracking system is incorporated into the power plant. Twice a year, the tilt angle is changed to 24° in the winter and 5° in the summer.

Table 1. Tilt angle alignment

Tilt Angle	**Summer Tilt 5º**
	Winter (October, November, December, January, February, March) tilt 24º
Azimuth	0º

The solar PV system is designed for optimal efficiency and reliability with key components including the Sunmodule Plus SW 285 Mono Solar Panel by SolarWorld and the Sunny Tripower 2500TL inverter from SMA Solar. Tables 2 and 3 provide a summary of their specifications, essential for evaluating the system's performance and energy output.

Table 2. Details of the Sunmodule Plus SW 285 Mono Solar Panel

Specification	Value
Model Number	SW 285 Mono
Standard Test Condition (STC) Rating	285 Wp
Open Circuit Voltage (Voc)	39.7 V
Maximum Power Point Voltage	31.3 V
Short Circuit Current (Isc)	9.84 A
Maximum power point current	9.20 A
Power Tolerance	0% to +5%
Module Efficiency	17.0%

Table 3. Sunny Tripower 2500TL specifications

Model	Sunny Tripower 2500TL
Max generated power	45000 Wp
DC rated power	25550 W
Max. input voltage	1000 V
Rated power (at 230 V, 50 Hz)	25000 W
Max. AC apparent power	25000 VA
Efficiency	98.3%

Table 4 provides a concise summary of the key technical specifications and design parameters of the solar PV system.

Table 4. Overview of the solar PV system

Parameter	Value
Installed Capacity	3000 kWh
Nominal Capacity	3300 kWp
Total Modules	11580
Module Configuration	579 string × 20 In series
Number of Inverters	123

3.2.2 Financial overview

Table 5 provides a summary of the financial investment required for the Sarishabari Solar Power Plant, including initial installation costs and ongoing operational expenses such as staff salaries and regular maintenance. This table offers a comprehensive view of the cost structure but does not account for unforeseen, significant damages resulting from plant failures or natural disasters.

Table 5. Financial overview of installation and operating costs for the Sarishabari Solar Power Plant

Item	Total (USD/Year)
Cost of installation	4,903,259 USD (Approximate)
Maintenance	15,959.56
Provision for inverter replacement	40,527.17
Administrative, accounting	
Total (OPEX)	56,486.73
Including inflation (1.50%)	65,309.01

3.3 Simulation and economic analysis

To thoroughly assess the performance and economic feasibility of the plant, we adopted a multifaceted approach. Critical data, including installation details, financial parameters, and operational conditions, were directly sourced from plant authorities to ensure the accuracy of our evaluation.

This methodology enabled a comprehensive analysis of the plant's operational efficiency and financial sustainability.

Our simulations meticulously replicated key components of a typical solar PV system, such as PV modules and inverters, allowing for the development of a highly customized model tailored to the unique characteristics of the Sarishabari Solar Plant. Using PVsyst, we analyzed the plant's energy generation, specific yield, and LCOE. These analyses were further refined by accounting for various environmental and operational scenarios, providing valuable insights into the system's performance under diverse conditions and enhancing the robustness of our findings.

Economic indicators, including payback period, ROI, and cost per kWh produced, were calculated to provide a holistic financial assessment of the plant's sustainability and profitability. To further quantify operational efficiency, we calculated the performance ratio, defined as the ratio of actual energy output to theoretical maximum production, which served as a benchmark for the plant's effectiveness in converting solar irradiance into usable electricity.

Tilt angle optimization was explored extensively to maximize energy capture. We analyzed multiple configurations, including the current seasonal adjustments (5° in summer and 24° in winter), a fixed-angle setup, as well as alternative systems: sun-shields, tracking along the horizontal axis, and dual-axis tracking. These configurations were compared to determine the optimal approach for year-round operation, with each option assessed for its impact on energy yield, economic viability, and operational efficiency. By aligning panel orientation with seasonal irradiance variations, the analysis aimed to enhance the plant's energy output and overall performance.

3.4 Battery and hybrid system integration

The potential role of a Tesla Powerwall 2 BESS was investigated to increase system resilience, support peak shaving, and improve performance during periods of low irradiance. Using PVsyst, we conducted simulations with and without the BESS to assess its effects on energy discharge rates, specific yield, and LCOE. These simulations provided insights into how BESS integration could improve overall system efficiency and economic feasibility.

To further understand the interaction between the BESS and the grid, we developed a detailed model in MATLAB Simulink, allowing us to simulate the impact of BESS on grid voltage stability, frequency regulation, and response to various fault conditions, including line-to-ground and line-line-ground faults. Special emphasis was placed on assessing the BESS's role in mitigating the effects of irradiance fluctuations, determining if storage integration could enhance the reliability and stability of power output under dynamic environmental conditions.

For additional sustainability and to explore a broader range of renewable energy sources, a hybrid solar-wind model was designed in HOMER Pro, incorporating 100 kW wind turbines alongside the optional BESS. This hybrid system was optimized for NPC, LCOE, and capacity factor, using wind data sourced from NASA's Prediction of Worldwide Energy Resources. By combining solar and wind resources with energy storage, the hybrid model aims to create a more robust and reliable renewable energy system capable of meeting energy demands under variable weather conditions.

3.5 Environmental impact analysis

Finally, a lifecycle analysis of CO_2 emissions quantified the environmental benefits of the solar PV system. Emission metrics were calculated over a 30-year operational period, comparing emissions produced versus displaced by renewable energy generation. These findings align the plant's performance with Bangladesh's national emission reduction goals, underscoring its environmental significance.

4. RESULTS

This section evaluates the solar PV system's performance and economic metrics using PVsyst software, combining data provided by plant officials with critical inputs, such as solar irradiance, obtained directly from the software.

4.1 Evaluation of current plant performance

Table 6 underscores the project's strong financial and energy production metrics while highlighting the performance ratio as an opportunity for further efficiency improvements.

Tables 7 and 8 summarize the CO_2 emission balance for a solar PV system over a 30-year lifecycle. It includes both the generated and replaced emissions based on system production and grid lifecycle emissions specific to Bangladesh. Additionally, the table provides details on the lifecycle emissions of key system components, including modules, supports, and inverters. The data illustrates the system's environmental impact, showcasing significant CO_2 savings compared to traditional grid-based energy sources.

Table 6. Key operational and economic metrics of the solar PV plant

Metric	Value
Produced Energy	3680 MWh/year
Specific Production	1115 kWh/kWp/year
Cost of Produced Energy	0.11 USD/kWh
Feed-in Tariff	0.18970 USD/kWh
Electricity Sales	14,646,393 USD
Payback Period	10.2 years
Return on Investment (ROI)	113.8%
Cumulative Profit	5,582,114 USD
Performance Ratio	70.06%

Table 7. CO_2 emission balance and system lifecycle emissions details for the solar PV system

Parameter	Value
Generated Emissions (Total)	49793.8 t CO_2
Replaced Emissions (Total)	64477.5 t CO_2
System Production	3680.22 MWh/year
Grid Lifecycle Emissions	584 g CO_2/kWh
Lifetime of System	30 years

Table 8. System lifecycle emissions details

Item	LCE	Quantity	Subtotal (kg CO_2)
Modules	1713 kg CO_2/kWp	3300 kWp	5652490
Supports	3.90 kg CO_2/kg	115800 kg	451073
Inverters	386 kg CO_2/units	123 units	47467

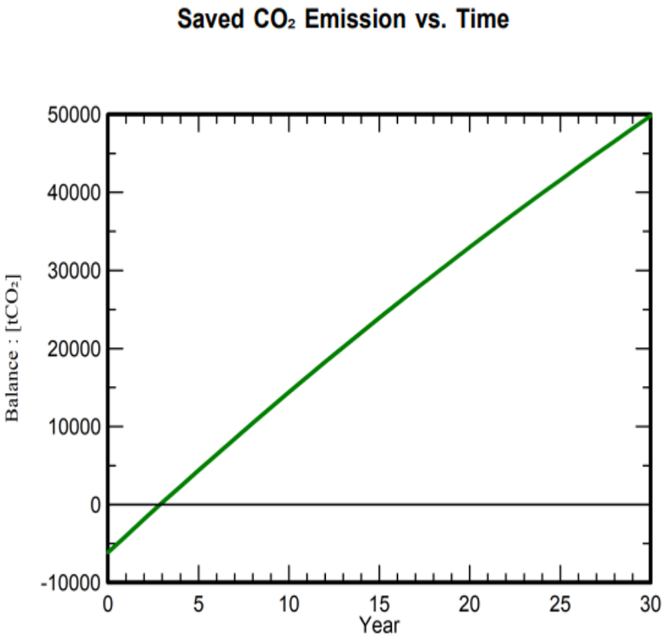

Figure 2. Saved CO_2 emissions over 30 years for the Sarishabari Solar PV system

Figure 2 illustrates the cumulative CO_2 emissions saved over a 30-year period by the Sarishabari Solar PV system. The graph shows a steady increase in CO_2 savings, reaching approximately 50,000 tons by the end of the system's lifespan.

5. STRATEGIES FOR ENHANCING SOLAR PV SYSTEM EFFICIENCY AND RELIABILITY

In our study, we conducted experiments with varying tilt angles to determine the most optimal and cost-effective configuration for the solar PV system. Additionally, we incorporated a BESS to assess its impact on system performance and reliability. Furthermore, to optimize energy production and lower operating expenses, a hybrid wind-solar system was investigated. The findings demonstrate that these strategies are effective and, if implemented, could play a pivotal role in advancing the green energy projects in Bangladesh.

5.1 Tilt angle optimization

In this section, we examined the impact of various solar panel configurations on the efficiency and economic performance of the Solar PV system. By assessing these variables, the study seeks to identify the tilt angle and setup that yields the highest energy production, improve system reliability, and offer the greatest economic benefit. The findings from this analysis provide valuable insights into selecting configurations that promote both energy efficiency and cost-effectiveness in solar PV installations.

Table 9 provides a comparison of different tilt angle configurations, highlighting how variations in tilt angle, tracking mechanisms, and additional features impact energy production, costs, and system performance.

Table 9. Performance metrics for different solar PV configurations

Tilt Angle	Produced Generation	Specific Production	Energy Cost	Payback Period	Performance Ratio
Summer 5º and Winter 24º	3680 MWh/year	1115 kWh	.11 USD/kWh	10.2 years	70.06%
Fixed 24º Tilt Angle	3886 MWh/year	1177 kWh	.10 USD/ kWh	9.5 years	71.84%
Sun-shields (Tilt Angle 20º, Azimuth 0º)	2822 MWh/year	855 kWh	.14 USD/kWh	14.3 years	52.19%
Tracking Horizontal axis	4122 MWh/year	1249 kWh	.09 USD/kWh	8.8 years	67.48%
Tracking Plane, Two Axis	4676 MWh/year	1417 kWh	.08 USD/kWh	7.5 years	71.37%

Key Insights and Recommendations

Tracking Plane, Two Axis: The two-axis tracking system emerged as the most efficient solution, maximizing energy production and maintaining a high-performance ratio. It is recommended for projects where financial resources and maintenance capabilities are available to support the tracking technology.

Tracking Horizontal Axis: Horizontal axis tracking systems present a good middle-ground solution, improving energy production while remaining financially viable. They are suitable for projects with moderate financial and technical resources to support additional maintenance and initial investment costs.

Fixed Tilt Angle: The fixed 24° tilt angle offers a practical and cost-effective alternative for projects with limited resources or where advanced tracking systems are not feasible. It provides a good balance of energy yield and financial returns with minimal intervention.

Seasonal Tilt Adjustments: Seasonal tilt adjustments (Summer 5° and Winter 24°) are not recommended due to the additional labor costs associated with the manual adjustments required for each season. Although this configuration provides some operational flexibility, it results in lower energy production compared to the fixed 24° tilt angle. The increased operational costs and the reduced energy yield make this approach less economically viable, particularly for projects that prioritize higher energy efficiency and reduced operational expenses.

Sun-Shields: The use of sun-shields with a fixed tilt of 20° resulted in significant shading and efficiency losses, leading to higher energy costs and extended payback periods. This configuration is not recommended for large-scale installations due to its inefficiency.

While tracking systems enhance energy yield, they may also involve higher initial investments, more frequent maintenance, and a shorter lifespan. Despite these challenges, the increased energy production often justifies the additional costs. Based on the findings, the two-axis tracking system is recommended for optimizing energy efficiency and profitability. However, in developing countries like Bangladesh, where financial constraints pose significant obstacles for renewable energy projects, the fixed 24° tilt angle offers a more viable alternative. This configuration prioritizes operational simplicity and cost-effectiveness, providing a balanced approach to efficiency and ease of maintenance.

5.2 Integration of energy storage for enhanced solar PV system performance

The integration of Tesla Powerwall 2 storage with a solar

PV system aims to enhance performance, reliability, and energy utilization. The storage system enables peak shaving, stores excess solar energy, and provides backup during outages. This setup increases energy efficiency, optimizes cost savings through load-shifting, and improves overall ROI. By storing energy during low-demand periods and discharging it during peak times, the system reduces reliance on grid power and contributes to environmental sustainability through better CO_2 utilization.

Table 10 presents the key specifications of the Tesla Powerwall 2, a widely used energy storage system. It highlights cost per unit and warranty details, emphasizing its suitability for peak shaving and scalable energy storage.

Table 10. Powerwall 2 specifications

Category	Powerwall 2
Capacity (usable)	13.5 kWh
AC/DC	AC
Max Output	5 kW continuous / 7 kW peak
Max amps of backup circuits	30 amps
Dimensions	45.3'H × 29.6'W × 5.8'D
Stackable output?	Yes
TOU load-shifting?	Yes
Warranty	10 Years / 70% Capacity Retention
Battery only cost (before incentives)	$7,500

Table 11 summarizes the configuration and key performance metrics of the Tesla Powerwall 2 battery storage system, including its design, energy capacity, efficiency, and lifecycle characteristics.

Table 11. Battery storage system configuration

Parameter	Details
Battery Manufacturer	Tesla
Battery Model	Powerwall2
Number of Units	224
Battery Pack Configuration	8 in series × 28 in parallel
Discharging Min. SOC	20.0%
Stored Energy (80 % of DOD)	2441.6 kWh
Max. Charging Power	100.0 kWdc
Max. Charging Efficiency	97.0% / 95.0%
Max. Discharging Power	620.0 kWac
Max. Discharging Efficiency	97.0% / 95.0%
Battery Pack Characteristics - Voltage	403 V
Battery Pack Characteristics - Nominal Capacity	7504 Ah (C10)
Battery Pack Characteristics - Temperature	Fixed 20 °C
Total Stored Energy During the Battery Life	2281.6 MWh
Number of Cycles at 50% DOD	1475

Table 12 presents the total integration cost, starting with the battery costs and detailing expenses for installation, wiring, safety measures, and monitoring. It provides a clear breakdown of the additional costs, justifying the financial outlay for the storage integration.

Table 13 compares system performance with and without storage, showing improvements in energy production, performance ratio, and specific production. It also highlights additional energy discharged from the battery and a slightly improved ROI, supporting the integration's effectiveness.

Table 12. Powerwall integration cost breakdown

Parameter/Cost Component	Details/Percentage	Estimated Cost (USD)
Number of Powerwall Batteries	224	
Cost per Battery	$7,500	
Total Battery Cost		$1,680,000
Installation and Labor	5%	$84,000.00
Wiring and Cabling	4%	$67,200.00
Safety and Protection Equipment	3%	$50,400.00
Monitoring and Control Systems	2%	$33,600.00
Miscellaneous and Regulatory Costs	1%	$16,800.00
Total Estimated Additional Cost		$252,000.00
Total Estimated Cost (Including Integration)		$1,932,000.00

Table 13. Impact comparison

Impact	Without Storage	With Storage	Improvement
Total Energy Produced (kWh/year)	3889425	3899307	+9882 kWh/year
Performance Ratio (PR)	71.84%	72.02%	+0.24%
Energy Discharged from Battery (kWh/year)	N/A	10211	10,211 kWh/year
Payback Period (years)	9.5	9.4	-0.1 year
Return on Investment (ROI)	129.1%	129.9%	+0.8%
CO_2 Emission Savings (t CO_2)	52,974.1 t CO_2	52,974.1 t CO_2 (improved utilization)	Better CO_2 utilization due to excess energy storage
Specific Production (kWh/kWp/year)	1179	1182	+3 kWh/kWp/year

5.3 System performance and irradiance impact with storage integration

This section presents a comparative analysis of the 3.3 MW solar PV system, simulated both with and without an integrated storage system, with an emphasis on the system's response to irradiance variations. The storage-integrated model demonstrates enhanced resilience, specifically in maintaining stable power output under fluctuating irradiance conditions, as outlined in the figures and metrics below.

Two configurations were analyzed: a base solar PV model without storage and an enhanced model integrated with a 3 MW storage system. Figure 3 (Base Model) and Figure 4 (Storage Model) visually represent the structure of each setup. For each model, the impacts of dynamic irradiance changes and fault conditions were assessed, focusing on key metrics such as power output stability, voltage, and frequency at the PCC.

Under varying irradiance conditions, the base model without storage experienced significant power output fluctuations. In contrast, the storage-integrated model maintained more stable output, demonstrating its resilience to irradiance changes. Both models performed comparably in fault scenarios, showing similar stability in voltage and frequency. Figure 5 illustrates the impact of irradiance variation without BESS, while Figure 6 presents the impact with BESS integration.

Table 14 summarizes the performance metrics, highlighting the difference in irradiance resilience. The inclusion of a storage system in solar PV setups enhances stability under variable irradiance, ensuring a more consistent power supply. This feature is especially valuable in regions with frequent irradiance fluctuations, where energy storage can contribute to grid reliability and resilience.

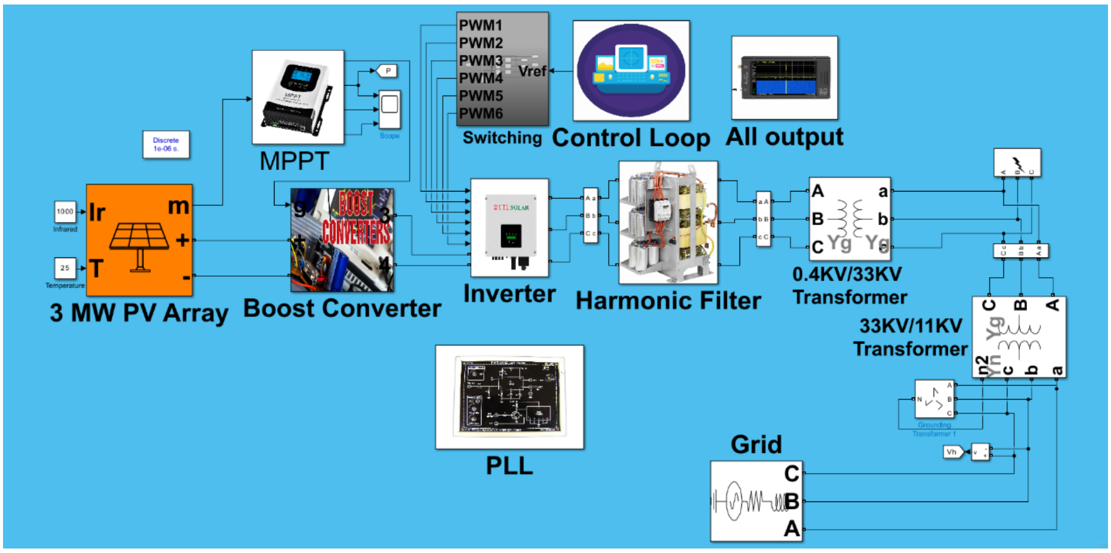

Figure 3. System model without storage integration without storage system

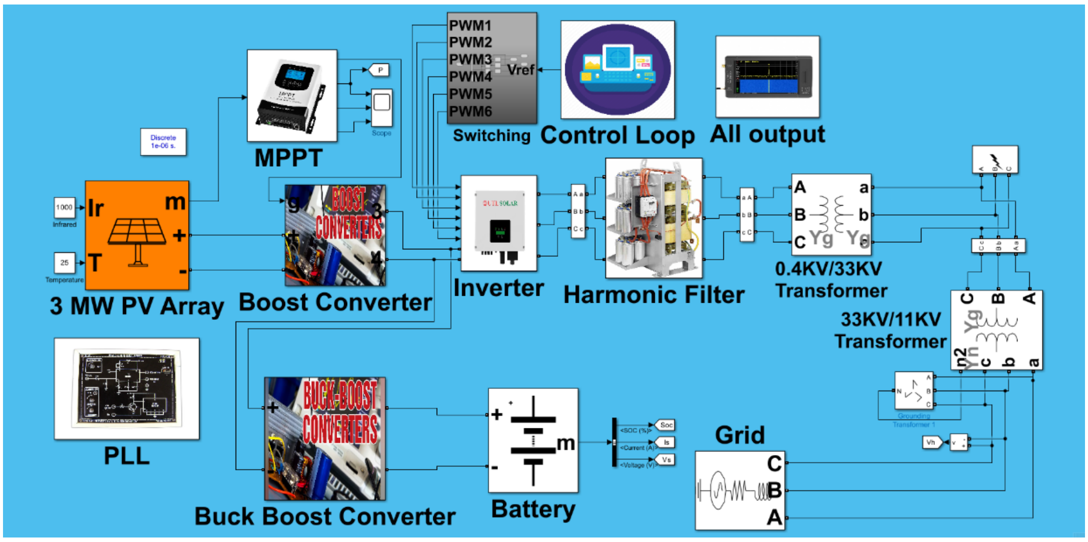

Figure 4. System model with storage integration with storage integration

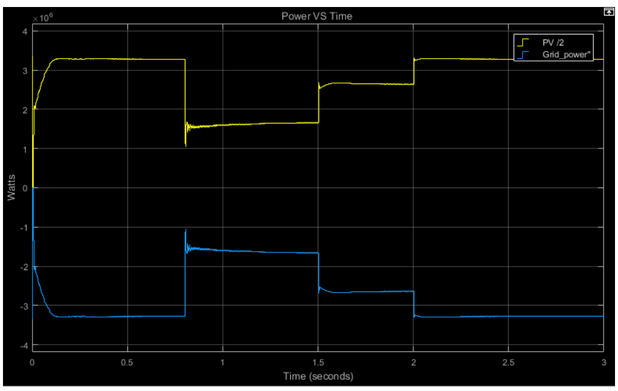

Figure 5. Impact of irradiance variation without BESS

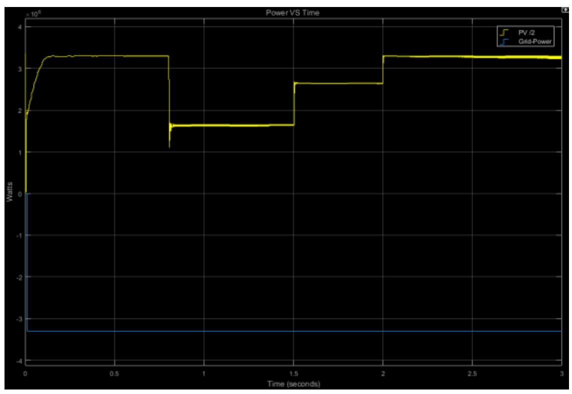

Figure 6. Impact of irradiance variation with BESS

Table 14. Comparative summary of system performance with and without storage under irradiance variations

Metric	Base Model (Without Storage)	Storage Model	Observations
Power Output Stability	Fluctuates under irradiance changes	Stable under irradiance changes	Storage integration provides resilience to irradiance drops
Voltage Stability	Stable	Stable	No significant difference observed
Frequency Stability	Stable	Stable	No significant difference observed
Fault Condition Response	Similar disruptions during fault scenarios	Similar disruptions during fault scenarios	Storage has minimal effect on fault responses

5.4 Hybrid-Wind-Solar-Smart System

A Hybrid Wind-Solar-Smart System in Bangladesh offers a promising solution to the country's growing energy demands and frequent power shortages. By integrating wind and solar energy with smart grid technologies, this system can enhance energy reliability, reduce dependency on fossil fuels, and improve overall efficiency. According to the Sustainable and Renewable Energy Development Authority, Bangladesh, the country currently generates 62.9 MW of electricity from wind turbines. Among these, the 60 MW Wind Power Project in Cox's Bazar stands out as a significant achievement. Additionally, a 2 MW wind power plant is set to join the national grid. Furthermore, plans are underway for 10 more wind projects across various locations, including Chattogram, Cox's Bazar, Satkhira, Feni, Bagerhat, Chandpur, and Patuakhali, with a combined potential capacity of 715 MW. The Government of Bangladesh aims to achieve a wind power capacity of 1,370 MW by 2030 and is actively promoting private sector investment in wind energy projects [28]. According to a technical assessment, the country has approximately 20,000 square kilometers of land with wind speeds ranging from 5.75 to 7.75 m/s, offering a potential to generate up to 30 GW of electricity from wind farms in these regions [29]. This approach not only promotes sustainable development but also aligns with the nation's objectives to expand renewable energy capacity and reduce environmental impacts.

Hybrid system design

This study utilized the HOMER Pro optimization tool to identify the optimal system configuration that maximizes efficiency by minimizing the cost of energy and net present cost while maximizing the renewable energy contribution. The analysis focused on an on-grid PV-wind hybrid system designed to supply power to the grid and meet load demands. The system configuration was guided by critical inputs, including wind and solar resource availability, technical specifications, and economic data obtained from plant officials, meteorological websites, specialized software, and the NASA Prediction of Worldwide Energy Resources database [30].

Figure 7 depicts the basic configuration of the hybrid system and its components. The PV panels are connected to the DC bus, where their DC output is converted to AC via a converter and fed into the AC bus. The wind turbines' AC output is directly connected to the AC bus. To maintain consistency, we used the same equipment as the Sarishabari Solar Power Plant, enabling a clear assessment of the impact of integrating wind energy into the existing solar system. For this simulation, we incorporated 100 kW wind turbines. Additionally, a battery storage system consisting of 3 MW lithium-ion batteries was included in the configuration to enhance flexibility. This setup allows HOMER to identify the optimal system configuration within its search parameters.

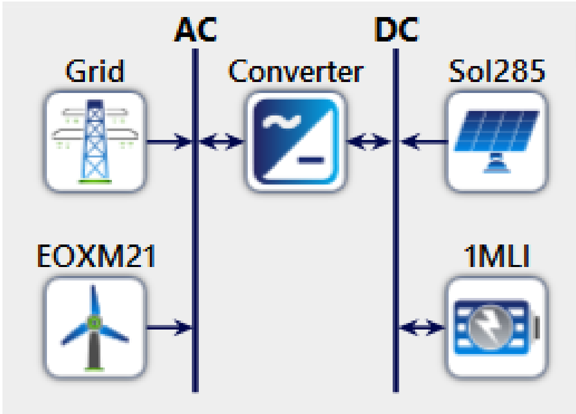

Figure 7. System configuration for the proposed hybrid model

Wind turbine

Table 15 provides a comprehensive overview of the EOX M-21 turbine's key specifications, including power output, blade dimensions, and operating wind speeds. Featuring a power rating of 100 kW and a robust design, this turbine is well-suited for the system integration, offering reliable performance across various wind conditions and long-term efficiency.

Table 15. EOX M-21 wind turbine specifications

Model	EOX M-21
Rated power (kW)	100
Blades Length (M)	10
Rotor Diameter (M)	21
Rated Voltage	400
Cut-in wind speed (m/s)	2.75
Cut-out wind speed (m/s)	20
Rated wind speed (m/s)	10
Extreme wind speed (m/s)	70
Number Of Blades	3
Tower - hub height (M)	32
Design Life	30

Table 16. System components and economic information

Component	Capital Cost (USD/kW)	Replacement Cost (USD/kW)	Operating Cost (USD/kW)
Solar Module (Sunmodule Plus SW 285 mono)	1151	1151	10
Wind Turbine (RX-HV100K)	490	350	5
Inverter (Sunny Tripower STP 25000TL-30)	162	80	1
Battery (1MWh Li-Ion)	700	700	10

Table 16 provides the economic specifications per kW for each major component in the hybrid solar-wind system, including the solar module, wind turbine, inverter, and battery. This information includes capital costs, replacement costs, and annual operating costs, essential for evaluating the economic feasibility of the system configuration.

Table 17 presents cost and performance metrics for two configurations of renewable energy systems, as derived from the HOMER Pro software.

Table 17. Cost and performance metrics for different renewable energy system configurations

Sunmodule Plus SW-285	RXHV 100kW	1MWh Li-Ion	Converter (Kw)	NPC ($)	LCOE ($/kWh)	Operating Cos ($/yr)	CAPX ($)
3300	30		2500	-16.5M	-0.137	-1.71M	5.67M
3300	30	3	2500	-14.8	-0.125	-1.64M	6.37M
3300			2500	-8.50M	-0.121	-982,604	4.20M
	30			-7.98M	-0.158	-730,867	1.47M
	30	1	100	-7.47M	-0.149	-710,550	1.72M
3300		3	2500	-7.42M	-0.106	-953,102	4.90M

A configuration with 3.3 MW solar PV and 3 MW wind without storage yields an NPC of -16.5 million USD, a LCOE of -0.137 $/kWh, and produces 5,719,146 kWh/year, though it lacks energy resilience during low-production periods. Adding 3 MWh of battery storage improves stability, with an NPC of -14.8 million USD and an LCOE of -0.125 $/kWh, allowing energy storage during peak production and optimizing supply during high-demand periods.

For densely populated Bangladesh, where land scarcity is high, hybrid systems offer a sustainable solution by allowing solar and wind installations to coexist on the same land, maximizing energy generation per unit area. Currently, most renewable projects are on leased public land with minimal payments, but as the sector expands, profitability challenges and land pressures are expected to rise. The hybrid solar-wind model, especially with storage, supports efficient land use, enhances grid stability, and reduces CO_2 emissions, aligning with Bangladesh's renewable energy goals and addressing land limitations.

6. CONCLUSION AND RECOMMENDATIONS FOR FUTURE DEVELOPMENT

This study provides a thorough evaluation of the Sarishabari Solar Plant's operational performance, economic viability, and improvement opportunities. Findings indicate that the system demonstrates strong financial feasibility with an LCOE of 0.11 USD/kWh and a 10.1-year payback period. This economic advantage is attributed primarily to low land costs; however, such financial outcomes might not be replicable where private land acquisition is required.

Despite the plant's notable impact on renewable energy contribution, its performance ratio of approximately 70.06% suggests room for efficiency gains. Key strategies proposed include tilt angle optimization, energy storage integration, and the potential for hybridization with wind energy. Optimizing the tilt angle alone could yield a 9.5-year payback period with a fixed 24° angle, balancing operational simplicity with energy yield. Integrating battery energy storage, such as the Tesla Powerwall 2, offers additional stability and reliability, ensuring a more consistent energy supply, particularly during peak demand.

Hybrid solar-wind configurations were also explored as feasible solutions for enhancing energy security and output. Such systems can complement solar PV, especially during monsoon seasons with higher wind speeds, thus addressing intermittency issues and enhancing resilience. Given Bangladesh's land limitations and renewable energy goals, hybrid systems present an effective model for maximizing land use and supporting national energy objectives.

This analysis highlights the critical need for implementing advanced technologies and strategic policies to enhance the performance and efficiency of solar PV systems in Bangladesh. Implementing these recommendations could serve as a framework for future renewable projects, promoting sustainability and contributing to the country's vision of a greener energy future.

To further improve the resilience and effectiveness of renewable energy technologies, the following recommendations are proposed:

- BESS offers significant potential to improve energy reliability, but their high installation and maintenance costs have deterred adoption. Extending government subsidies to projects integrating storage solutions would alleviate these financial burdens, making BESS a more viable option for plant officials and promoting a stable energy supply.
- To mitigate the shortage of skilled professionals in the renewable energy sector, the establishment of short-term training or diploma programs in renewable energy is recommended.
- A gender-based analysis is essential to identify and address the barriers that limit female participation in renewable energy. Scholarships, mentorship programs, and diversity-focused workplace policies are recommended to create a more inclusive environment and enhance women's representation in this field.
- Universities should expand their curricula to include renewable energy subjects and encourage student engagement through scholarships and research grants.
- A specialized research center for renewable energy would streamline innovation, policy analysis, and technology development efforts.
- Renewable energy investments often entail longer payback periods than conventional energy sources. Facilitating quick access to bank loans, potentially backed by government guarantees, and offering affordable insurance schemes would reduce financial risks, encouraging more investment in the sector.
- High initial setup costs are a major barrier to renewable energy adoption. Reducing or removing import duties on

essential equipment could lower these costs, making renewable energy investments more financially attractive.

- Given Bangladesh's limited land availability, prioritizing hybrid renewable energy systems that integrate solar and wind can maximize land use efficiency and optimize energy generation, thus overcoming the challenges posed by land scarcity.
- Since tilt angle plays a crucial role in maximizing solar yield, especially in fixed-tilt systems, recommend conducting comprehensive studies to determine optimal angles for specific locations. Developing guidelines for regional tilt angle adjustments based on local irradiance patterns could significantly improve system performance and energy output.
- Implement Continuous Training Programs for Plant Operators: Ongoing training for plant officials and engineers, both domestically and internationally, is essential to keep them updated on industry breakthroughs. This continuous skill enhancement will enable more effective and innovative management of renewable energy facilities.
- Allocating non-arable land for renewable energy projects at minimal or no cost can support sector growth without competing with agricultural needs. This approach would ensure sustainable energy development while preserving Bangladesh's agricultural productivity.
- With the growth of renewable installations, there will be a rising need for effective management of solar panel and battery waste. The establishment of policies for the safe disposal and recycling of renewable equipment is essential to minimize environmental impact and ensure sustainability over the full lifecycle of these systems.
- Public awareness and community support are critical to the successful expansion of renewable energy. It is recommended that public awareness campaigns be launched to educate citizens on the benefits of renewable energy, energy conservation practices, and the environmental impacts of fossil fuel dependence.

The implementation of these recommendations is expected to result in substantial advancements in the country's renewable energy projects and contribute significantly to the achievement of sustainable development goals.

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