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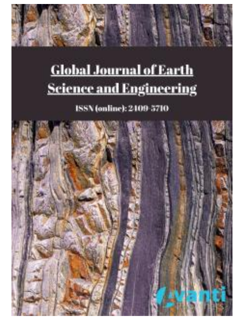

Review Study on Solar Energy in Bangladesh: Current Status, Challenges, and Future Prospects for Sustainable Development

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ABSTRACT

This review paper examines the current status, challenges, and future prospects of solar energy development in Bangladesh, with a focus on its integration into sustainable architecture and urban planning. Given Bangladesh's growing energy demand and vulnerability to climate change, solar energy is highlighted as a key renewable resource for enhancing energy security and reducing greenhouse gas emissions. The paper reviews major solar technologies- including rooftop photovoltaic systems, solar home systems, solar irrigation pumps, floating solar plants, and concentrated solar power-and evaluate their suitability across both urban and rural contexts. Based on a systematic review of recent studies and policy frameworks, the paper identifies major barriers to large-scale solar adoption, such as financial limitations, technical challenges, fragmented policies, and issues related to social acceptance. Despite these obstacles, the review emphasizes the significant social, economic, and environmental benefits of solar energy, including expanded rural electrification, improved public health, and reduced environmental pollutions. The study stresses the need for integrated approaches combining technological innovation, supportive and coherent policy frameworks, financial incentives and active stakeholder participation to accelerate solar energy deployment, particularly in response to Bangladesh's dense urban environment and climatic constraints. Finally, this study recommends future directions such as advanced energy storage systems, smart grid integration, life-cycle environmental assessments, and evaluation of social impacts. Overall, the paper aims to guide policymakers, researchers, and practitioners toward building a sustainable, resilient, and inclusive solar-powered Bangladesh.

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1. Introduction

A renewable energy source, solar energy is the sun's thermal radiation energy, which is mostly expressed as sunlight. The massive energy generated by the fusion of hydrogen nuclei at extremely high temperatures inside the sun is the source of solar energy. The sun provides the great bulk of the energy that humans require, either directly or indirectly.

Due to the more than 1°C increase in temperature since 1950 and the ensuing climate change challenges, which are linked to an approximate 80% increase in carbon dioxide (CO2) since 1970, industrial decarbonization has attracted international attention on the path to a net-zero carbon transition, as required by the Paris Agreement [1, 2]. The primary causes of yearly CO2 emissions are extensive deforestation and the use of fossil fuels for energy security [3].

The primary sources of global greenhouse gas (GHG) emissions, according to UN studies based on the EDGAR data repository, include energy sources for industrial sectors like transportation, manufacturing and construction, agriculture, and power and heat [4]. The electricity sector accounts for 38% of global CO_2 emissions caused by fossil fuels, followed by transportation (21%), non-combustion (10%), buildings (9%), and other industrial combustion (21%) [5].

The sun is classified among the brightest of the renewable energy sources in the world. It is now considered to be the long-term solution to many of the problems, such as national dependence on foreign fuels, environmental degradation, and economic development. The latter has been a sustainable resolution to a broad spectrum of issues linked to energy security, environmental degradation, and economic development. The growing concerns about global warming and the need to discover an alternative to the conventional fossil fuel-based sources of electricity have been added to the ever-growing data about the world's energy needs. Due to its cost-effectiveness, eco-friendliness, and endless potential, solar energy has been regarded as one of the most practical and expandable forms of power consumption in homes. Since a significant amount of energy demand in the world comes from domestic electricity consumption, the government has been promoting the use of solar photovoltaic (PV) systems by providing incentives, subsidies, and even raising awareness in different countries [6].

Despite these steps, the transition from conventional electricity to solar energy is not uniform across all homes. While there are long-term savings on electricity bills, energy security, and a carbon footprint associated with solar adoption, the upfront cost and the cost of an opportunity factor that influences the decision-making process are important considerations. When compared to traditional grid-based electricity, solar energy systems continued to be seen negatively by many families due to financial risk or technological uncertainty [7].

Solar energy is a potentially good but off-grid energy source that can help diversify Bangladesh's energy portfolio, as its energy potential is quite significant (4.0-6.0 kWh/m^2/day) (Fig. **1**). It has been integrated into the country to meet the growing demand [8, 9]. Bangladesh has set challenging goals for renewable energy power, where the country hopes to achieve about 10% renewable energy by 2021, which will increase to 17% by 2041, and solar energy will be an unavoidable component [10, 11].

Over the past few decades, the share of renewable energy sources in the world's energy mix has grown gradually but steadily. Even while renewable energy sources have a lot of potential, their sporadic nature can cause power supply fluctuations in the event of an unexpected shortfall [12, 13]. Therefore, it is clear that there are issues with the dependability of power systems that incorporate renewable energy sources. This is because most current power producing facilities are unable to react quickly enough to compensate for the losses brought on by renewable energy sources' intermittent nature [14]. On the other hand, any excess renewable energy must be limited in the absence of energy storage facilities, which immediately lowers the potential income of renewable energy farms. Energy storage devices are a feasible solution to the aforementioned problems in light of these factors [15, 16]. Through their time-shifting function, which stores excess renewable energy for later use, energy storage devices can match renewable energy with real-time demand. The intermittency and loss issues that frequently arise while generating electricity from renewable energy sources are successfully resolved by this approach [17].

Figure 1: Spatial distribution of average daily solar irradiance across Bangladesh, showing regional variation from 4.0 to 6.0 kWh/m²/day. The map demonstrates Bangladesh's favorable and relatively uniform solar energy potential for renewable energy deployment.

Finding ways to cut energy or other operating costs has been the goal of several studies [16, 18]. The efficient management of direct power and heat loads is a prerequisite for building energy flexibility. Flexibility in the electricity context is accomplished by controlling on-site generation, making direct changes to consumption plans, and managing energy charging and discharging. To lower the overall energy cost of buildings, Wei *et al*. [19] proposed a co-scheduling method for battery consumption, electric vehicle charging, and air conditioning. Flexible loads were categorized by Tang *et al.* [20] according to their purpose and possible contribution to building response technologies. Flexible sources and associated control techniques in building energy systems are outlined and discussed. The building structure's passive thermal storage capacity or the use of active thermal storage through charging and discharging provide flexibility in terms of thermal energy.

A considerable amount of research has been conducted to investigate the technical and economic viability of solar technologies in the local context. These are grid-connected photovoltaic (PV) systems, solar home systems (SHS), solar irrigation pumps, microgrids, floating photovoltaic systems, concentrating solar power (CSP), and emerging applications such as electric vehicle (EV) charging stations and virtual power plants [21-25]. As many studies have found that the socioeconomic benefits of switching to solar energy in Bangladesh are very high, especially in off-grid and rural communities, which are defined by the lack of credible electricity companies, the gains are enormous, especially in rural communities [26, 27].

However, even with the achievements, several obstacles remain, including funding, insufficient policy support, technical setbacks in the large-scale implementation, grid connection, as well as the issue of environmental sustainability and waste handling of solar PV [28-30]. Moreover, smart grids and energy storage systems need to be combined with advanced solar technologies to make the grid more stable and solar-penetrated [31, 32].

This review compiles recent articles and reports on the topic, synthesizing the research results of numbers of articles and reports to analyze the current situation, challenges, policy landscape, technology, and prospects of solar energy in Bangladesh. It is geared towards filling knowledge gaps by aligning technical, economic, social, and environmental outlooks. It provides policymakers, researchers, and other stakeholders with an opportunity to contribute to the creation of a sustainable and resilient solar energy future in Bangladesh.

The primary objective of this study is to provide a comprehensive and critical review of the current status, progress, and future potential of solar energy development in Bangladesh. To achieve this overarching goal, the study pursues the following specific objectives: i) To systematically review and synthesize existing literature on solar energy technologies implemented in Bangladesh, including rooftop solar, solar home systems, floating photovoltaic systems, solar irrigation, and emerging applications; ii) To analyze the evolution of solar energy policies, regulatory frameworks, and institutional mechanisms in Bangladesh and evaluate their effectiveness in promoting large-scale and decentralized solar adoption; iii) To assess the techno-economic feasibility of different solar energy systems, drawing on published case studies, feasibility analyses, and comparative evaluations across urban, rural, and industrial contexts; iv) To examine the socioeconomic and environmental impacts of solar energy deployment, with particular emphasis on energy access, employment generation, agricultural productivity, emissions reduction, and public health benefits; v) To identify key technical, financial, institutional, and social barriers that hinder the scaling of solar energy in Bangladesh, including grid integration challenges, financing constraints, policy fragmentation, and capacity limitations and vi) To highlight research gaps and emerging trends related to energy storage, smart grids, hybrid microgrids, digitalization, and lifecycle sustainability of solar technologies and vii) To propose strategic future research directions and policy priorities that can support a resilient, inclusive, and sustainable solar energy transition in Bangladesh.

2. Synthesis of Existing Research

The implementation environment of solar energy in Bangladesh has undergone rapid and multidimensional transformation, driven by advances in technology, evolving policy frameworks, and growing socioeconomic relevance. Recent literature consistently characterizes this transition as fast-paced and increasingly diversified, reflecting Bangladesh's emerging role within the global renewable energy landscape. International comparative studies position of Bangladesh as a high potential growth market for solar energy, while simultaneously emphasizing the need to accelerate institutional, technological, and financial reforms to sustain this momentum [33, 34].

At the technological level, solar photovoltaic (PV) deployment- particularly rooftop systems and solar home systems (SHS)-has expanded substantially, largely due to off-grid electrification programs and rural energy access initiative [35, 36]. These systems have not only improved electricity access but also reshaped household energy consumption patterns. In parallel, solar-powered irrigation pumps represent a transformative innovation within the agricultural sector, enhancing irrigation efficiency while significantly reliance on diesel-based pumping systems [37, 38]. Collectively, these applications demonstrate how solar technologies are being integrated into both livelihood and productivity-oriented sectors.

Policy interventions have played a decisive role in scaling these technological applications. The Renewable Energy Policy 2025 sets an ambitious target of achieving 30% renewable energy capacity by 2040, including a planned expansion of 3,000 MW of rooftop solar installations [39, 40]. Complementary mechanisms such as net metering and financial incentives have stimulated adoption among industrial and residential users. However, the literature also highlights bureaucratic complexity, financial constraints, and institutional inefficiencies continue to limit large-scale and rapid deployment [41, 42].

Beyond conventional PV systems, Bangladesh has begun exploring advanced solar technologies, including photovoltaic systems, concentrated solar power (CSP), and solar-powered electric vehicle (EV) charging infrastructure [43, 44]. Floating solar installations on water bodies such as Hatirjheel Lake offer a promising space-efficient solution in densely populated urban environments [45]. Meanwhile, CSP technology has been identified as a potential pathway for large-scale, dispatchable renewable energy generation, leveraging Bangladesh's favourable direct normal irradiance conditions, although economic and infrastructural feasibility remain key concerns [40, 41].

Recent studies increasingly emphasize the importance of energy storage systems, smart grids, and virtual power plants to enhance system stability and enable higher solar penetration levels [2, 37].

Despite these advancements, several structural challenges persist. High upfront costs, grid integration complexities, limited energy storage capacity, and the absence of comprehensive policies for PV waste and end-of-life management pose significant barriers to sustainable expansion [46, 47]. Recent studies increasingly emphasize the importance of energy storage systems, smart grids, and virtual power plants to enhance system stability and enable higher solar penetrative levels [48, 49].

From a socioeconomic and environmental perspective, solar energy development in Bangladesh has contributed to income generation, job creation, reduced greenhouse gas emissions, and improved public health outcomes through the displacement of fossil-fuel-based electricity generation [50, 51]. However, the literature also reveals a notable gap in comprehensive lifecycle sustainability assessments, particularly concerning environmental externalities and long-term system impacts, indicating a critical area for future research [46].

Fig. (**2**) synthesizes these interconnected technological, policy, economic, and socioeconomic dimensions into a unified framework. By adopting an integrative perspective, this review moves beyond isolated assessments to identify systematic gaps and strategic priorities, thereby providing a robust foundation for guiding future research and policy interventions towards a sustainable solar energy transition in Bangladesh.

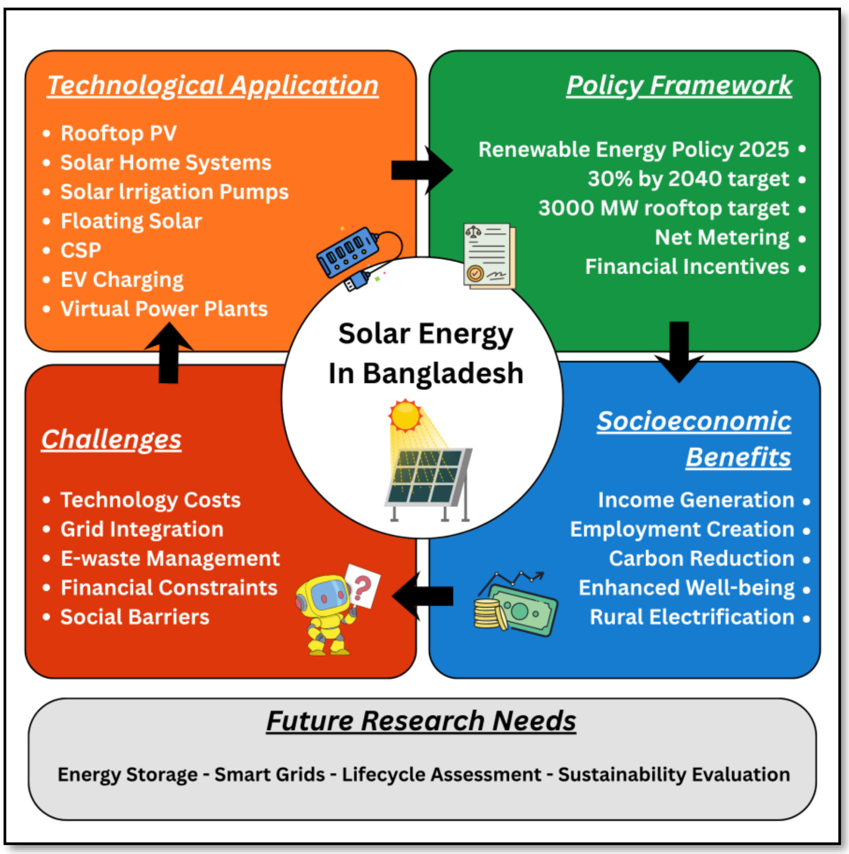

Figure 2: Comprehensive framework of solar energy implementation in Bangladesh, illustrating the interconnections between technological applications, policy initiatives, socioeconomic impacts, implementation challenges, and future research priorities.

Between 2018 and 2025, the quantitative comparison of solar energy technologies in Bangladesh highlights distinct performance, cost, and application profiles across different systems are explored in the following Table **1**.

Table 1: Quantitative comparison of solar energy technologies in Bangladesh (2018-2025).

Technology	Levelized Cost of Electricity (LCOE)	Energy Efficiency / Performance	Key Advantages	Limitations / Barriers	References
Rooftop PV systems	0.08 – 0.12 USD/kWh	Standard efficiency: 15–20%	Easy installation, scalable for households	Limited roof space, initial investment	[47, 49, 54]
Floating PV arrays	0.10 – 0.15 USD/kWh	Efficiency gain: ~5–10% above rooftop PV	Saves land, reduces water evaporation	Higher maintenance, corrosion risk	[50, 51, 55]
Concentrated Solar Power (CSP)	0.14 – 0.18 USD/kWh	Thermal efficiency: 25–35%	High energy yield, suitable for large-scale use	High capital cost, requires large land area	[50, 52]
Solar Home Systems (SHS)	0.12 – 0.16 USD/kWh	Typical capacity: 50–300 W	Off-grid electricity, accessible in remote areas	Limited power output, battery degradation	[47, 53, 56]
Solar Irrigation Pumps	N/A (cost per pump: 1000–2000 USD)	Energy efficiency gain: 20–35% vs diesel	Reduces fossil fuel use, increases crop yield	Seasonal dependence, u pfront cost	[48, 57, 58]
Solar + Microgrid Integration	0.09 – 0.14 USD/kWh	System efficiency: 18–22%	Supports community-level energy access	Requires coordination, higher system complexity	[51, 54, 58]
Solar EV Integration	N/A	Can supply 20–30 km/day per kW installed	Reduces fossil fuel dependence	Charging infrastructure needed	[50, 53]

Despite the expanding literature on solar energy deployment in Bangladesh, several critical research gaps persist. Existing studies remain largely fragmented and technology-specific, with limited system-level analyses integrating rooftop PV, solar home systems, floating PV, irrigation pumps, and emerging applications within a unified energy framework. Research on grid integration, energy storage optimization, and high solar penetration scenarios is insufficient, constraining informed planning for grid stability and resilience. Most techno-economic assessments rely on short-term simulations, while long-term empirical data on system performance, degradation, and lifecycle costs under Bangladesh's climatic conditions are scarce.

Policy analyses often discuss regulatory frameworks descriptively, but few quantitatively evaluate their impacts on adoption rates, investment behavior, or grid performance. Additionally, innovative financing mechanisms such as microcredit, blended finance, and risk-sharing models remain underexplored. Environmental sustainability assessments largely emphasize emissions reduction, overlooking PV waste management, recycling, and circular economy pathways. Finally, socio-technical dimensions—including social acceptance, capacity building, and digital optimization using artificial intelligence and smart grids—are inadequately addressed. Addressing these interconnected gaps is essential to transition Bangladesh's solar sector from access-oriented deployment toward an integrated, resilient, and sustainable energy system.

3. Methodology

This review synthesized information from numbers of academic sources published between 2018 and 2025 to provide a comprehensive overview of solar energy development in Bangladesh. The literature search involved systematic queries in scientific databases such as Scopus, Web of Science, Google Scholar, and institutional repositories, using keywords including solar energy Bangladesh; solar PV feasibility; renewable energy policy Bangladesh; solar home systems; floating photovoltaic power; concentrated solar power and solar irrigation pumps [47, 49]. The overall methodological workflow is summarized in Fig. (**3**).

The inclusion criteria comprised peer-reviewed journal articles, conference papers, and government and nongovernmental reports addressing solar energy application in Bangladesh, socio-technical implications, and policy frameworks. Emerging technologies, such as floating PV arrays, CSP plants, and solar integration with electric vehicles and microgrids, were prioritized [50-53]. Studies lacking relevance to Bangladesh or empirical/technical rigor were excluded.

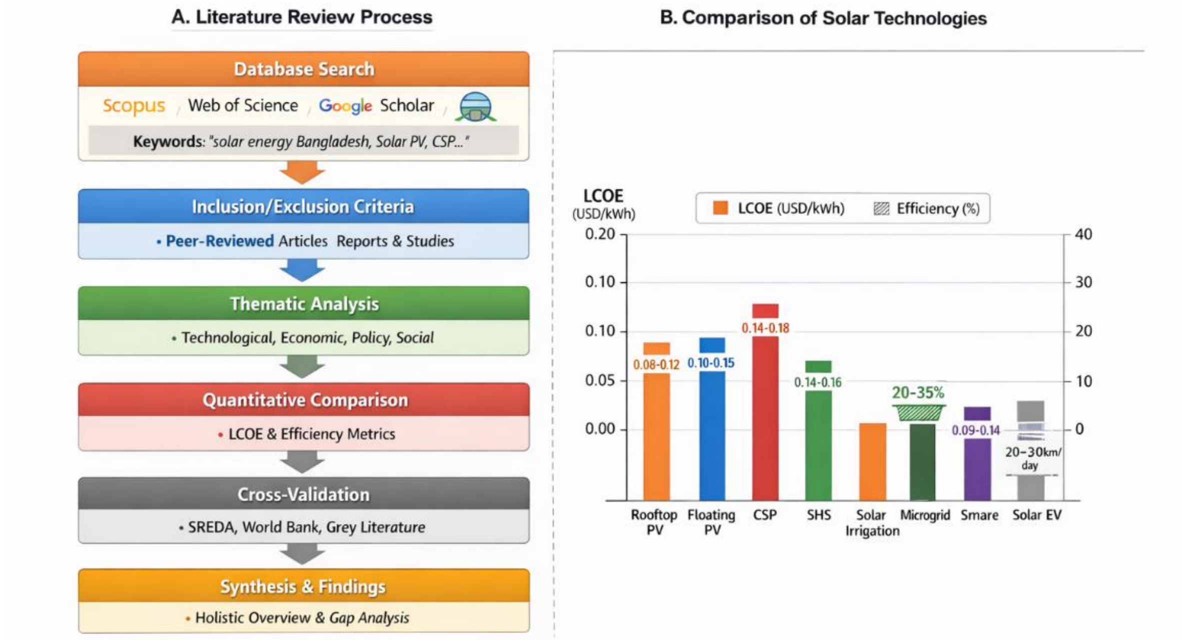

Figure 3: Illustration of the systematic methodology for literature selection, screening, thematic analysis, and synthesis in a review of solar energy research in Bangladesh (2018-2025).

The selected literature underwent thematic analysis, categorizing insights into technological advancements, economic feasibility, policy instruments, environmental and social benefits, and barriers to adoption [54-58]. Where possible, quantitative comparisons were extracted: for example rooftop PV systems were found to have a levelized cost of electricity (LCOE) ranging from 0.08–0.12 USD/kWh, whereas floating PV arrays ranged from 0.10–0.15 USD/kWh, and CSP plants had a higher LCOE of 0.14–0.18 USD/kWh. Solar irrigation pumps demonstrated energy efficiency gains of 20–35% compared to diesel-powered pumps. These comparisons enabled critical evaluation of the relative efficiency, cost-effectiveness, and scalability of different approaches.

Accounting for differences between positive and null outcomes enhances the robustness and general scientific interest of the review [50, 51]. Potential publication bias and study scope limitations were addressed through cross-validation with grey literature, technical reports, and policy documents from organizations such as SREDA and the World Bank [59, 60]. Accounting for differences between positive and null outcomes enhance the robustness and general scientific interest of the review [50, 51].

4. Results and Discussion

4.1. Technological Advancements in Solar Energy

The utilization of solar energy in Bangladesh has been substantial technological progress, reflecting both diversification and adaptation to local contexts. For instance, solar micro-grid networks in island communities not only provide sustainable energy access but also demonstrate socio-economic benefits by improving living standards [52]. Compared with conventional off-grid solutions such as rooftop photovoltaic (PV) systems and solar home systems (SHS), these micro-grids offer a more integrated approach, combining energy access with community development [53-55]. This suggests that solar technology in Bangladesh is evolving beyond more electrification toward holistic socio-technical interventions.

Emerging high-tech solutions, such as floating PV power plants, indicate an innovate use of space constraints in urban and water-rich areas like Hatirjheel Lake [45, 46, 61]. These systems offer higher energy density and operational efficiency than conventional ground-mounted PVs. The comparative advantages of floating PV over rooftop installations lies in its ability to mitigate land scarcity, reduce urban heat, and integrate with water bodies, thereby linking environmental and energy management objectives. Similarly, offshore solar projects in coastal regions have been identified as techno-economically viable and environmentally sustainable [62], highlighting the potential for geographically targeted solutions. In combination with battery storage, micro-grids employing these technologies enhance resilience in energy-dependent infrastructure, such as data centers, indicating a trend toward multifunctional energy systems [63]. The principal technological domains and their interconnections are depicted in Fig. (**4**).

The Concentrated Solar Power (CSP) represents another avenue for large-scale energy generation with reduced carbon footprints. While it is potential in Bangladesh is significant, widespread adoption requires addressing financial and technical barriers [64]. Studies suggest that regions with sufficient direct normal irradiance can benefit from CdTe solar modules to stabilize grids and mitigate peak demand issues [40, 41]. This emphasizes the importance of matching technology type with local climatic and infrastructural conditions to maximize performance.

The adoption of solar-powered irrigation systems in northern Bangladesh demonstrates not only environmental benefits but also economic feasibility, confirming their role as climate smart solutions [42, 43, 65]. Compared to diesel-based irrigation, solar pumps reduce fuel dependency and operational costs, highlighting a clear synergy between agricultural sustainability and renewable energy deployment. Similarly, urban-scale interventions such as rooftop PVs on metro rail stations in Dhaka indicate the potential for high energy yield and cost reduction, illustrating how solar technologies can be scaled across both rural and urban contexts [66].

Integration with electric vehicles (EVs) and virtual power plant (VPPs) represents the next frontier in intelligent energy management. Tools like PVsyst, Homer, and RET screen allow real time techno-economic optimization, enhancing the planning and performance of PV systems [67]. Case studies such as Gazipur illustrates how EV charging stations powered by solar can function as decentralized urban energy hubs, bridging the gap between mobility and electric supply [68]. The Rickshaw VPP, which leverages EV batteries in two- and three-wheelers, exemplifies how decentralized technologies can provide grid flexibility and empower end-users [69, 70]. Collectively, these innovations indicate a shift from conventional centralized energy generation to distributed, adaptive, and user-integrated systems.

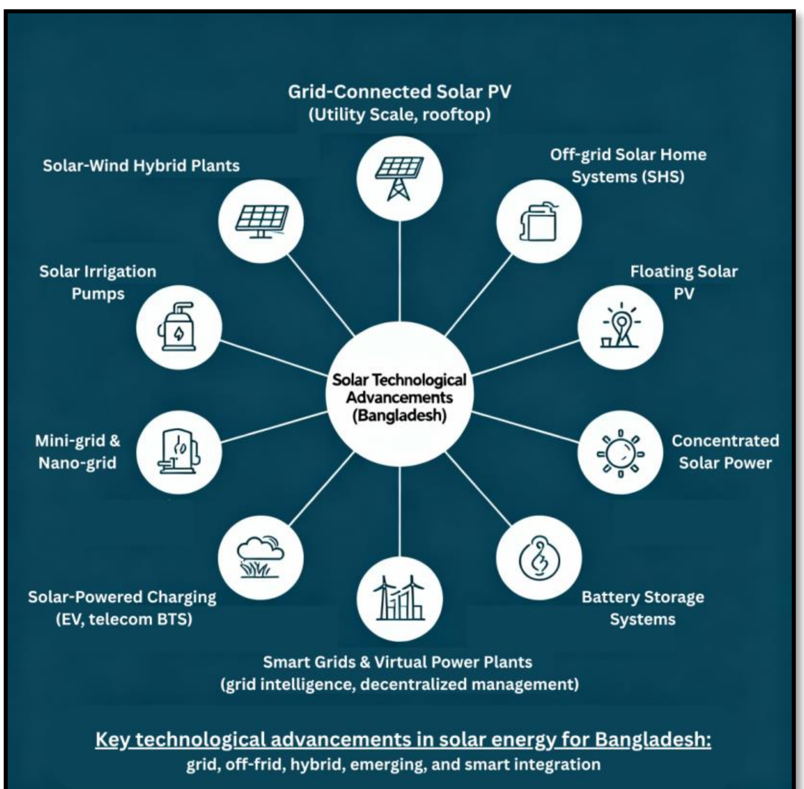

Figure 4: Key technological advancements in solar energy deployment in Bangladesh.

Overall, the synthesis of these studies suggests that technological advancements in Bangladesh's solar sector are not isolated developments but part of an interconnected ecosystem. Rural micro-grids, floating PV, CSP, solar irrigation, and EV-integrated VPPs collectively demonstrate the multidimensional potential of solar energy—enhancing energy access, economic viability, environmental sustainability, and socio-technical resilience. The emerging pattern highlights those future strategies should prioritize hybrid and context-specific solutions rather than one-size-fits-all implementations, ensuring optimal socio-economic and environmental outcomes.

4.2. Policy Framework and Implementation

The Government of Bangladesh has undertaken several policy initiatives to accelerate their solar energy deployment, most notably through the Renewable Energy Policy 2025, which sets an ambitious target of achieving 30% renewable energy share by 2040 and scaling rooftop solar capacity to 3,000 MW [41, 42]. With this policy signals strong political intent, its effectiveness varies across sectors. Industrial solar adoption-supported by net metering regulations and fiscal incentives- has shown relatively faster uptake compared to residential systems. However, bureaucratic bottlenecks, complex approval processes, and limited access to affordable financing continue to constrains large-scale diffusion, particularly among small and medium consumers [40] (Fig. **5**). This highlights a structural gap between policy ambition and implementation capacity.

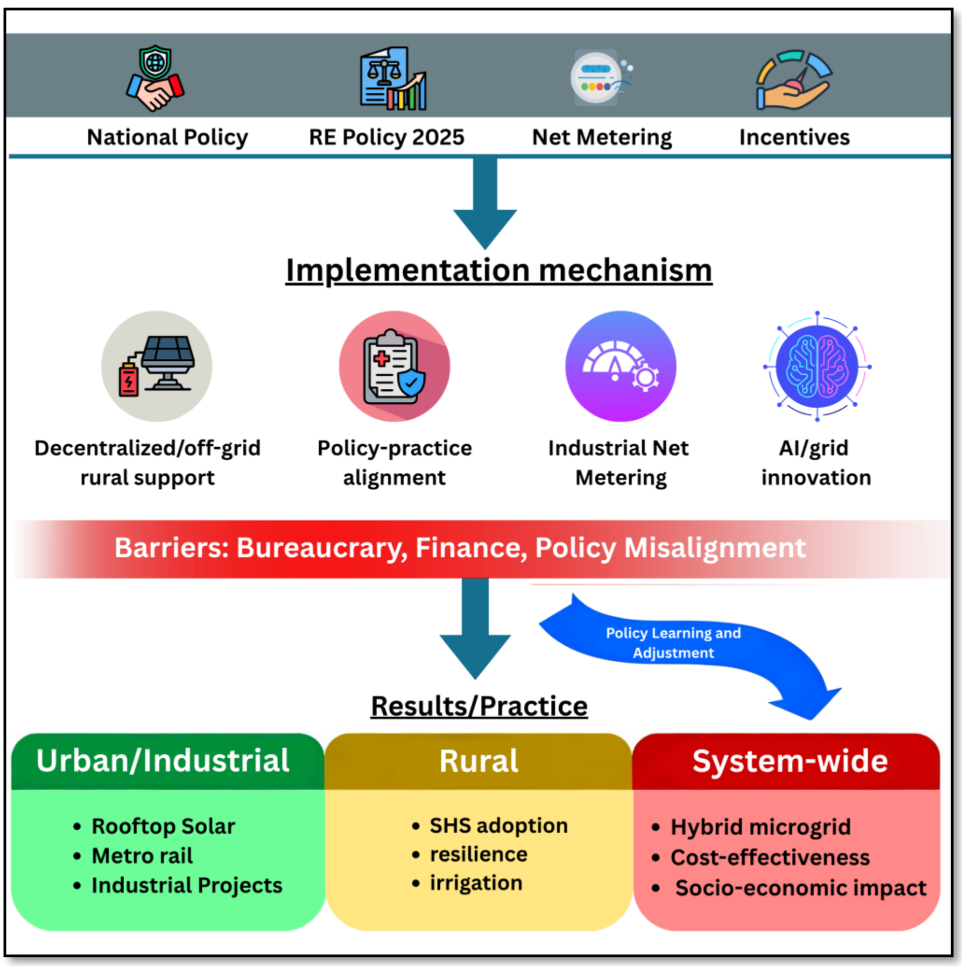

Figure 5: Policy-to-practice pathways for solar energy implementation in Bangladesh.

Policy emphasis has also been placed on decentralized off-grid solutions, such as solar home systems (SHS) and rural microgrids, which have played a critical role in expanding electricity access in remote regions. Despite their success, these systems often operate in isolation from national energy planning and long-term grid expansion strategies, creating fragmentation and limiting scalability [71, 72]. The lack of institutional integration raises concerns about sustainability once grid connectivity reaches these areas. Hybrid renewable microgrids offer a compelling pathway to address these limitations. Case studies such as the Kutubdia island hybrid microgrid-where solar is combined with other renerwable resources-demonstrate improved energy reliability, reduced generation costs, and enhanced system resilience in geographically isolated locations [73]. Comparative analyses suggest that hybrid configurations outperform single-source solar systems in terms of both economic viability and supply stability, particularly in climate-vulnerable coastal regions.

Recent research also points towards a paradigm shift in policy and system optimization through the application of artificial intelligence. AI-driven forecasting demand management and performance optimization tools have the potential to improve both technical efficiency and policy outcomes by enabling data-informed decision making in Bangladesh [74]. When coupled with advanced grid technologies and energy storage, solar generation can contribute to a more resilient and adaptive power system capable of managing intemittency and peak demand [75]. Synthesizing these findings, it becomes evident that the future of electrification and decentralized energy systems in Bangladesh lies in integrated hybrid solar based solutions rather than standalone technologies. Studies consistency show that hybrid microgrids are more sustainable and cost-effective over the long-term, reinforcing the need for policy frameworks that promote system integration, digital optimization, and alignment between off-grid and national energy strategies [45]. In short, Bangladesh's solar policy trajectory must now shift from expansion-focused targets to coordination, resilience, and intelligent system design—otherwise, ambition risks outpacing impact.

4.3. Economic Feasibility and Financial Barriers

Economic analysis across the literature consistently indicates that solar energy in Bangladesh has become increasingly competitive, driven because of a decrease in the price of the panels, along with high efficiencies [41, 42]. These cost reductions have shifted in the literature on viability analysis of grid-connected and off-grid solar power from a subsidized alternative to a financially attractive mainstream option. Comparative various studies of both grid-connected and off-grid systems reveal favourable returns on investment, particularly when supportive, it is easy to find the lucrative returns on the investments with conducive policy frameworks and accessible ies and financing mechanisms are in place systems [30, 31]. This demonstrates that policy design and financial structures are decisive factors in translating technical fesibility into economic success.

Among available deployment models, one such effective remedy for energy in Bangladesh is solar systems on the rooftop solar systems emerge as one of the most effective solutions for Bangladesh's energy transition. Multiple studies suggest that the scale of, which are currently being studied to demonstrate that the size of potential rooftop adoption is substantial, offering simultaneous will be significant and potentially beneficial to the environmental benefits through emission reductions and economic gains via distributed generations [75]. Most importantly, Iin the urban centres of Bangladesh, where electricity demand and rooftop availability are high, rooftop solar presents a particularly strong economic case. Recent analysis indicate that improved regulatory clarity and market-oriented policies can further accerlerate adoption by reducing transaction costs and driving price competitiveness is plainly huge and is making more progress with a better policy that will push the market to grow and lower the prices [76]. At the utility scale, feasibility assessment of grid-connected solar installations-such as the economic potential indicates encouraging economic outcomes of a 1.5 MW power grid-connected solar plant-report robust economic performance, reinforcing the role of, a feasibility study, which confirms the role of solar in the energy as a viable contributor to change of Bangladesh's long-term energy transition [77]. These findings collectively suggest that solar power can compete with conventional energy sources under current market conditions. Despite these positive economic indicators, high upfront Nonetheless, initial capital costs remain a critical barrier, particularly for small scale that is not yet available to most small users and households. The literature emphasizes the need for innovative financing mechanisms, including, which requires some inventive funding, such as microcredit schemes, blended finance models, and purpose-driven public-private partnerships, to unlock broader participation in the solar market-based alliances [45] (Fig. **6**). Without addressing these financial entry barriers, the economic potential of solar energy risks remaining concentrated among large investors rather than achieving inclusive, nationwide impact (Fig. **6**).

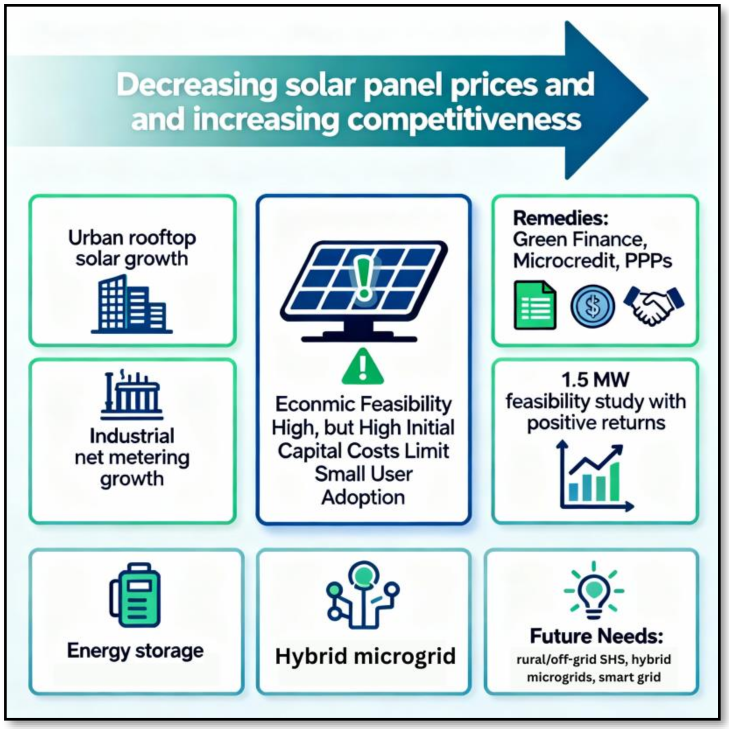

Figure 6: Economic feasibility and financial barriers for solar energy in Bangladesh.

4.4. Socioeconomic and Environmental Impacts

Solar energy deployment in Bangladesh has generated wide-ranging socio-economic benefits that extend beyond electricity access. Empirical studies report positive impacts on income generation, employment creation, , and public health, particularly through reductions in indoor air pollution associated with traditional biomass and kerosene use [75, 76]. These outcomes highlight solar energy's role as a development intervention rather than merely an energy technology, especially in low-income and energy-poor communities.

In urban contexts, solar powered auto-rickshaw charging systems demonstrate a dual benefit by reducing air pollution while simultaneously supporting a transition toward cleaner urban transportation systems [77]. Compared with conventional fuel-based charging, these systems contribute to improved air quality and lower operating costs for drivers, illustrating how decentralized solar solutions can directly influence livelihoods and environmental quality in densely populated cities.

At the rural scale, solar irrigation pumps represent a transformative intervention in agricultural practices. Studies indicate that their adoption reduces dependence on diesel, lowers operational costs, and supports sustainable farming, thereby improving food security and strengthening rural economic resilience [40]. The literature consistently emphasizes that access to reliable solar-powered irrigation not only increases crop productivity but also empowers farming communities by reducing exposure to volatile fuel prices.

From an environmental perspective, solar energy contributes significantly to greenhouse gas (GHG) emission reductions by displacing fossil-fuel-based electricity generation, aligning with Bangladesh's national climate commitments [75, 78]. Case -specific assessments from Dhaka quantify measurable reductions in GHG emissions attributable to solar PV installations, providing empirical validations of their climate mitigation potential [79]. These findings reinforce solar energy's strategic importance in both mitigation and urban sustainability agendas.

However, the literature also cautions that long -term environmental sustainability requires addressing emerging challenges related to solar PV lifecycle impact. Issues such as end-of-life panel management, recycling infrastructure, and waste handling remain underexplored and weakly regulated in Bangladesh [80, 81]. Without proactive planning, the environmental gains achieved through emissions reduction may be partially offset by future waste management problems (Table **2**).

Table 2: Socioeconomic and environmental impacts of solar energy projects in Bangladesh.

Impact Category	Positive Effects	Specific Examples / Evidence	Challenges / Additional Needs
Income & Employment	Increased income and job creation	Auto-rickshaw solar charging systems creating urban jobs	—
Public Health	Improved health outcomes via reduced indoor pollution	Reduced indoor air pollution levels	—
Urban Environmental	Reduced air pollution from cleaner transportation	Cleaner air in urban centers due to solar-powered transport	—
Rural Agriculture	Enhanced food security via solar-powered irrigation	Solar irrigation pumps empowering rural farmers	—
Greenhouse Gas Reduction	Cutback in emissions through reduced fossil fuel use	Dhaka case study evidencing measurable GHG reduction	—
Environmental Concerns	Lifecycle environmental impact and waste management	Need for solar PV waste handling and recycling policies	Development of waste management infrastructure and standards

Synthesizing these findings, it is evident that solar energy in Bangladesh delivers substantial socioeconomic and environmental co-benefits, ranging from improved health outcomes and livelihood opportunities to climate mitigation and agricultural sustainability. Nevertheless, maximizing these benefits requires an integrated approach that couples solar deployment with environmental governance, circular-economy strategies, and inclusive development planning. In this way, solar energy can evolve from a clean power solution into a comprehensive driver of sustainable development.

4.5. Challenges and Barriers to Scaling Solar Energy

Despite significant technological progress and favorable economic trends, the large-scale expansion of solar energy in Bangladesh continues to face a compelx set of interrelated challenges. On the technical front, grid integration remains a major constraint due to the intermittent nature of solar generation, limited grid flexibility, and insufficient energy storage capacity to absorb variable outputs [40, 41]. These challenges are amplified by the country’s aging grid infrastructure, which was not originally designed to accommodate high penetration levels of variable renewable energy.

System reliability is further affected by issues related to photovoltaic panel degradation and ageing. Studies emphasize that long-term performance losses, if not properly managed, can undermine both the economic returns and sustainability of solar installations [82]. This highlights the need for standardized maintenance protocols. Performance monitoring, and life cycle management strategies-areas that remain underdeveloped in the current deployment landscape.

Institutional and policy-related barriers compound these technical challenges. Policy fragmentation, overlapping mandates, and limited institutional capacity hinder effective implementation and coordination across sectors [45]. While multiple incentives and programs exist, their inconsistent application often results in regulatory uncertainty, discouraging private investment and slowing project execution. In this context, governance weakness emerges as a critical bottleneck, even where technology and market demand are strong.

Financial constraints remain among the most significant barriers, particularly for small-scale users and low-income households. High upfront capital costs, limited access to low-interest credit, and underdeveloped financial instruments restricts broader participation in the solar market [83]. These constraints are especially pronounced in rural areas, where income instability and risk aversion further reduce adoption, despite the long-term cost savings associated with solar systems.

Beyond technical and financial issues, social acceptance and human capacity building are frequently underemphasized yet essential for sustained adoption. The literature consistently highlights the importance of community engagement, local technical training, and awareness building initiatives to ensure system ownership, proper maintenance, and long-term functionally [84, 85]. Without adequate social integration, even well-designed solar projects risk underutilization or premature failure (Fig. **7**).

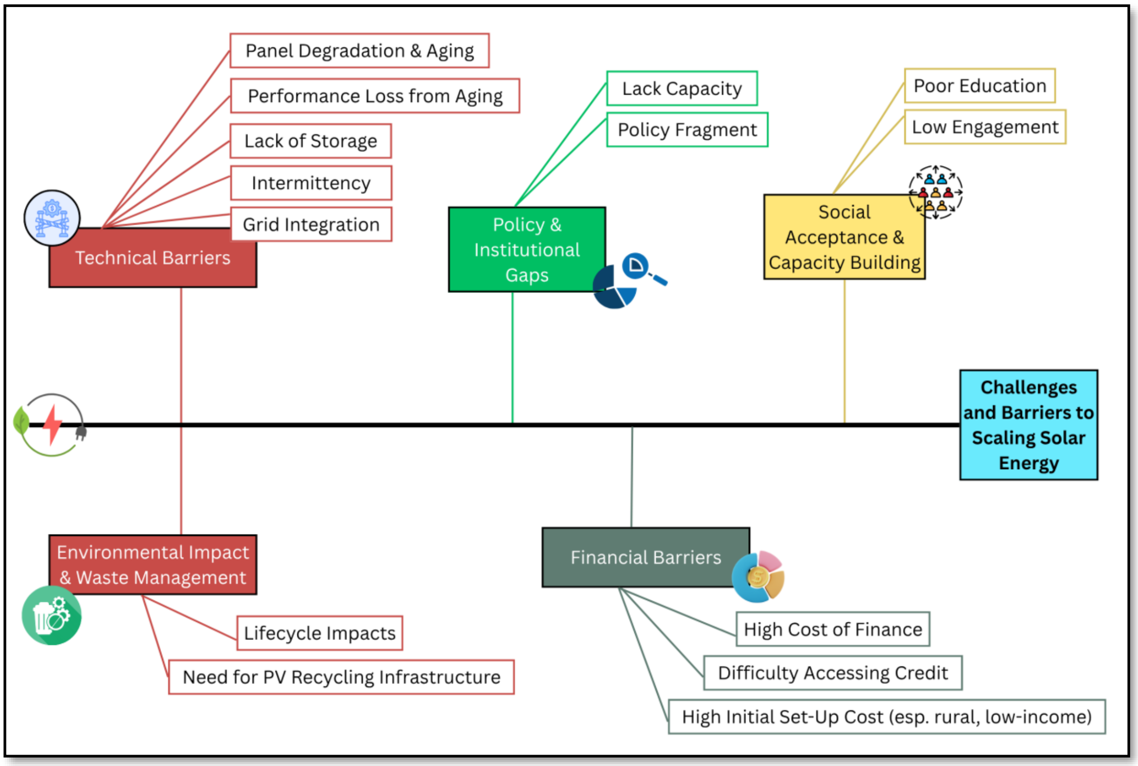

Figure 7: Fishbone (Ishikawa) diagram illustrating major challenges and barriers to scaling solar energy in Bangladesh.

Synthesizing these findings, it becomes evident that barriers to scaling solar energy in Bangladesh are systemic rather than isolated. Technical limitations, financial constraints, institutional weaknesses, and social factors reinforce one another, creating a cycle that slows deployment despite favorable market conditions. Overcoming these challenges will therefore require coordinated solutions—combining grid modernization, financial innovation, institutional reform, and community-centered approaches—rather than piecemeal interventions.

5. Strategic Directions for Future Solar Energy Research in Bangladesh

About the general analysis of the solar energy development in Bangladesh, specific crucial findings are pointed out and research priorities that can be suggested to aid in the further establishment of solar energy integration in Bangladesh.

First of all, strong emphasis should be placed on policies. The essential number of particular advancements in the state institutions, the decreased expenditure in the controlling process, and the amount of funds increase, also might be essential to the realization of the integration of the use of solar [40, 41]. They must also solve the problem with the expansion of net metering, the subsidies of low-income households, and the cultivation of renewable energy startups to make the market grow and innovate [86].

Second, the technical problems must be resolved. The grid infrastructure investments, energy storage, and smart grid technology are to be invested in to support high solar PV penetrations to overcome the problem of intermittency [87]. High potential would be seen in the development of battery storage technologies in off-grid hybrid microgrids to enhance the capacity of the system to be efficient and sustainable in a vast spectrum of rural localities in Bangladesh [88]. The emphasis should be put on the hybrid systems (solar and some other renewables or storage) as requiring improvement to be more reliable and cost-effective [42].

The financing mechanism should be diversified to overcome the barrier of the initial cost. The gaps may be closed with specialized green finance, micro credit and public-private collaboration, particularly with rural and small-scale clients who are currently not sufficiently served by the legacy finance [89, 90]. The expansion of the business models that were tested as part of SHS programs to other solar subsectors is an opportunity to replicate the action [80].

The topics of social acceptance and community need to be addressed both by means of sensitization programs and capacity building, and the approach to the project design that involves empowering the local stakeholders [81, 82].

The concerns regarding environmental sustainability will be holistically included. The government and industry should be involved in the development of solar PV waste management and recycling, and its standard and infrastructure to mitigate the potential ecological impact [91, 92].

Further research is to be conducted to:

1) New solar technologies in the scenario in Bangladesh (floating PV, CSP, solar-powered EV infrastructure) should be evaluated technologically-economically (in detail) to make investment decisions [93].
2) Social evaluation of the possibility of solar energy to decrease poverty and women's empowerment in other regions [80, 81].
3) Integrated research, which is interested in multi-sectoral advantages and difficulties of solar irrigation systems in agricultural activities [82-84]. Modular DC nanogrids are novel in offering effective, scalable solar-based energy control to off-grid nodes that facilitate energy availability in remote Bangladesh [94].
4) An original grid integration strategy that will integrate solar and energy storage, demand response, and distributed generation to run the grid [70, 71].
5) Reviews of the policy impacts to identify the performance after some intervals and recommend a reform in order to respond to the changes in the markets and technologies [50, 51].

With these suggestions, Bangladesh stands a chance to stabilize its path with a robust and environmentally friendly future, as solar energy will be applied on a grand scale when its sustainable use is adopted (Table **3**).

6. Sustainability for Solar Energy Development

System-level optimisation and long-term sustainability should be the focus of future solar energy research in Bangladesh, rather than deployment-focused studies. High-penetration grid integration is an important area of study, especially when it comes to intermittency, voltage stability, and frequency management under growing solar participation. Insufficient research has been done on advanced modelling of smart grids, hybrid renewable systems, and large-scale energy storage that is adapted to Bangladesh's grid restrictions.

The study of decentralised and hybrid energy systems is another top goal. Only a small amount of research has looked at the long-term operational performance, governance structures, and scalability of solar-based microgrids, despite previous studies confirming their techno-economic viability. For rural and island electrification options, comparative studies assessing solar-only, hybrid renewable, and grid-interactive microgrids in various geographic and socioeconomic contexts would be helpful.

Research in economics and finance must also advance. Innovative financing strategies like blended finance, pay-as-you-go models, green bonds, and carbon-linked incentives should be examined in future research to determine how well they lower entry barriers for low-income people and small businesses. In particular, longitudinal studies that compare the risk profiles and lifespan costs of various financing options are required.

Table 3: Summary of key recommendations and future research directions for solar energy development in Bangladesh, detailing policy, technical, finance, social, environmental priorities, and specific research needs to guide effective solar integration and sustainable energy transition.

Area	Key Recommendations	Priority Research Directions
Policy & Governance	- Reform institutions - Reduce administrative costs - Increase funding - Expand net metering - Support RE startups - Subsidize low-income adoption	- Assess impact of net metering and subsidies - Policy reviews and reform proposals
Technical Solutions	- Invest in grid upgrades - Promote energy storage - Advance smart/grid tech - Support hybrid solar/storage systems	- Battery/off-grid microgrid research - Technology evaluation (PV, CSP, floating PV) - Integrated solar irrigation systems - Grid integration strategies
Finance Mechanisms	- Diversify green finance - Expand microcredit - Foster PPPs - Scale proven business models (from SHS experience)	- Financing models for rural & small-scale users - Replication of SHS success - Green banking adoption
Social/Community Engagement	- Run sensitization programs - Build local capacity - Empower communities/stakeholders	- Solar's role in poverty reduction - Women's empowerment studies - Social acceptance research
Environmental Sustainability	- Develop PV waste management/recycling - Set standards/regulation - Mitigate ecological impacts	- Life-cycle assessment - Long-term sustainability impacts
Integrated/Advanced Research	—	- Tech-economic analysis of advanced solar (floating PV, CSP, solar EV) - Multi-sector evaluation in agriculture - Modular DC nanogrid deployment - Policy performance reviews and market/tech adaptation

More studies on regulatory efficacy and institutional coordination are needed from a policy standpoint. Finding gaps between the design and execution of policies can be aided by empirical assessments of net metering, subsidy programs, and renewable energy targets. Decentralised solar projects and national energy plans would better match with scenario-based policy modelling, which would encourage evidence-based decision-making.

Another new area of study is environmental sustainability. As solar deployment picks up speed, little is known about recycling technologies, circular economy frameworks, and PV module end-of-life management in Bangladesh. To guarantee that long-term environmental advantages are maintained, life-cycle assessment studies that take into account local trash infrastructure and environmental conditions are crucial (Fig. **8**).

Last but not least, despite their disruptive potential, digitalisation and artificial intelligence are still not fully explored in present research. To improve system resilience and efficiency, future research should examine AI-driven forecasting, demand-side management, predictive maintenance, and policy optimisation tools. Bangladesh may transition from reactive energy management to adaptive and intelligent energy systems by combining digital solutions with solar energy planning.

In general, engineering, economics, policy, and social sciences should all be integrated in future study using an interdisciplinary and systems-oriented approach. Transforming Bangladesh's solar potential into a resilient, inclusive, and sustainable energy transition requires such a strategy.

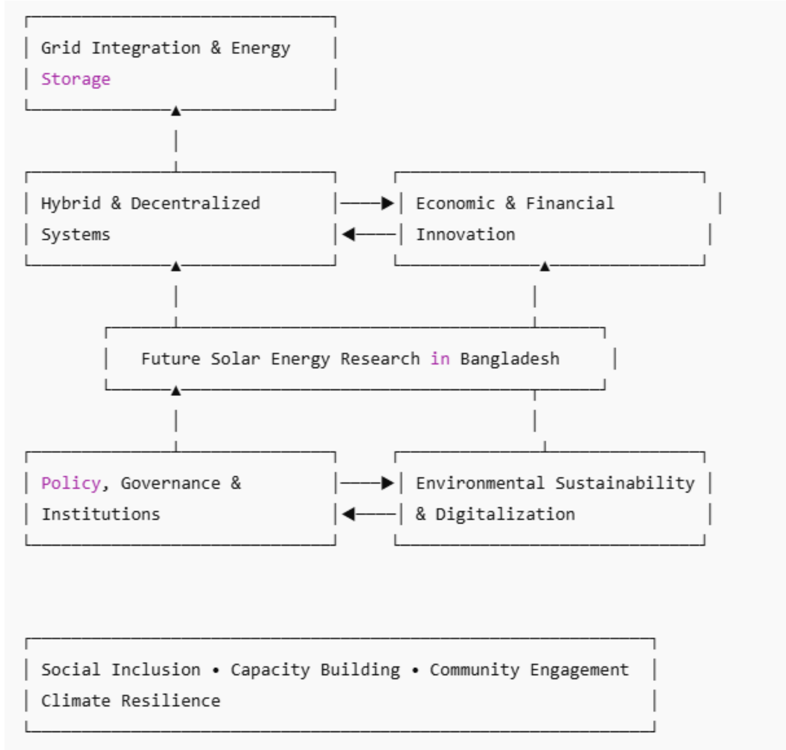

Figure 8: Sustainability of solar energy development and research opportunity in Bangladesh.

7. Conclusions

This review study brings a generative overview of the development of solar energy in Bangladesh, with the significant technological improvements, policy impacts, economic limits, social advantages, and unremitting difficulties. The proliferation of solar photovoltaic technologies such as rooftop, solar home, floating photovoltaics, and other new forms of concentrated solar power is an indication of the progressive development of energy diversification and sustainability in Bangladesh. Bangladesh's increasing energy needs might be met by solar energy, which would also help with climate change mitigation and sustainable development. The deployment of solar household systems, rooftop photovoltaics, and solar irrigation technologies has advanced significantly, but there are still a number of obstacles to overcome, such as high upfront prices, poor infrastructure, a lack of technical expertise, and difficulties implementing policies. Solar energy adoption can be accelerated by addressing these issues with robust government backing, corporate sector participation, public awareness campaigns, and ongoing research and innovation. Solar energy has the potential to significantly improve Bangladesh's socioeconomic development, environmental sustainability, and energy security with careful planning and dedication. If coordinated efforts are undertaken to remove current obstacles and take advantage of the nation's plentiful solar resources, solar energy has a bright future.

In the case of renewable energy, the government’s policy has provided a strong base. However, more coordination, support systems, and new funding facilities are important to achieve the grandeur of renewable energy in the country. High-resolution GIS analyses support it by refining the solar PV potential estimates and therefore help with more precise planning and policy decisions).

Solar energy is also used to promote inclusive development through socioeconomic benefits, including better rural electrification, income generation and mitigation of climate change. However, long-term resilience goals towards such technical issues as grid integration, energy storage, and environmental issues, such as waste management, are supposed to be taken into account.

The review highlights the fact that improved research, a change in policy, and collaboration among the stakeholders are necessary to help the nation of Bangladesh realize the potential of solar energy. The practical implementation of the recommendations provided will help to hasten the shift towards the sustainable, safe, and fair future of energy and comply with worldwide climate targets and national priorities in the nation's development.

In conclusion, Bangladesh stands at a critical juncture where solar energy can evolve from incremental deployment to a cornerstone of a resilient, low-carbon energy system. Achieving this transformation will depend on shifting from fragmented interventions toward coordinated, intelligent, and people-centered energy strategies.

Conflict of Interest

The authors declare that there are no competing interests.

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