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Optimization of Solar PV System Efficiency in Bangladesh

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ABSTRACT

This paper presents a comprehensive review and analysis of Sarishabari Engreen Solar Plant Ltd., a 3.3 MW grid-connected solar photovoltaic (PV) system located in Sarishabari, Jamalpur, Bangladesh. The study evaluates the plant's economic and operational performance, revealing a competitive payback period of 10.1 years and a levelized cost of energy (LCOE) of 0.11 USD/kWh. These metrics highlight the plant's financial viability, largely due to the low cost of public land used for construction. However, profitability may be challenged if similar projects require significant investments in private land acquisition. Key areas for improvement identified include optimizing the tilt angle and integrating smart automation systems. Additionally, the potential for hybrid renewable energy systems combining solar and wind power is discussed. The paper also provides actionable recommendations for future renewable projects, emphasizing the importance of advanced technologies, and supportive policies. These insights aim to inform the optimization of existing solar PV systems and guide the development of future renewable energy projects in Bangladesh, contributing to the country's sustainable energy goals.

Keywords: *Hybrid Systems, Renewable Energy, Solar PV, Smart PV Systems, Tilt Angle Optimization.*

INTRODUCTION

The increasing global energy demand, along with the limited nature of fossil fuels and their negative environmental impact, has sparked a worldwide search for sustainable energy alternatives (Wang & Azam, 2024). Bangladesh, a nation experiencing rapid development and a growing energy deficit, is actively transitioning towards renewable energy sources to meet its energy needs and address environmental concerns (Gulagi et al., 2020). The government's ambitious goal of achieving 40% renewable energy in electricity generation by 2041, with a substantial contribution from solar energy, underscores the nation's dedication to a sustainable energy future (Raihan et al., 2024).

Bangladesh's advantageous geographical location, boasting abundant solar radiation ranging from 4 to 6.5 $kWh/m^2/day$ and expansive land areas suitable for solar installations, presents a unique opportunity to harness solar energy on a large scale (Hossain et al., 2017; Lipu et al., 2013; Masud et al., 2020; Halder et al., 2015). The National Renewable Energy Laboratory estimates the country's solar capacity at an impressive 240,000 MW, requiring a mere 1.5% of its total land area (Teske et al., 2019). Utility-sale grid-connected solar energy emerges as a significant prospect in Bangladesh, particularly considering the country's escalating energy demand and the government's commitment to increasing renewable energy sources (Bhuiyan et al., 2021).

In this context, the Engreen Sarishabari Solar Plant Ltd., a 3.3 MW grid-connected solar PV power plant in Bangladesh, serves as a valuable case study to examine the performance, economic viability, and potential for improvement of solar PV systems in the country. The plant's operational efficiency, grid integration capabilities, and financial performance have been analyzed in previous study (Babu & Basher, 2024). This study has highlighted the plant's success in generating electricity from renewable sources and its contribution to Bangladesh's energy landscape. The plant's performance ratio, a key indicator of efficiency, was found to be approximately 71%, with an average annual energy production of 3132 MWh. However, the solar PV system's performance ratio in Bangladesh lags behind neighboring countries. To address this and improve overall efficiency, an in-depth analysis of the challenges and factors that may be contributing to this disparity is needed.

In Bangladesh, the expansion of utility-scale grid-connected solar energy faces significant land challenges due to the country's limited land availability and the need to conserve land for agriculture (Maliha et al., 2019; Muhammad et al., 2022; Sakib et al., 2021). Despite the vast potential for solar energy in Bangladesh, the slow diffusion of solar energy in rural areas highlights the need to overcome barriers such as land constraints, technical issues, and pricing challenges to ensure sustainable renewable energy market growth (Rahman et al., 2019). Furthermore, integrating large-scale and safe energy storage technologies has been suggested as a supporting measure to increase renewable energy integration while maintaining electricity supply stability in the face of land and meteorological constraints (Halim et al., 2023). The challenges facing the low number of smart solar PV systems and hybrid solar-wind plants in Bangladesh for integrating large-scale solar PV systems stem from various factors (Hassan et al., 2023). While Bangladesh has made significant progress in deploying solar home systems (SHSs) (Rumi et al., 2022), the transition to more advanced systems like smart PV and hybrid plants faces obstacles such as high upfront costs, a lack of technical expertise, and limited awareness among stakeholders (Mojumder et al., 2022; Mahmud et al., 2022; Karim et al., 2019). A study by Hossain et al. (2023) found that the lack of awareness and understanding of smart PV technology among decision-makers and investors is also a significant barrier to adoption.

Smart solar PV systems offer significant cost-effectiveness compared to conventional solar PV plants (Corti et al., 2020; Mohamad et al., 2023; Dranka et al., 2020). By incorporating IoT for remote supervision and maintenance, smart systems can increase efficiency and yield while minimizing human intervention and costs (Chaabane et al., 2019). Additionally, the implementation of innovative smart monitoring systems with electronic sensors enhances the performance monitoring of crucial components like PV arrays, leading to increased detection speed, improved efficiency rates, and higher quality operation of solar power plants (Chaladi et al., 2022). The combination of these advancements showcases the superior cost-effectiveness of smart solar PV systems over conventional ones. By implementing innovative technologies such as smart monitoring with electronic sensors (Hasan et al., 2023) for better energy management in smart grids (Shiny et al., 2023), these systems can enhance performance, increase detection speed, improve quality, and reduce power loss due to factors like hot spots, soiling, and limited solar radiation capture (Ammach et al., 2022). However, the high initial cost is a significant obstacle to the wider adoption of solar energy systems (Bhatane et al., 2023).

The tilt angle of a solar PV system is crucial for maximizing energy generation efficiency (Mansour et al., 2021). Research has shown that the optimal tilt angle significantly impacts the performance of PV panels, affecting the amount of solar energy captured and the overall energy production (Davut et al., 2023; Hameedullah et al., 2023; Marcelo et al., 2023; Hasanuzzaman et al., 2022; Merisa et al., 2023). Studies have explored various tilt angles to determine the most efficient positioning, considering factors like dust accumulation, solar radiation utilization, and seasonal variations. However, many existing solar PV systems in Bangladesh, including the Engreen Sarishabari plant, still rely on manual tilt angle adjustments, which can lead to suboptimal energy production and increased labor costs. Different studies have found that implementing automatic tilt angle adjustment systems could increase energy yield significantly, but the cost of these systems and the potential complexity of system setup and maintenance can be a barrier to adoption for projects (Mohamed et al., 2021).

In Bangladesh, solar and wind potential is significant (Saddamul et al., 2022). The integration of wind energy into solar PV systems could enhance the overall power generation sustainability (Abdul et al., 2023; Ali et al., 2023; Tummala et al., 2023) Therefore, coupling wind energy with solar PV systems, especially in coastal areas with sufficient wind resources, could provide a more reliable and sustainable power generation solution for Bangladesh (Aghaloo et al., 2023). Integrating wind energy into solar PV systems in Bangladesh has been a focal point for enhancing renewable energy generation and cost-effectiveness (Sakib et al., 2023). Studies in Bangladesh have shown that hybrid energy systems combining wind and solar power can significantly reduce electricity costs and CO_2 emissions (Ahmed et al., 2023). A study found that the LCOE of hybrid wind solar power is 0.0725 and the payback period is 6.4 years (Hasan et al., 2022). However, the development of hybrid wind-solar projects in Bangladesh has been limited due to challenges such as the intermittent nature of wind resources (Saifullah et al., 2023), the need for additional infrastructure and technology, and the complexities of integrating wind power into the existing grid (Noman & A.N., 2022;

Supti. 2022). A recent study by Rahman et al. (2024) suggests that a supportive policy framework, including incentives for hybrid projects and streamlined approval processes, could accelerate the deployment of wind-solar hybrid systems in Bangladesh (Shufian et al., 2022). Additionally, research by Ahmed et al. (2023) indicates that community engagement and awareness programs are crucial for the successful implementation of hybrid projects, as local acceptance and support can significantly impact project outcomes. Furthermore, the importance of accurate wind resource assessment and forecasting for the optimal design and operation of hybrid wind-solar systems in Bangladesh is highlighted (Shafi et al., 2023; Hasan et al., 2023).

Wind-solar hybrid (WSH) projects in India have shown potential for higher transmission efficiency, cost-effectiveness, and improved grid stability, with significant capacity already operational or in various bidding phases (Majid et al., 2023). Co-locating wind and solar PV plants in hybrid systems can reduce transmission infrastructure costs and variability in output power profiles, making it a strategic approach to accelerate renewable energy deployment in India (Marty et al., 2022). The integration of wind energy into solar PV systems in India has been extensively studied for its cost-effectiveness and efficiency. Research has shown that hybrid systems combining solar and wind power, along with battery storage, offer a reliable and sustainable solution for rural electrification (Kawadgave & Unde, 2022; Rahul & Sharma, 2022). Furthermore, the optimization of hybrid renewable energy systems (HRES) in locations like Haldia has demonstrated the potential for significant cost savings and enhanced agricultural sustainability (Vijay et al., 2021). These findings from India provide valuable insights for developing similar hybrid systems in Bangladesh, given the numerous similarities between the two neighboring countries in terms of wind resources and solar irradiance.

The integration of wind energy into solar PV systems in Pakistan has been extensively studied for its cost-effectiveness and feasibility. Research indicates that small-scale hybrid solar-wind systems offer a decentralized power generation alternative with low manufacturing and operational costs, making them ideal for both rural and urban environments (Muhammad et al., 2019). Studies in Gwadar have shown that combining wind and solar resources in hybrid systems can significantly reduce the levelized cost of electricity (LCOE) and provide an optimal solution for energy generation (Ali et al., 2022). Furthermore, the integration of wind and solar power in hybrid renewable energy systems has been proven to be effective in areas like Tattapani (Syed et al., 2019).

This study is to optimize the efficiency and profitability of the Engreen Sarishabari Solar Plant and other solar PV projects in Bangladesh. This includes proposing recommendations for upgrading to a smart PV system with automatic tracking, optimizing the tilt angle of solar panels, and exploring the feasibility of hybrid wind-solar systems. By addressing the challenges of land acquisition and efficiency optimization, the research aims to contribute to the sustainable development of renewable energy in Bangladesh and provide valuable insights for policymakers, energy stakeholders, and investors.

METHODOLOGY

This study employs a multi-faceted approach, integrating a literature review, data analysis, and simulation modeling to assess and optimize the performance of solar PV systems in Bangladesh.

First, a comprehensive literature review was conducted to identify key trends, challenges, and opportunities in the development of solar PV systems in Bangladesh. The analysis focused on the technical aspects of solar PV systems, such as the impact of tilt angle and tracking systems on energy yield, as well as the economic factors influencing the viability of solar PV projects, including the payback period and levelized cost of energy (LCOE). The literature review also explored the potential of hybrid wind-solar systems and smart PV systems to enhance the efficiency and profitability of renewable energy projects.

In addition to the literature review, the study also draws upon data and findings from previous studies on Engreen Sarishabari Solar Plant Ltd. (Babu & Basher., 2024). This data includes the plant's performance ratio, annual energy production, payback period, and LCOE. By integrating this data with the insights gleaned from the literature review, the study aims to provide a comprehensive and nuanced understanding of the challenges and opportunities associated with solar PV systems in Bangladesh.

To evaluate the feasibility of hybrid renewable energy systems, the study used HOMER Pro software, a tool designed for optimizing microgrid design. The simulation considered various configurations of solar PV, wind turbines, and energy storage systems to identify the most cost-effective and reliable setup for the given location and load profile.

Furthermore, to evaluate the impact of tilt angle on the energy yield of the solar PV system, PVsyst software was employed. PVsyst is widely used software for simulating and analyzing the performance of solar PV systems. By modeling the Engreen Sarishabari Solar Plant in PVsyst and adjusting the tilt angle of the solar panels, the study can assess the potential energy gains that can be achieved through tilt angle optimization. This analysis will inform recommendations for improving the efficiency of the plant and other solar PV projects in Bangladesh.

Evaluation of Current Plant Performance

The performance of Engreen Sarishabari Solar Plant Ltd. is evaluated through a comprehensive economic and performance analysis. Key metrics of the system are summarized in Table 1.This table is adapted from Babu & Basher (2024).

Table 1: Economic and Performance Analysis of the Engreen Sarishabari Solar Plant Ltd

Metric	Value
Produced Energy	3132 MWh/year
Specific Production	949 kWh/kWp/year
Cost of Produced Energy	0.1132 USD/kWh
Feed-in Tariff	0.18970 USD/kWh
Electricity Sales	11,882,808 USD
Payback Period	10.1 years
Return on Investment (ROI)	92.3 %
Cumulative Profit	4,526,693 USD
Performance Ratio	0.7

The analysis demonstrates that Engreen Sarishabari Solar Plant Ltd. is performing efficiently, with a strong ROI and a reasonable payback period. The performance ratio of 0.7 suggests there is room for improvement in operational efficiency, potentially through optimizing maintenance practices or upgrading system components.

Recommendations for Efficiency Improvements

Based on the findings from the simulations and analysis, several recommendations are proposed:

- Smart PV System Upgrade: Implementing a smart PV system with automatic tracking to enhance performance and optimization.
- Tilt Angle Optimization: Setting the tilt angle to 24° to increase energy efficiency and reduce labor costs associated with manual adjustments.
- Hybrid-Wind-Solar-Smart System: Exploring the feasibility of integrating wind energy with the existing solar PV system to enhance energy production and reduce costs.

Smart PV System Upgrade

We explored the potential energy generation of a 3.3 MW solar PV plant in Jamalpur, Bangladesh, under ideal conditions. We present a step-by-step calculation of the expected annual energy output, taking into account solar irradiance and system efficiency. Furthermore, we introduce a novel smart PV system designed to optimize performance and seamlessly integrate with energy storage solutions for future expansion.

Energy Generation Calculation

To estimate annual energy generation, we use the following parameters:

- **Solar irradiance:** 5.4 kWh/m²/day (average)
- **System efficiency:** 80% (typical range for solar PV systems)
- **Power rating:** 3.3 MW (3300 kW)

With these values, we can calculate the daily and annual energy generation:

- **Daily Energy Output:**
  - Daily energy output = power rating * effective sunlight hours
  - Daily energy output = 3300 kW * 5.4 hours/day = 17820 kWh/day
- **Annual Energy Generation:**
  - Annual energy generation = daily energy output * number of days in a year
  - Annual energy generation = 17820 kWh/day * 365 days/year = 6501300 kWh/year

Accounting for system efficiency, the effective annual energy generation is:

- Effective annual energy generation = 6501300 kWh/year * 0.80 = 5201040 kWh/year (approximately 5201 MWh/year)

FINANCIAL ANALYSIS

Considering a feed-in tariff of \$0.1897 USD/kWh and an annual operational cost of \$55,000 USD, we can calculate the financial metrics:

- **Annual Revenue:**
  - Annual revenue = annual energy generation * feed-in tariff
  - Annual revenue = 5201040 kWh/year * $0.1897 USD/kWh = $986,695.97 USD/year (approximately)

- **Net Annual Revenue:**
  - Net annual revenue = annual revenue - annual operation cost
  - Net annual revenue = $986,695.97 USD/year - $55,000 USD/year = $931,695.97 USD/year

- **Payback Period:**
  - Payback period = installation cost / net annual revenue
  - Payback period = $6,700,000 USD / $931,695.97 USD/year = 7.19 years (approximately)

- **Levelized Cost of Energy (LCOE):**
  - Total lifetime cost = total installation cost + (annual operation cost * project lifetime)
  - Total lifetime cost = $6,700,000 USD + ($55,000 USD/year * 20 years) = $7,800,000 USD
  - Total lifetime energy generation = annual energy generation * project lifetime
  - Total lifetime energy generation = 5201040 kWh/year * 20 years = 104,020,800 kWh
  - LCOE = total lifetime cost / total lifetime energy generation
  - LCOE = $7,800,000 USD / 104,020,800 kWh = $0.075 USD/kWh (approximately)

It's important to note that if the installation cost were aligned with international standards, the payback period could be reduced to 5.29 years, with an LCOE of 0.049 USD/kWh.

Introducing the Smart PV System

It is evident that effective operational management and smart automation of the plant can lead to optimal efficiency, enhancing its economic feasibility. To maximize efficiency and cost-effectiveness, we have developed a smart solar PV system. This system offers several advantages:

- **Smart Automation:** Optimizes plant operation, potentially increasing energy yield and reducing maintenance costs.
- **Energy Storage Ready:** Easily integrates with energy storage systems for greater flexibility and resilience.
- **Minimal Additional Cost:** The smart features introduce minimal cost overhead, especially without an initial energy storage component.
- **Monitoring and Control:** Enables real-time monitoring and remote control for proactive issue identification and resolution.

- **Data Analytics:** Provides valuable insights into plant performance, informing decision-making for further optimizations.

Figure 1 illustrates the energy flow in our smart PV system. The process begins with the solar panels and ends with the grid connection and user interface. The system also integrates an energy storage component and is monitored and controlled via a communication network.

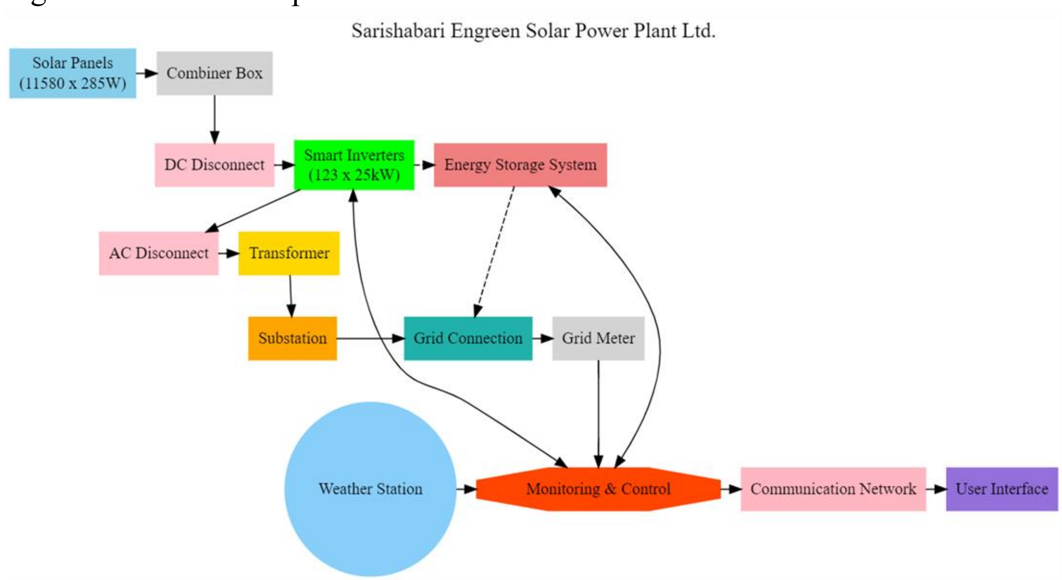

Figure 1: Energy Flow Diagram of the Smart PV System

TILT ANGLE OPTIMIZATION

Sarishabari Engreen Solar Power Ltd. features a manual solar tracking system. During the summer months, the tilt angle adjusts to 5°, while in the winter, it adjusts to 24°. These manual adjustments result in significant labor costs and, more importantly, reduce the plant's efficiency.

Through our PVsyst software simulations and comparisons with solar PV systems in our country and others, we have determined that the optimal tilt angle for solar panels corresponds to the latitude of the area. While a tracking system presents itself as an alternative, its widespread application is hindered by certain drawbacks.

Since Sarishabari is located at 24.7417°N, 89.8333°E, taking this into consideration, the tilt angle of our solar PV system should ideally be set at 24°. Readjusting the tilt angle will significantly enhance the plant's efficiency and reduce the payback period.

Table 2 presents a comparative analysis of solar panel installations at different tilt angles. The efficiency of each installation is assessed based on specific production, energy cost, payback period, and performance ratio. This comparison sheds light on the impact of tilt angles on the overall performance and economic viability of solar energy systems.

Table 2: Comparative efficiency analysis of solar panel installations at different tilt angles

Tilt Angle	Produced Generation	Specific Production	Energy Cost	Payback Period	Performance Ratio
Summer 5^{o}and Winter 24^{o}	3132 MWh/year	949 kWh	.11USD/kWh	10.1 years	70.62%
Fixed 24^{o} Tilt Angle	3886 MWh/year	1177 kWh	.10 USD/ kWh	9.5 years	71.78%

HYBRID-WIND-SOLAR-SMART SYSTEM

The Government of Bangladesh has set a target of achieving a wind power capacity of 1370 MW by 2030 and has encouraged private entities to invest in wind power projects (Das et al., 2018). A report on the country's technical capacity found that Bangladesh has around 20,000 square kilometers of land where wind blows at 5.75-7.75 m/s. It means wind farms covering these areas can produce a total of 30 GW of electricity (Mamun et al., 2022).

With the projected increase in land costs, future investors may find it challenging to ensure profitability for solar PV systems alone (Karim et al., 2020). To address this challenge and enhance the economic viability of renewable energy projects, we propose the implementation of a hybrid-wind-solar-smart system. By harnessing both wind and solar resources, this hybrid system aims to increase energy production while simultaneously reducing costs. The model is designed to be adaptable and can be applied to both the current Sarishabari solar PV plant and future renewable energy projects. It offers a flexible framework that can be tailored to the specific conditions and requirements of different locations, making it a valuable tool for optimizing energy generation in various contexts.

HYBRID SYSTEM DESIGN

We've meticulously crafted a comprehensive design for the hybrid system tailored for Sarishabari, leveraging its abundant solar and wind resources. Our proposal centers on a wind-PV hybrid system poised to unlock the full potential of these renewable energy sources. Following a thorough assessment of horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT) for the power plant, we've determined that VAWT stands out as the optimal choice for this application. VAWT can be installed closer to the ground, it has a respected performance against lower wind speeds, and its effect on birds and aircraft is lower compared to HAWT (Paraschivoiu & I. 1988; Olabi et al., 2021; Ferrigno & K. J. 2010).

WIND TURBINE

This study uses a 100 kW vertical-axis wind turbine made by Nantong R&X Energy Technology Co., Ltd., China, since VAWT is the optimal option for this evaluation. Table 3 provides the technical specifications of the chosen wind turbine. This turbine is of the H-type.

Table 3 provides detailed specifications of the RX-HV100K wind turbine model. These specifications highlight the performance capabilities and operational requirements of the RX-HV100K wind turbine, offering insights into its suitability for various wind energy projects.

Table 3: Technical Specifications of the RX-HV100K Vertical Axis Wind Turbine

Model	RX-HV100K
Rated power (kW)	100
Blades Length (M)	15
Wheel Diameter (M)	6
Rated Voltage	380
Start Up Speed (m/s)	2
Cut In Wind Speed (m/s)	3
Survival Wind Speed (m/s)	50
Number Of Blades	3
Lifespan (Years)	20
Gross Weight (kg)	250
Install Height (M)	2-12

Table 4 provides an overview of the key characteristics of the hybrid system. The information is crucial for evaluating the economic and operational feasibility of deploying these technologies in renewable energy projects.

Table 4: Cost and Performance Characteristics of Hybrid-Wind-Solar-Smart System Components

Characteristic	Solar panel	Wind turbine	Inverter	Battery
Model	Sunmodule plus SW 285 Mono	RX-HV100K	Sunny Tripower STP 25000TL-30	100kWh Li-Ion
Power (kW)	.285	100kW	25	100kWh
Capital cost (USD)	328	49000	4057	40000
Replacement cost (USD)	300	30000	2000	40000
O& M cost per equipment/year	2	1000	8	500

SOFTWARE SIMULATION TOOLS

Our study will advance with simulations aimed at assessing the viability of suggested system configurations. Our objective is to thoroughly analyze and refine energy production systems utilizing HOMER Pro simulation software. Acting as an invaluable optimization tool, HOMER Pro plays a crucial role in determining the most cost-effective and efficient combination of energy sources and components. It facilitates the simulation of diverse setups, incorporating elements like photovoltaic (PV) solar panels, wind turbines, hydroelectric generators, and energy storage devices. Through comprehensive evaluation, HOMER identifies optimal configurations based on predefined criteria, primarily focusing on reducing the system's net present cost (NPC).

HOMER SIMULATION RESULTS

The primary objective of this study was to determine the most effective configuration for a grid-connected PV-wind hybrid power system. Efficiency was assessed based on factors such as the cost of energy (COE), the net present cost (NPC), and the proportion of renewable energy utilized to fulfill the load demand. Utilizing HOMER Pro, a simulation software equipped with optimization capabilities, enabled us to achieve this aim.

The analysis concentrated on a system incorporating crucial inputs such as wind and solar resource data, technical specifications of components, and economic variables. Figure 1 illustrates the fundamental system configuration along with its components. Solar PV panels convert sunlight into DC electricity, which is then directed to the DC bus. An inverter converts the DC output into AC electricity that is subsequently supplied to the AC bus. Wind turbines directly contribute AC electricity to the AC bus. To enhance HOMER's flexibility in exploration and optimize the selection of system configurations, a battery storage system was integrated.

Figure 2 shows a schematic diagram of a Hybrid-Wind-Solar-Smart Power System with battery storage and grid connection.

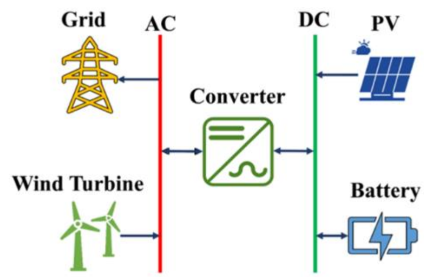

Figure 2: System configuration for the proposed hybrid model

Table 5 presents cost and performance metrics for two configurations of renewable energy systems, as derived from the HOMER Pro software.

Table 5: Cost and Performance Metrics for Different Renewable Energy System Configurations

Sunmodule Plus Sw-285	RXHV 100kW	100kWh LA	Converter (Kw)	NPC ($)	LCOE ($/kWh)	Operating Cos ($/yr)	CAPX ($)
3300	20		25	$9.56M	$0.073	$75000	$8.7M
3300	20	20	20	$10.03	$0.1453	$80,500	$9.4M

Table 6 provides a detailed breakdown of the results derived from HOMER Pro software for a renewable energy system with an installed capacity of 5.3 MW, comprising 3.3 MW of solar and 2 MW of wind turbines.

Table 6; Breakdown of HOMER Pro Results

Installed Capacity	5.3 MW (Solar 3.3MW+wind turbines 2MW)
Total Annual Generation	6,986 MWh
Total Initial Installation Cost	$8,700,000

Total Operation Cost	$75,000 per year
Annual Revenue	$1,325,154.2
Annual Profit	$1,250,154.2
Net Present Cost (NPC)	$9,560,250
LCOE	$0.073 per kWh
Payback Period	6.96 years
Ren Frac (%)	100

Summary after adding storage system
Total CAPEX: $9,400,000
Total Operating Cost: $80,500 per year
NPC: Approximately $10,036,268
LCOE: Approximately $0.1453/kWh
Payback Period: Approximately 8.59 years

Figure 3 illustrates the energy flow of our proposed hybrid wind-solar-smart system, incorporating solar PV, wind turbines, and hybrid energy storage systems. Energy from these sources is channeled through a substation switchyard to the grid connection point, managed by an advanced energy management system (EMS). This model is developed considering both the current solar PV plant and future projects.

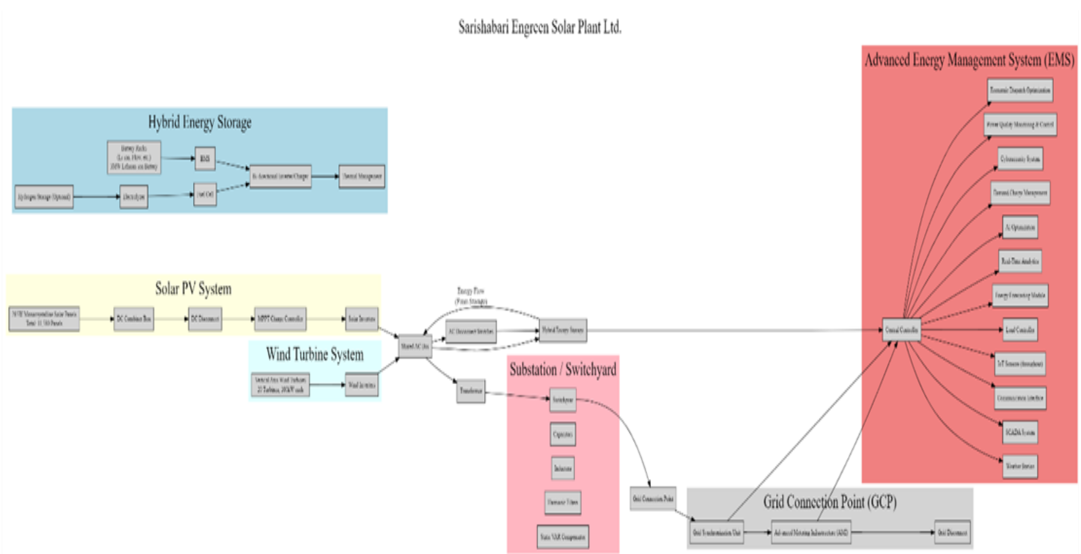

Figure 3: Design of our proposed improved Hybrid-Wind-Solar Smart System

RECOMMENDATIONS FOR FUTURE DEVELOPMENT

Since the adoption of Bangladesh's first renewable energy strategy in 2002, significant progress has been made (Masud et al., 2020). To further enhance the sustainability and impact of renewable energy technologies, the following recommendations are proposed:

- Foster closer collaboration between policymakers, researchers, and academics to ensure that renewable energy policies are informed by scientific insights and innovative ideas.
- Create a dedicated research institution focused on renewable energy to conduct cutting-edge research, develop innovative technologies, and provide valuable insights for policymakers and industry stakeholders.
- Incorporate energy education programs into the national curriculum at all levels of education.
- Develop insurance schemes that offer affordable coverage for renewable energy investments.
- Remove import duties on tools and machinery for renewable energy plants to reduce the initial setup costs.
- Adopt modern energy modeling software, such as the Long-range Energy Alternative Planning System (LEAP), to analyze energy systems, forecast future energy consumption, and assess the potential of renewable energy sources.
- Allocate non-arable land at minimal or no cost to investors for the development of green energy projects.
- Encourage the development of hybrid power plants that integrate multiple renewable energy sources, such as wind and solar.
- Invest in smart energy infrastructure and grid technologies to optimize the integration of renewable energy sources into the electricity grid.
- Each renewable energy project should have a website providing detailed information for the public.
- Our study found that accessing information about renewable energy projects in Bangladesh is challenging, with officials often reluctant to share details. If there are no major security or operational concerns, power plants should be more open and accessible, particularly for students, academics, and researchers.
- Researchers should focus on developing renewable energy projects that do not disrupt local biodiversity.
- Authorities should plan ahead for the recycling and disposal of solar and wind plant waste.

- Strengthen collaboration with neighboring countries to enhance renewable energy development.
- Explore ways to design renewable energy project sites for multiple uses, such as growing vegetables, seasonal foods, or integrating other forms of sustainable agriculture, to maximize land use efficiency.
- The government should prioritize the long-term environmental benefits of renewable energy over immediate profitability for the next 10–20 years.
- Universities should offer generous incentives, such as scholarships and research grants, to encourage students to major in or conduct research on renewable energy, addressing the current lack of enthusiasm and job opportunities in this field.

Adopting these recommendations will enable Bangladesh to significantly strengthen its renewable energy sector, ensuring its sustainability and boosting its contribution to the national energy mix.

CONCLUSION

This study presents a comprehensive analysis of the Sarishabari Engreen Solar Plant Ltd., a 3.3 MW grid-connected photovoltaic (PV) system in Bangladesh. The evaluation highlights both the economic and operational performance of the plant, demonstrating a competitive payback period of 10.1 years and a levelized cost of energy (LCOE) of 0.11 USD/kWh. These metrics underscore the plant's financial viability, primarily attributed to the low cost of the public land used for its construction. However, the profitability of similar projects may face challenges if significant investments in private land acquisition are required.

Key recommendations for improving the efficiency and profitability of the Engreen Sarishabari Solar Plant, as well as other solar PV projects in Bangladesh, have been identified. Upgrading to smart PV systems with automatic tracking, optimizing the tilt angle of solar panels, and exploring the feasibility of hybrid wind-solar systems are crucial steps.

Implementing smart PV systems can significantly enhance performance and efficiency by incorporating IoT for remote supervision and maintenance. Our study has found that turning the present system into a smart system can reduce the payback period to nearly 7.19 years, with the LCOE as low as \$0.075 USD/kWh. Because of the rapid decline in the price of PV systems, future projects can expect even lower payback periods and

LCOE. This reduces human intervention and costs while increasing energy yield. Smart systems also enable real-time monitoring and control, allowing for proactive issue identification and resolution.

The optimal tilt angle for solar panels is crucial for maximizing energy generation. This study recommends setting the tilt angle to 24°, corresponding to the latitude of the area. This adjustment can improve the plant's electricity generation from 3132 MWh/year to 3886 MWh/year, increase overall efficiency, and reduce the labor costs associated with manual adjustments.

Integrating wind energy with solar PV systems presents an opportunity to enhance energy production and reduce costs. The hybrid approach leverages the complementary nature of solar and wind resources, providing a more reliable and sustainable power generation solution. The potential for hybrid systems in Bangladesh, particularly in coastal areas with sufficient wind resources, is substantial. While the initial investment will increase, a payback period of 7 years and a $0.073 levelized cost of energy justify it.

The economic analysis indicates that Engreen Sarishabari Solar Plant Ltd. is performing efficiently, with a strong return on investment and a reasonable payback period. However, there is room for improvement in operational efficiency, which can be achieved through the recommended upgrades and optimizations.

Furthermore, the study underscores the importance of advanced technologies and supportive policies in promoting the sustainable development of renewable energy in Bangladesh. The integration of smart PV systems, optimal tilt angles, and hybrid wind-solar systems can significantly contribute to the country's renewable energy targets and address its growing energy needs.

In conclusion, the findings and recommendations from this study aim to inform policymakers, energy stakeholders, and investors about the potential for optimizing existing solar PV systems and guide the development of future renewable energy projects in Bangladesh. By addressing the challenges of land acquisition and efficiency optimization, the research contributes to the sustainable energy goals of Bangladesh, promoting a cleaner and more resilient energy future. Future research should focus on long-term performance monitoring and the impact of emerging technologies on solar PV efficiency.

REFERENCES

Abdul Baseer, M., & Alsaduni, I. (2023). A Novel Renewable

Smart Grid Model to Sustain Solar Power Generation. Energies, 16(12), 4784. https://doi.org/10.3390/en16124784.

Aghaloo, K., Ali, T., Chiu, Y. R., & Sharifi, A. (2023). Optimal site selection for the solar-wind hybrid renewable energy systems in Bangladesh using an integrated GIS-based BWM-fuzzy logic method. Energy Conversion and Management, 283, 116899. https://doi.org/10.1016/j.enconman.2023.116899

Ahmed, M. R., Hasan, M. R., Al Hasan, S., Aziz, M., & Hoque, M. E. (2023). Feasibility Study of the Grid-Connected Hybrid Energy System for Supplying Electricity to Support the Health and Education Sector in the Metropolitan Area. Energies, 16(4), 1571. https://doi.org/10.3390/en16041571.

Ahmed, N., Hasnaine, Q. R., Mahmud, S., & Thushar, M. I. (2023). Design and Cost Analysis of a Decentralized Hybrid Renewable Energy System-based Microgrid for Insular Rural Area: Hatiya of Bangladesh as an off-grid solution. In 2023 International Conference on Control, Communication and Computing (ICCC) (pp. 1-6). IEEE. https://doi.org/10.1109/iccc57789.2023.10165548

Ali, M. (2023). The Implementation of PV-Battery Storage-Wind Turbine-Load-on Grid System. Brilliance: Research of Artificial Intelligence, 3(1), 9-18.

Ali, M. S., Ali, S. U., Mian Qaisar, S., Waqar, A., Haroon, F., & Alzahrani, A. (2022). Techno-Economic Analysis of Hybrid Renewable Energy-Based Electricity Supply to Gwadar, Pakistan. Sustainability, 14(23), 16281. doi: 10.3390/su142316281.

Ammach, S., & Qaisar, S. M. (2022). A Smart Energy-Efficient Support System for PV Power Plants. Intelligent Green Technologies for Sustainable Smart Cities, 111-142.

Babu, M. T., Nei, H., & Kowser, M. A. (2022). Prospects and necessity of wind energy in Bangladesh for the forthcoming future. Journal of The Institution of Engineers (India): Series C, 103(4), 913-929. https://doi.org/10.1007/s40032-022-00834-8.

Babu, R. M., Basher, E. (2024). Performance Evaluation and Economic Analysis of a Grid-Connected Solar Power Plant: A Case Study of Engreen Sarishabari Solar Plant Ltd. in Bangladesh. Ecological Engineering & Environmental

Technology, 25(5). https://doi.org/10.12912/27197050/185934.

Bhatane, G. A., & Gond, V. J. (2023). A Smart Monitoring of Solar PV Panel with Performance Amplification using IoT. In 2023 International Conference on Inventive Computation Technologies (ICICT) (pp. 1367-1370). IEEE. https://doi.org/10.1109/icict57646.2023.10134226.

Bhuiyan, M. R. A., Mamur, H., & Begum, J. (2021). A brief review on renewable and sustainable energy resources in Bangladesh. Cleaner Engineering and Technology, 4, 100208.

Chaabane, M., Charfi, W., Mhiri, H., & Bournot, P. (2019). Performance evaluation of solar photovoltaic systems. International journal of green energy, 16(14), 1295-1303. doi: 10.1080/15435075.2019.1671405

Chaladi, S, Ganga, Bhavani., N., Bhanu, Prasad., D., Ravi, Kishore. (2022). Performance Evaluation of solar photovoltaic systems. In 2022 IEEE 2nd International Symposium on Sustainable Energy, Signal Processing and Cyber Security (iSSSC) (pp. 1-6). IEEE.

Corti, P., Capannolo, L., Bonomo, P., De Berardinis, P., & Frontini, F. (2020). Comparative analysis of BIPV solutions to define energy and cost-effectiveness in a case study. Energies, 13(15), 3827. https://doi.org/10.3390/en13153827.

Das, A., Halder, A., Mazumder, R., Saini, V. K., Parikh, J., & Parikh, K. S. (2018). Bangladesh power supply scenarios on renewables and electricity import. Energy, 155, 651-667.

Davut, Solyali., Amir, Mollaei. (2023). A Simulation Model Based on Experimental Data to Determine the Optimal Tilt Angle for a Fixed Photovoltaic Pane. Archives of Advanced Engineering Science, 1-11. doi: 10.47852/bonviewaaes3202907.

Dranka, G. G., Ferreira, P., & Vaz, A. I. F. (2020). Cost-effectiveness of energy efficiency investments for high renewable electricity systems. Energy, 198, 117198.

Ferrigno, K. J. (2010). Challenges and strategies for increasing adoption of small wind turbines in urban areas (Doctoral dissertation, Massachusetts Institute of Technology).

Gulagi, A., Ram, M., Solomon, A. A., Khan, M., & Breyer, C. (2020). Current energy policies and possible transition scenarios adopting renewable energy: A case study for Bangladesh. Renewable Energy, 155, 899-920.

https://doi.org/10.1016/j.renene.2020.03.119.

Halder, P. K., Paul, N., Joardder, M. U., & Sarker, M. (2015). Energy scarcity and potential of renewable energy in Bangladesh. Renewable and SustainableEnergy Reviews, 51, 1636-1649.

Halim, M. A., Akter, M. S., Biswas, S., & Rahman, M. S. (2023). Integration of Renewable Energy Power Plants on a Large Scale and Flexible Demand in Bangladesh's Electric Grid-A Case Study. Control Systems and Optimization Letters, 1(3), 157-168. https://doi.org/10.59247/csol.v1i3.48.

Hameedullah, Zaheb., Mikaeel, Ahmadi., H., Fedayi., Atsushi, Yona. (2023). Maximizing Annual Energy Yield in a Grid-Connected PV Solar Power Plant: Analysis of Seasonal Tilt Angle and Solar Tracking Strategies. Sustainability. doi: 10.3390/su151411053.

Hanjalic, M., & Melic, E. (2023, March). Impact of the Tilt Angle on the Electrical Output, Characteristics and Performance of a Grid-Connected Photovoltaic System.22nd International Symposium INFOTEH-JAHORINA (INFOTEH) (pp. 1-6). IEEE.

Hasan, S., Hazari, M. R., & Mannan, M. A. (2023). Fuzzy logic-based design optimization and economic planning of a microgrid for a residential community in Bangladesh. In 2023 3rd International Conference on Robotics, Electrical and Signal Processing Techniques (ICREST) (pp. 34-39). IEEE.

Hassan, Q., Algburi, S., Sameen, A. Z., Salman, H. M., & Jaszczur, M. (2023). A review of hybrid renewable energy systems: Solar and wind-powered solutions: Challenges, opportunities, and policy implications. Results in Engineering, 101621. https://doi.org/10.1016/j.rineng.2023.101621

Hassan, Yazdani., Mehdi, Radmehr., Alireza, Ghorbani. (2023). Smart component monitoring system increases the efficiency of photovoltaic plants. Clean energy. doi:10.1093/ce/zkac071.

Hossain Lipu, M. S. & Uddin, Md & Miah, Muhammad. (2013). A feasibility study of solar-wind-diesel hybrid system in rural and remote areas of Bangladesh. International Journal of Renewable Energy Research. 3. 892-900.

Hossain, M. F., Hossain, S., & Uddin, M. J. (2017). Renewable energy: Prospects and trends in Bangladesh. Renewable and

Sustainable Energy Reviews, 70, 44-49.

J, Charles, Rajesh, Kumar., Masoud, Ali, Majid. (2023). Advances and development of wind–solar hybrid renewable energy technologies for energy transition and sustainable future in India. Energy & environment, doi: 10.1177/0958305x231152481.

Karim, M. E., Karim, R., Islam, M. T., Muhammad-Sukki, F., Bani, N. A., & Muhtazaruddin, M. N. (2019). Renewable energy for sustainable growth and development: An evaluation of law and policy of Bangladesh. Sustainability, 11(20), 5774. https://doi.org/10.3390/su11205774.

Karim, R., Muhammad-Sukki, F., Hemmati, M., Newaz, M. S., Farooq, H., Muhtazaruddin, M. N., ... & Ardila-Rey, J. A. (2020). Paving towards strategic investment decision: a SWOT analysis of renewable energy in Bangladesh. Sustainability, 12(24), 10674. https://doi.org/10.3390/su122410674.

Kawadgave, D. A., & Unde, M. G. (2022, November). Design and Optimization of Renewable Hybrid Energy System for Rural India-Feasibility Study. In 2022 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME) (pp. 1-6). IEEE.

Mahmud, H., & Roy, J. (2021). Barriers to overcome in accelerating renewable energy penetration in Bangladesh. Sustainability, 13(14), 7694. https://doi.org/10.3390/su13147694.

Maliha, Muzammil., Raihan, Uddin, Ahmed. (2019). Solar Home Systems in Bangladesh. . Confronting Climate Change in Bangladesh: Policy Strategies for Adaptation and Resilience, 175-192.

Mamun, M. A. A., Islam, M. M., Hasanuzzaman, M., & Selvaraj, J. (2022). Effect of tilt angle on the performance and electrical parameters of a PV module: Comparative indoor and outdoor experimental investigation. Energy and Built Environment,3(3),278-290.

Mansour, R. B., Khan, M. A. M., Alsulaiman, F. A., & Mansour, R. B. (2021). Optimizing the solar PV tilt angle to maximize the power output: A case study for Saudi Arabia. IEEE access, 9, 15914-15928. https://doi.org/10.1109/access.2021.3052933.

Gomes, Alexandro, Oliveira, Maria, Musci & Marcelo. (2023). Optimal Tilt Angle of Photovoltaic Panels: A Case

Study in the City of Rio de Janeiro. Environmental Management and Sustainable Development.12.54.10.5296/emsd.v12i2.20992.

Marty, Schwarz., Amy, Rose., Patrick, Duncan, Brown., Ilya, Chernyakhovskiy., David, Palchak. (2022). Opportunities for Hybrid Wind and Solar PV Plants in India.doi: 10.2172/1845272.

Masud, M. H., Nuruzzaman, M., Ahamed, R., Ananno, A. A., & Tomal, A. A. (2020). Renewable energy in Bangladesh: current situation and future prospect. International Journal of Sustainable Energy, 39(2), 132-175. https://doi.org/10.1080/14786451.2019.1659270.

Md., Mehadi, Hasan, Shamim., Sidratul, Montaha, Silmee., Md., Mamun, Sikder. (2022). Optimization and cost-benefit analysis of a grid-connected solar photovoltaic system. AIMS energy, doi: 10.3934/energy.2022022.

Mohamed, Nageh., Pauzi, Abdullah., Belal, Yousef. (2021). Optimum tilt angle for maximizing large scale solar electrical energy output. Jurnal Teknologi, 83(3), 133-141.

Mohammad, A., & Mahjabeen, F. (2023). Revolutionizing solar energy: The impact of artificial intelligence on photovoltaic systems. International Journal of Multidisciplinary Sciences and Arts, 2(1). https://doi.org/10.47709/ijmdsa.v2i2.3210.

Mojumder, M. R. H., Hasanuzzaman, M., & Cuce, E. (2022). Prospects and challenges of renewable energy-based microgrid system in Bangladesh: a comprehensive review. Clean Technologies and Environmental Policy, 24(7), 1987-2009. https://doi.org/10.1007/s10098-022-02301-5.

Muhammad, Talut., AbuBakr, S., Bahaj., Patrick, James.(2022). Solar Power Potential from Industrial Buildings and Impact on Electricity Supply in Bangladesh. Energies, doi: 10.3390/en15114037.

Noman, A. N. (2022). Wind Energy: The Promising Future of Bangladesh Power Sector. ScienceOpen Preprints. https://doi.org/10.14293/s2199-1006.1.sor-.ppgrax2.v1.

Olabi, A. G., Wilberforce, T., Elsaid, K., Salameh, T., Sayed, E. T., Husain, K. S., & Abdelkareem, M. A. (2021). Selection guidelines for wind energy technologies. Energies, 14(11), 3244.

Paraschivoiu, I. (1988). Double-multiple streamtube model for studying vertical-axis wind turbines. Journal of propulsion and power, 4(4), 370-377. https://doi.org/10.2514/3.23076.

Rahul, S., Sharma., Yashwant, Sawle. (2022). Economic Analysis of Pv/Wind Grid Connected Microgrid System. doi: 10.1109/catcon56237.2022.10077637.

Raihan, Selim & Bidisha, Sayema & Islam, Kazi & Hossain, Israt & Ahmed, Md. Tuhin & Chowdhury, Omar & Asaduzzaman, Mohammad & Aahad, Md & Surid, Takrem. (2024). Understanding the Renewable Energy Landscape in Bangladesh.

Rumi, Shammin., A., K., Enamul, Haque. (2022). Small-Scale Solar Solutions for Energy Resilience in Bangladesh. Insights from South Asia, 205-224. https://doi.org/10.1007/978-981-16-0680-9_14.

Saddamul, Islam., Mohammed, Tarique. (2022). The Implementation of Solar-Wind Cascading Power Station in Bangladesh. iRASD Journal of Energy & Environment, 3(2), 61-71.

Saifullah, M. K., Halder, R., Afroz, S., Shatil, A. H., & Ahmed, K. F. (2023). Design of an off-grid solar-wind-bio hybrid power generation for remote areas of chapainawabgonj district in Bangladesh using homer. In 2 3rd International Conference on Robotics, Electrical and Signal Processing Techniques (ICREST) (pp. 56-61). IEEE. https://doi.org/10.1109/icrest57604.2023.10070032.

Sakib, Bin, Amin., Mainul, Islam, Chowdhury., S.M., Asif, Ehsan., S.M., Zahid, Iqbal. (2021). Solar energy sustainability in Bangladesh: tackling the management challenges. In Design, Analysis, and Applications of Renewable Energy Systems (pp. 705-734). Academic Press.

Sakib, M. N., & Matin, M. A. (2023). Design of mini-grid for solar home systems with NPV in Bangladesh. In 2023 International Conference on Electrical, Computer and Communication Engineering (ECCE) (pp. 1-6). IEEE. https://doi.org/10.1109/ecce57851.2023.10101668.

Shafi, I., Khan, H., Farooq, M. S., Diez, I. D. L. T., Miró, Y., Galán, J. C., & Ashraf, I. (2023). An Artificial Neural Network-Based Approach for Real-Time Hybrid Wind–Solar Resource Assessment and Power Estimation. Energies, 16(10), 4171. https://doi.org/10.3390/en16104171.

Shiny, S., Beno, M. M., & Rex, C. E. S. (2023). Efficiency

Improvement in Smart grid using Enhanced Chaotic Crow Search Optimization. In 2023 Advanced Computing and Communication Technologies for High Performance Applications (ACCTHPA) (pp. 1-6). IEEE.

Shufian, A., Hoque, M. J. A. M., Kabir, S., & Mohammad, N. (2022). Modeling & Economical Analysis of Hybrid Solar-Wind-Biomass-H 2-based Optimal Islanding Microgrid in Bangladesh. In 2022 IEEE 10th Region 10 Humanitarian Technology Conference (R10-HTC) (pp. 61-66). IEEE.

Supti, S. A. (2022). Renewable Energy and Policy in Bangladesh. In 2022 IEEE 13th Annual Ubiquitous Computing, Electronics & Mobile Communication Conference (UEMCON) (pp. 0251-0256). IEEE. https://doi.org/10.1109/uemcon54665.2022.9965627.

Sven Teske, Tom Morris, and Kriti Nagrath, "100% Renewable Energy for Bangladesh: Access to Renewable Energy for All within One Generation," World Future Council, August 29, 2019, https://www.worldfuturecouncil.org/100re-bangladesh.

Syed, Wajjahat, Saleem, Kazmi., Muhammad, Imran, Sheikh. (2019). Hybrid geothermal–PV–wind system for a village in Pakistan. SN Applied Sciences, 1(7), 754. https://doi.org/10.1007/s42452-019-0643-9.

Tummala, S. K., Rakesh, G., Al-Kharsan, I. H., & Shah, P. K. (2023). Integration of solar and wind energy systems with PI and PID controller. In E3S Web of Conferences (Vol. 391, p. 01002). EDP Sciences. https://doi.org/10.1051/e3sconf/202339101002.

Vijay, Mudgal., Preeti, Singh., Sourav, Khanna., Chandan, Pandey., Victor, M., Becerra., Tapas, K., Mallick., K.S., Reddy. (2021). Optimization of a novel Hybrid Wind Bio Battery Solar Photovoltaic System Integrated with Phase Change Material. Energies, doi: 10.3390/EN14196373 .

Wang, J., & Azam, W. (2024). Natural resource scarcity, fossil fuel energy consumption, and total greenhouse gas emissions in top emitting countries. Geoscience Frontier.