

Evaluation of Renewable Energy Pathways for Bangladesh Based on a Multi-Dimensional Analysis of Institutional Energy Demand Vis-à-vis Socio-Economic Indicators and Income level

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Abstract: Bangladesh is at a critical stage in its energy transition, facing increasing institutional energy demand while ensuring affordable and equitable energy access across different income groups. This study evaluates renewable energy pathways for Bangladesh's built environment through a multidimensional assessment of major building sectors. Using a multi-criteria decision-making framework, the research assesses the technical, economic, and environmental performance of five renewable energy technologies: solar photovoltaics, wind, hydropower, biomass, and geothermal energy. The evaluation incorporates factors such as capital cost, operational feasibility, lifespan, carbon footprint, and strategic benefits, while also examining the relationship between energy consumption, household energy expenditure, income levels, and national energy tariffs. The findings identify solar photovoltaics as the most suitable renewable energy option for Bangladesh due to its scalability, declining costs, and compatibility with both urban and rural energy systems. This research also provides a context-specific framework for advancing Bangladesh's energy transition by aligning renewable energy deployment with socio-economic resilience, institutional capacity, and sustainable development goals, recommended valuable guidance for policymakers, professionals, and energy stakeholders.

Keywords: Renewable Energy, Carbon Footprint, Energy Expenditure, National Energy Tariffs, Solar Photovoltaics, Bangladesh's Energy Transition, Urban and Rural Energy Systems.

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I. INTRODUCTION

Renewable energy is generally defined as energy collected from resources that are naturally replenished on a human timescale. These self-replenishing sources of electrical energy are characterized by a significantly lower carbon footprint than traditional fossil fuel-based generation methods. The renewable generation sector has experienced rapid and transformative growth over the past decade, driven by technological advancements, economic scaling, and the critical imperative to mitigate global climate change. [1]

As global populations expand and urbanization accelerates, energy generation is no longer confined to remote industrial facilities. Buildings are related to a significant portion of the world's energy consumption and environmental degradation. [2] Modern architectural and engineering practices increasingly embed passive design with renewable energy systems directly into the built environment, spanning a building's design, construction, and operational lifecycle to reduce reliance on non-renewable fossil fuels. [3] Passive architecture is a design approach that uses natural elements such as sunlight, wind, shading, temperature variations, and greenery to maintain indoor comfort while minimizing energy use, through climate-responsive design, building orientation, form, and materials, it enhances energy efficiency and environmental sustainability with incorporating the greening system. This greening system plays a vital role in cleaning up the air, adjusting the microclimate, eliminating noise, beautifying the surroundings, etc. Apart from these benefits, they also support the construction of high-quality human settlements, since green spaces act as the “lungs” of the city. [4]

➤ Objectives:

• Broader:

The broader objectives of this study are anchored in the pursuit of sustainable energy transition within the developing economy context of Bangladesh.

• Specific:

To operate the broader aims, this study pursues the following specific objectives:

- ✓ To assess energy consumption patterns across major building occupancy types in Bangladesh and identify renewable energy integration opportunities.
- ✓ To compare renewable energy technologies using multi-criteria indicators such as cost, lifespan, suitability, and carbon footprint.
- ✓ To analyze Bangladesh's key socio-economic energy indicators, including per capita energy use and energy costs.
- ✓ To evaluate tools and methods for the design, simulation, and management of integrated renewable energy systems in the built environment.
- ✓ To develop strategic recommendations for renewable energy deployment, demand-side management, smart grid integration, and hybrid microgrids in Bangladesh.

➤ Conceptualization:

To conceptualize this issue in Fig. 01, it is necessary to bridge the gap between large-scale energy production models and local, architectural implementation. To effectively provide a deep understanding of this transformation, the study analyzes how energy systems are physically and functionally integrated with the built environment. The conceptualization of this study is discussed below:

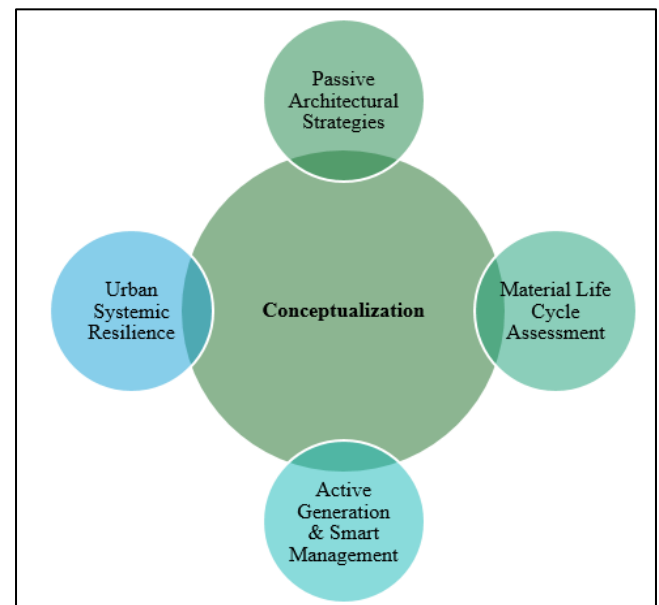


Fig 1 Conceptualization of Renewable Energy Used

• Passive Architectural Strategies:

Establish baseline energy efficiency by optimizing thermal regulation, shading, and natural airflow to minimize mechanical loads before any active power is generated.

• Material Life Cycle Assessment:

Evaluate the embodied energy of structural materials from extraction to operation. This includes analyzing how material choices drive compliance with green standards like LEED, BEEER, EDGE, etc.

• Active Generation & Smart Management (BMS):

Analyze the strategic integration of on-site renewables and how intelligent Building Management Systems distribute power, adjust HVAC settings, and route excess energy to battery storage.

• Urban Systemic Resilience:

Zoom out to assess how decentralized, renewable-powered buildings interact with the broader city grid. This includes evaluating how these structures contribute to regional disaster resilience and support localized blue-green infrastructure during grid disruptions.

➤ Operationalizations:

Policymakers can use the tools provided below in Table 01 to understand how the renewable energy strategies deliver output before and after the design and use of different energy sources can achieve the desired outcomes while fulfilling the main objectives.

Table 1 Operational Tools for Understanding the Output of Renewable Energy.

Tool Name	Category	Primary Use	Capabilities
Design Builder	Passive Strategies	Architectural Design	BIM Thermal
IESVE	Passive Strategies	Architectural Design	HVAC Solar Simulation
Energy Plus	Passive Strategies	Engineering/Yield	Open Source CLI
One Click LCA	LCA	Architectural Design	Carbon BIM Integration
Tally	LCA	Architectural Design	Revit Embodied Carbon
Sima Pro	LCA	Academic Research	Life cycle LCI Database
HOMER Pro	Active/BMS	Engineering/Yield	Microgrid Renewables
PVsyst	Active/BMS	Engineering/Yield	Solar PVY field Analysis
TRNSYS	Active/BMS	Academic Research	Dynamic Systems Modular
ENVI-met	Urban Resilience	Academic Research	Microclimate Urban Heat
EPA SWMM	Urban Resilience	Policy/Urban Planning	Hydrology Stormwater

➤ Importance of Study

This study is significant because it addresses the interconnected challenges of energy security, climate change, and socio-economic equity in Bangladesh. By evaluating renewable energy options for major energy-intensive building sectors, it provides a context-specific framework for reducing dependence on imported fossil fuels, enhancing energy resilience, and supporting sustainable urban development. The research integrates technical, economic, environmental, and socio-economic considerations, including income levels, energy affordability, and carbon reduction potential, to ensure that renewable energy solutions are both effective and inclusive. The findings offer practical guidance for policymakers, planners, architects, and energy stakeholders in advancing a low-carbon, resilient, and economically sustainable energy transition in Bangladesh.

II. LITERATURE REVIEW

The accelerating global transition toward renewable energy systems is driven by the imperatives of climate change mitigation, energy security, and the finite nature of fossil fuel reserves. Tiismus *et al.* [5] present a comprehensive state-of-the-art review of emerging renewable generation technologies, documenting the rapid technological maturation and cost reductions that have reshaped the energy landscape over the past decade. Within the built environment, this transition necessitates the integration of passive and active strategies. Chen *et al.* [6] review green building practices for embedding renewable energy within the construction sector, while Anand *et al.* [7] examine passive building approaches that leverage climate-responsive design to minimize mechanical energy demand. Complementing these, Toroxel and Silva [8] and Santos *et al.* [9] investigate passive solar heating and cooling technologies rooted in bioclimatic and vernacular architecture, demonstrating their efficacy in reducing thermal loads prior to active system deployment.

Among active renewable technologies, solar photovoltaic systems have experienced transformative growth due to declining module costs and efficiency improvements [10]. Wind energy has similarly expanded, with offshore installations offering superior capacity factors relative to onshore alternatives [11]. Hydropower remains the dominant source of renewable electricity worldwide,

providing dispatchable baseload power and grid stability through pumped-storage facilities, albeit with significant environmental and social trade-offs [12]. Biomass energy offers dispatchable generation from organic feedstocks, though its sustainability depends on lifecycle carbon accounting and responsible feedstock management [13]. Geothermal energy provides continuous baseload power with minimal emissions, but geographical constraints and high exploration costs limit its applicability [14]. Ocean energy technologies, encompassing tidal, wave, and thermal conversion systems, retain substantial theoretical potential yet remain largely in the demonstration phase due to technological complexity and high capital requirements [15].

The inherent intermittency of renewable sources necessitates advanced integration strategies. Smart grid architectures facilitate real-time monitoring, demand-response programs, and distributed energy resource management, enabling higher renewable penetration while maintaining reliability [16]. Energy storage technologies, particularly lithium-ion batteries, play a critical role in balancing supply and demand fluctuations [17]. Hybrid renewable systems that combine multiple generation sources with storage improve overall reliability, especially in remote and off-grid contexts [18]. Microgrids integrate localized generation with intelligent control systems, capable of autonomous or grid-parallel operation to enhance resilience and reduce transmission losses [19]. Demand-side management strategies, including load shifting and dynamic pricing, align consumption patterns with renewable availability, thereby optimizing system-wide utilization [20]. Furthermore, artificial intelligence and machine learning models are increasingly deployed for forecasting solar irradiance, wind speeds, and electricity demand, reducing operational uncertainty and improving planning accuracy [21].

➤ Renewable Energy Sources

• Solar Energy:

Solar energy is one of the most abundant renewable resources available worldwide. According to the research of A. Jäger-Waldau, [22] Photovoltaic technology converts sunlight directly into electricity, while concentrated solar power systems use mirrors to generate thermal energy for electricity production. The rapid decline in PV module costs

and improvements in efficiency have significantly increased solar deployment globally. However, solar power generation is highly dependent on weather conditions and daylight availability, necessitating storage and grid management solutions.

- *Wind Energy:*

Based on the statement of Global Wind Energy Council, [23] wind energy has become one of the fastest-growing renewable technologies. Modern wind turbines convert kinetic energy from wind into electricity with increasing efficiency. Offshore wind farms offer higher and more consistent wind speeds compared to onshore installations. Nevertheless, wind energy suffers from intermittency and variability, requiring forecasting systems and flexible grid operations for reliable integration.

- *Hydropower:*

Hydropower remains the largest contributor to renewable electricity generation worldwide. According to the International Hydropower Association, [24] large-scale dams and run-of-river systems provide reliable and dispatchable electricity. Hydropower also supports grid stability through frequency regulation and energy storage via pumped-storage facilities. However, environmental impacts, ecosystem disruption, and social displacement remain major concerns.

- *Biomass Energy:*

Biomass energy is derived from organic materials such as agricultural residues, forestry waste, and municipal solid waste, D. O. Hall et al. [25]. Biomass can be converted into electricity, heat, and biofuels through combustion, gasification, and anaerobic digestion processes. Unlike solar and wind energy, biomass provides controllable power generation. However, sustainability depends on feedstock management and lifecycle carbon emissions.

- *Geothermal Energy:*

As per the International Energy Agency, Renewables, [26] geothermal energy utilizes heat stored beneath the Earth's surface for electricity generation and direct heating applications. It offers continuous baseload power with high reliability and low emissions. The main limitations include geographical restrictions, high initial investment costs, and potential environmental impacts associated with drilling operations.

- *Ocean Energy:*

Ocean energy technologies include tidal, wave, and ocean thermal energy conversion systems. J. Cruz states that [27] these resources possess enormous theoretical potential but remain largely in the demonstration and early commercialization stages due to technological complexity and high costs.

➤ *Strategic Integration Methods of Renewable Energy*

- *Smart Grid Integration:*

Smart grids utilize advanced communication, sensing, and automation technologies to improve grid flexibility and

reliability. Smart grid systems enable real-time monitoring, demand-response programs, and distributed energy resource management, facilitating higher penetration levels of renewable energy. X. Fang et al. [28].

- *Energy Storage Systems:*

Energy storage technologies play a critical role in addressing renewable energy intermittency. Batteries pumped hydro storage, compressed air energy storage, and hydrogen-based storage systems help balance supply and demand while enhancing grid stability. M. Aneke and M. Wang [29] Lithium-ion batteries have emerged as the dominant storage technology due to declining costs and high energy density.

- *Hybrid Renewable Energy Systems:*

Hybrid renewable energy systems combine multiple energy sources such as solar, wind, biomass, and storage technologies. H. Rezk et al. [30]. Such systems improve reliability by compensating for the limitations of individual renewable resources. Hybrid systems are particularly effective in remote and off-grid regions.

- *Microgrids and Distributed Generation:*

Microgrids integrate localized renewable energy generation with energy storage and intelligent control systems. They can operate independently or in conjunction with the main grid, improving energy resilience and reducing transmission losses. Distributed generation enhances energy access, particularly in rural and underserved areas, N. Hatziargyriou [31].

- *Demand-Side Management:*

According to the P. Palensky and D. Dietrich [32] Demand-Side management strategies involve modifying electricity consumption patterns to match renewable energy availability. Techniques include load shifting, peak shaving, dynamic pricing, and energy efficiency measures. DSM reduces stress on power systems and improves renewable energy utilization.

- *Artificial Intelligence and Forecasting Technologies:*

Artificial intelligence, machine learning, and advanced forecasting models are increasingly used to predict solar irradiance, wind speed, and electricity demand. Accurate forecasting improves operational planning and reduces uncertainty associated with renewable energy generation, A. Mosavi et al. [33].

III. RESULTS & FINDINGS

Following a comprehensive review of renewable energy technologies, a detailed comparative assessment of their performance characteristics is presented. The evaluation encompasses a broad spectrum of renewable energy sources and examines their suitability for integration within the built environment, urban development strategies, and wider policy frameworks. Beyond conventional performance indicators such as energy output and economic feasibility, the assessment adopts a multidimensional approach by giving equal consideration to critical factors, including land and spatial requirements, life-cycle greenhouse gas emissions,

infrastructure and structural demands, environmental impacts, operational efficiency, and capital investment costs. This holistic evaluation framework facilitates a more informed

understanding of the relative strengths, limitations, and long-term sustainability of different renewable energy technologies in diverse planning and development contexts.

Table 2 Properties of Different Renewable Energy Sources

Solar Panels (PV)	
Cost & Economics	Utility-scale installations drive the cost per watt down significantly, while residential or building-integrated photovoltaics lean slightly higher due to structural mounting and inverter costs.
Lifespan & Maintenance	Highly durable with zero moving parts. They typically degrade at a rate of 0.5% per year, meaning they still operate at 80% capacity after 25 years. Maintenance is largely limited to surface cleaning.
Suitability	Excellent for decentralized power grids and integration into existing urban infrastructure without requiring additional land acquisition.
Carbon Footprint	Zero operational emissions. The 40–50g of CO ₂ /kWh comes almost entirely from the manufacturing process and global supply chain transport.
Wind Turbines	
Cost & Economics	Highly cost-effective at utility scales but less viable for micro-generation due to the complexity of the moving parts and structural requirements.
Lifespan & Maintenance	Averages 20–25 years. Because turbines rely on mechanical components, they require rigorous, scheduled maintenance to prevent mechanical failure.
Suitability	Requires strict zoning and spatial planning. Best suited for open topographies or coastal regions with consistent wind speeds (ideally above 5-6 m/s). They are generally unsuitable for dense urban environments due to turbulence, noise, and structural vibrations.
Carbon Footprint	Has one of the lowest lifecycle carbon footprints of all energy sources, averaging just 11-12g of CO ₂ /kWh.
Hydropower	
Cost & Economics	High upfront capital and civil engineering costs but offer some of the lowest Levelized Cost of Energy over its lifetime.
Lifespan & Maintenance	The civil structures (dams, weirs) can last a century or more, while the electromechanical turbines typically need refurbishing every 30–50 years.
Suitability	Requires specific topographical conditions. Run-of-river or micro-hydro projects are excellent for localized grid support without the massive ecological disruption of large reservoir dams.
Carbon Footprint	Very low, though large reservoirs in tropical climates can emit methane from decomposing organic matter.
Biomass and Biogas	
Cost & Economics	Moderate installation costs, but operational costs are tied to the steady supply and transportation of feedstock.
Lifespan & Maintenance	Digesters and combustion plants generally last 20–25 years. They require continuous operational management, much like a traditional thermal power plant.
Suitability	A highly strategic asset for municipal infrastructure. It effectively turns a waste management crisis into dispatchable baseline power, solving two infrastructural challenges at once.
Carbon Footprint	Considered carbon-neutral in a closed loop. However, processing and transport add to the lifecycle footprint.
Geothermal Energy	
Cost & Economics	The most expensive to initiate due to high-risk exploration drilling and specialized subterranean engineering.
Lifespan & Maintenance	The surface power plants last 30-50 years, while the geothermal wells can remain productive for up to a century if managed properly to avoid thermal depletion.
Suitability	Offers an incredibly dense energy yield with a very small physical footprint on the surface. It provides 24/7 baseline power, unlike intermittent solar or wind.
Carbon Footprint	Very low. Some natural greenhouse gases trapped underground are released during operation, but their emissions are negligible compared to those from fossil fuels.

➤ *Summary of the Findings:*

The summary of the findings of this study is provided below table:

Table 3 Multi-Criterial Analysis of RE

Energy Source	Cost	Lifespan	Suitability	Carbon Footprint	Outcome	Rank
Geothermal	Expensive	30–50 years	Moderate	Very low	Moderate	4
Biomass	Low	20–25 years	High	High	Moderate	5
Hydropower	High	30–50 years	Moderate	Very low	High	3
Wind Turbines	Moderate	20–25 years	Moderate	Very low	High	2
Solar Panels	Low	25–30 years	High	Very low	High	1

Appraisal Key: 1 = Excellent, 2 = Very good, 3 = Good, 4 = Fair, 5=Poor.

The comparative analysis of five renewable energy technologies across six dimensions reveals a clear hierarchy of strategic viability within the Bangladeshi context.

- *Solar Photovoltaic (Rank 1):*

Solar PV is the most suitable renewable energy technology for Bangladesh due to its low cost, scalability, long lifespan (25–30 years), minimal maintenance, and zero operational emissions. Its flexibility for rooftop, floating, and utility-scale applications, combined with Bangladesh's favorable solar irradiance, makes it the primary driver of renewable energy expansion and grid decarbonization.

- *Wind Energy (Rank 2):*

Wind power offers a very low carbon footprint and strong utility-scale generation potential. However, its deployment is largely limited to coastal and offshore regions due to geographic constraints and is less suitable for dense urban environments. It remains an important complementary source of solar energy.

- *Hydropower (Rank 3):*

Hydropower provides reliable, low-carbon baseload electricity and long-term operational benefits. However, its expansion potential is limited by Bangladesh's flat topography, with opportunities mainly confined to small-scale projects in hilly and northeastern regions.

- *Geothermal Energy (Rank 4):*

Geothermal energy delivers continuous low-carbon power with a small land footprint, but high exploration costs and limited geological suitability restrict its large-scale application in Bangladesh.

- *Biomass and Biogas (Rank 5):*

Biomass and biogas benefit from abundant agricultural and organic waste resources and can support waste-to-energy initiatives. However, operational complexities, feedstock management challenges, and higher lifecycle emissions reduce their overall strategic priority compared to other renewable technologies.

➤ *Maximum Energy-Consuming Occupancy Types in Bangladesh*

In Bangladesh, energy consumption patterns vary significantly across different building occupancy types due to differences in operational schedules, equipment intensity, occupant density, and environmental control requirements. From a built-environment and sustainability perspective, identifying high-energy-consuming occupancy categories is essential for integrating renewable energy, planning for energy efficiency, developing carbon-reduction strategies, and advancing sustainable urban development.

Table 4 Ranking of Maximum Energy-Consuming Occupancy Types

Occupancy Type	Typical EUI (kWh/m ² /year)	Main Energy Drivers
Hospitals and Healthcare Facilities	300–800+	HVAC, Medical Equipment, Operation
Data Centers	500–2,000+	Servers, cooling systems, UPS
Industrial Buildings and Factories	200–2,000+	Manufacturing processes, motors, boilers
Hotels and Resorts	250–600	Air conditioning, hot water, laundry
Shopping malls	250–500	HVAC, lighting, escalators
Airports and Transport Hubs	200–500	HVAC, security systems, lighting
Universities and Research Campuses	150–400	Laboratories, ICT infrastructure
Commercial Office Buildings	150–350	Cooling, lighting, office equipment
Institutional and Government Buildings	120–300	HVAC, lighting, ICT systems
High-Rise Residential Buildings	80–250	Cooling, appliances, pumping systems

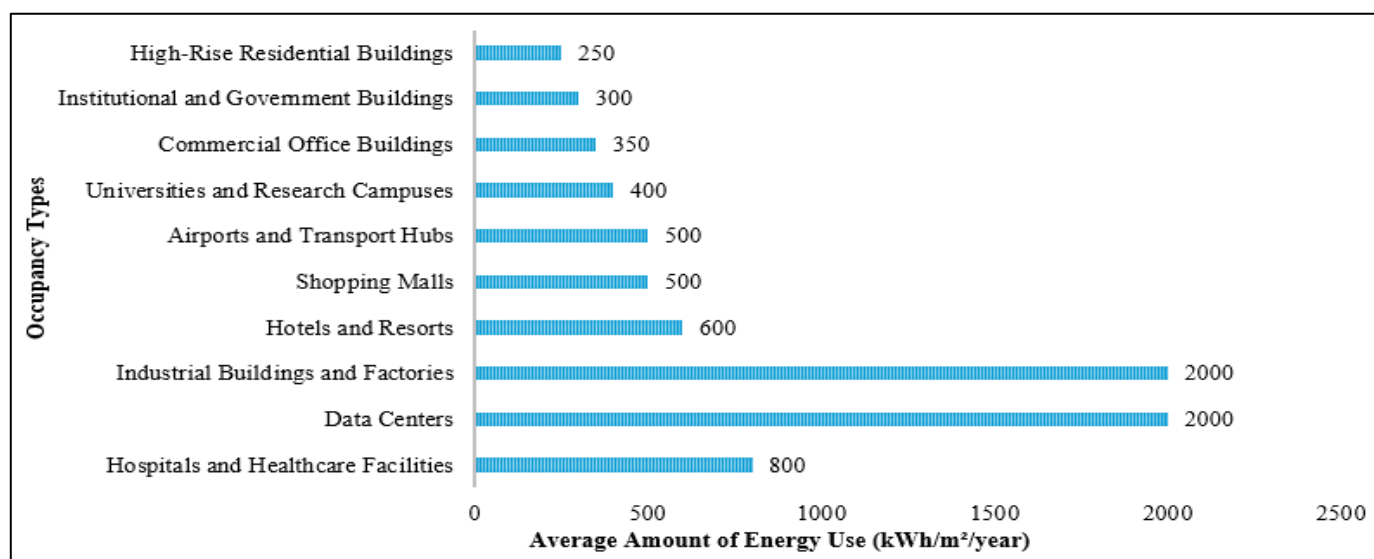


Fig 2 Building Energy Use Index per Year

Here, industrial buildings, data centers, hospitals, and other such facilities consume more energy. To find out more details about it, here preparing energy consumption patterns of different types of buildings in Bangladesh in the following

table, reflecting differences in activity schedules, equipment usage, occupancy density, and environmental control requirements:

➤ *Energy Consumption Patterns of Different Types of Buildings*

Table 5 Energy Consumption Patterns of Different Types of Buildings

Occupancy Types	Major Energy Demands	Energy Loads	Operation Time	Renewable Energy Potential
Hospitals and Healthcare Facilities	HVAC Systems	40–60%	24 hours a day 365 days a year	✓ Rooftop Solar PV ✓ Solar Water Heating ✓ Heat Recovery Systems ✓ Battery Storage for Critical Loads
	Medical Equipment	20–30%		
	Lighting Systems	10–15%		
	Water Heating and Sterilization	5–10%		
	Ventilation and Air Filtration Systems	5–10%		
Data Centers	IT Equipment	40–50%	24 hours a day 365 days a year	✓ Solar PV Integration ✓ Green Power Purchase Agreements ✓ Battery Storage Systems ✓ Waste Heat Recovery
	HVAC Systems	30–40%		
	Power Distribution	10–15%		
	Lighting/Other	5–10%		
Industrial Buildings and Manufacturing Facilities	Motors	30–45%	8-24 hours shift-based 6 days/week	✓ Industrial Rooftop Solar ✓ Biomass/Biogas from Agricultural Waste ✓ Waste-to-Energy Systems
	Process Heating	20–30%		
	HVAC Systems	15–20%		
	Lighting	5–10%		
	Compressed Air	5–10%		
Hotels and Resorts	HVAC Systems	40–50%	24 hours	✓ Solar Water Heating ✓ Rooftop Solar PV ✓ Heat Recovery Systems ✓ Solar Pool Heating
	Hot Water	15–20%		
	Kitchens	10–15%		
	Lighting	10–15%		
	Laundry Pools Lifts	5–10%		
Shopping Malls and Retail Complexes	HVAC Systems	45–55%	10-14 hours Daily	✓ Rooftop Solar PV ✓ Smart Building Energy Management Systems ✓ Energy-Efficient LED Retrofits
	Lighting	20–25%		
	Escalators	10–15%		
	Food Courts	10–15%		
	Signage	5–10%		
Airports and Transportation Terminals	HVAC Systems	30–40%	18-24 hours Daily (Operations) Peak passenger hours variable	✓ Large-Scale Solar PV on Terminal Roofs and Open Land ✓ Solar-powered Ground Support Equipment
	Lighting	20–25%		
	Security	15–20%		
	Baggage Handling	10–15%		
	Passenger Info	5–10%		
Universities and Research Campuses	Laboratories	25–35%	8-16 hours (aca. buildings) 24-hours dormitories	✓ Campus Solar Farms ✓ Smart Grid Integration ✓ Biogas from Campus Organic Waste
	HVAC Systems	20–30%		
	ICT	15–20%		
	Lighting	10–15%		
	Dormitories	10–15%		
Commercial Office Buildings	HVAC	50–70%	8-12 hours 5-6 days a week	✓ Rooftop Solar ✓ Building Envelopes ✓ Smart Lighting
	Lighting	15–25%		
	Equipment	10–20%		
	Elevators	5–10%		
Government and Institutional Buildings	HVAC	40–50%	8-10 hours, 5-6 days a week	✓ Rooftop Solar PV ✓ Solar Street Lighting
	Lighting	20–25%		
	ICT Equipment	15–20%		
	Security	5–10%		
High-Rise Residential Buildings	HVAC	30–40%	24 hours	✓ Rooftop Community Solar ✓ Solar Water Heating for Common Facilities ✓ Energy-Efficient Pump and Lift Systems
	Appliances	20–25%		
	Water Pumping	10–15%		
	Lighting	10–15%		
	Elevators	5–10%		

Table 6 Statistical Data on Energy Consumption Patterns of Different Types of Buildings

Functions	Mean	Median	Mode	Range	Minimum	Maximum
HVAC Systems	42.0	40.0	35.0	35.0	25.0	60.0
Lighting	16.3	16.3	22.5	15.0	7.5	22.5
Water Heating and Sterilization	10.6	10.0	10.0	12.5	5.0	17.5
Laundry Pools	7.5	7.5	7.5	.0	7.5	7.5
Elevator Escalators	6.1	5.0	2.0	11.5	1.0	12.5
Food Processing	10.0	12.5	12.5	7.5	5.0	12.5
Signage	7.5	7.5	7.5	.0	7.5	7.5
Security	4.5	2.0	2.0	16.5	1.0	17.5
Baggage Handling	12.5	12.5	12.5	.0	12.5	12.5
Passenger Lounge	7.5	7.5	7.5	.0	7.5	7.5
Laboratories	30.0	30.0	30.0	.0	30.0	30.0
ICT	26.7	17.5	17.5	27.5	17.5	45.0
Dormitories	5.3	5.3	.5 ^a	9.5	.5	10.0
Equipment	22.5	22.5	12.5 ^a	25.0	12.5	37.5
Water Pumping	2.7	2.0	1.0 ^a	11.5	1.0	12.5
Effluent Treatment Plant	10.0	10.0	7.5 ^a	5.0	7.5	12.5
Sewage Treatment Plant	3.0	2.0	2.0	7.0	.5	7.5

- Multiple Modes Exist. The Smallest Value is Shown

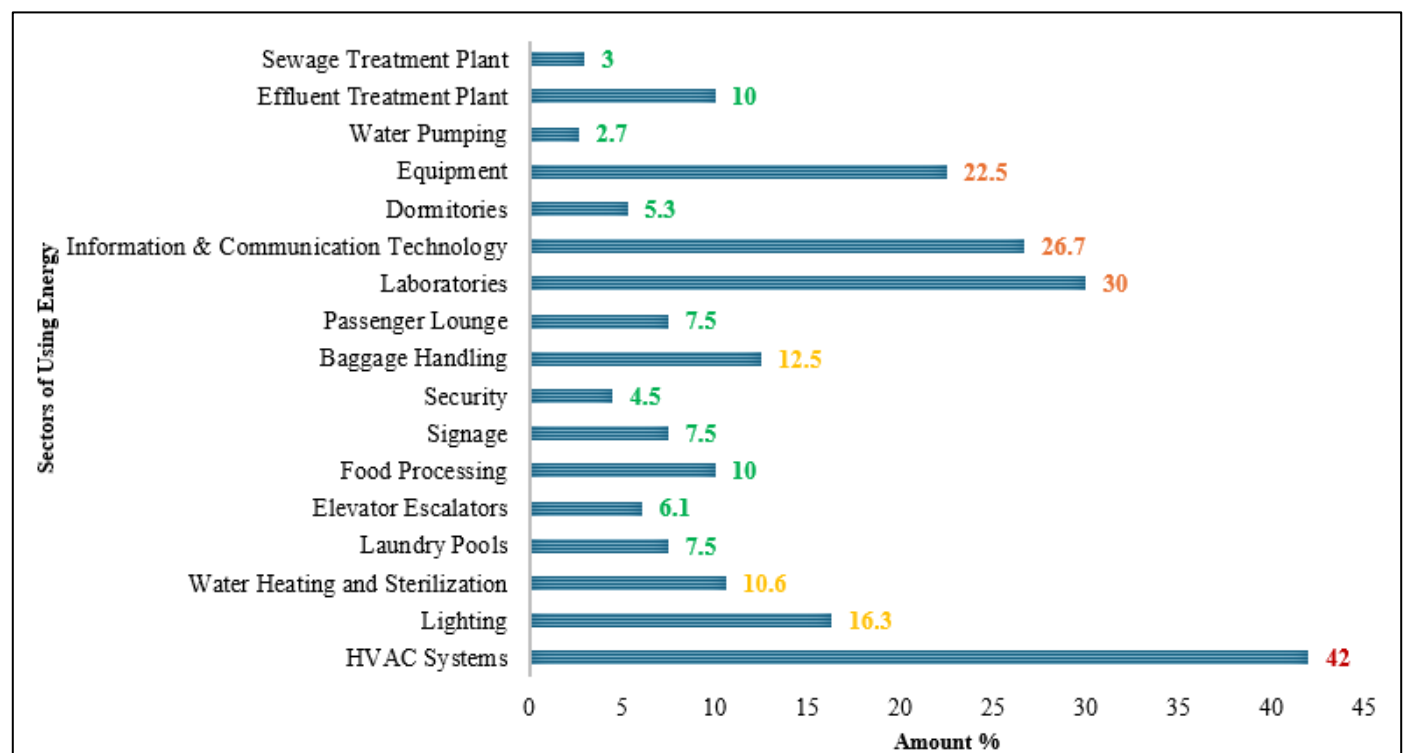


Fig 3 Average Amount of Energy Used in Various Functions

Table 7 Building Functions Energy Consumption Matrix

Functions	Extreme > 40%	High (31-40) %	Moderate (21-30) %	Fare (11-20) %	Low (1-10) %
HVAC Systems					
Lighting					
Water Heating and Sterilization					
Laundry & Pools					
Elevator / Escalators					
Food Processing					
Signage					
Security					

Baggage Handling					
Passenger Lounge					
Laboratories					
Information & Communication Technology					
Dormitories					
Equipment					
Water Pumping					
Effluent Treatment Plant					
Sewage Treatment Plant					

A multi-level classification of the energy use functions of different buildings in this study reveals a clearly uneven distribution across operating categories. It is found that HVAC systems are the only function that is at an extreme level (>40%), highlighting its disproportionate energy demand compared to all other building functions. No usage is observed at the high level (31-40%), indicating a clear gap between the main thermal demand and the subsequent operating demand. Three knowledge-intensive functions, namely laboratories, ICT, and equipment, show moderate usage (21-30%), reflecting the energy intensity of research, computing, and process-specific infrastructure. The medium level (11-20%) includes lighting, water heating and disinfection, and material handling, which represent incidental but undeniable operating demands. All other activities, including laundry pools, elevator and escalator

systems, food processing, signage, security, passenger lounges, dormitories, water pumping, wastewater treatment plants, sewage treatment plants and miscellaneous, are included in the lower tier (1-10%), which collectively contribute insignificantly to the total energy use of the building. This stratification highlights that- “The need for targeted demand-based interventions, particularly in the thermal control and specialized equipment sectors, to achieve meaningful reductions in institutional energy use.”

➤ Socio-Economic Energy Indicators of Bangladesh

Based on the latest 2025-2026 fiscal year and energy sector report, the current data and statistical analysis of Bangladesh according to specific energy and economic indicators are given below in different Tables:

Table 8 Per Capita Energy Consumption Indicators (FY 2025–2026)

Indicator	Range	Unit	Contextual Notes
Primary Energy Consumption (National Average)	297	kg of oil equivalent to each capita annually	Reflects aggregate energy from all sources including fossil fuels, electricity, and biomass; indicates low per capita energy access relative to global averages.
Electricity Consumption (Per Capita)	600-610	kWh per capita annually	Significantly below the global average (~3,500 kWh); indicative of suppressed demand and limited grid penetration in rural areas.
Traditional Biomass Consumption (Rural Households)	60-105	kg per month	Varies by income tier, 95% of rural households remain dependent on firewood, cow dung, and agricultural residue for thermal energy needs.
Rural Household Dependency on Traditional Fuels	95	% of households	Highlights persistent energy poverty and the pre-electrification character of rural thermal energy consumption.

Table 9 Unit Cost of Electricity by Consumer Category (Post-June 2026 BERC Tariff Revision)

Consumer Category	Tariff Rate (Tk/kWh)	Tariff Characteristics	Policy Implication
Average Retail Tariff	10.63	Average across all consumer classes	Benchmark rate for macroeconomic energy cost modeling and LCOE comparison for renewable energy projects.
Residential Lifeline Slab (0–50 units)	5.32	Subsidized rate for low-consumption households	Social protection mechanism to ensure basic energy access for economically vulnerable populations; cross-subsidized by higher slabs.
High-End Residential Slab (>600 units)	17.35	Premium rate for high-consumption households	Progressive tariff structure designed to discourage excessive consumption and recover revenue from affluent consumers.
Commercial & Industrial (Peak Hours)	12.12 - 18.40	Voltage-differentiated and time-of-use (TOU) based	Variable pricing reflects marginal cost of generation during peak demand, incentivizes load shifting and renewable self-generation for C&I consumers.

Table 10 Per Capita Income Indicators (FY 2025–2026, Provisional BBS Estimates)

Economic Indicator	Value (\$)	Development Context
Gross National Income (GNI) per capita	3,020	Milestone achievement crossing the \$3,000 threshold; positions Bangladesh at lower-middle-income status with implications for energy subsidy rationalization.
Gross Domestic Product (GDP) per capita	2,866	Slightly lower than GNI, indicating net outward factor income payments; relevant for domestic purchasing power and energy affordability assessments.

Table 11 Household Energy Expenditure as a Percentage of Income

Household Income Bracket	Monthly Energy Expenditure (%)	Interpretation
National Average (All Households)	4.3% – 5.0%	Aggregate burden including electricity, LPG, biomass, and kerosene; moderately low at the national means but masks significant intra-population inequality.
Lower-Income Households	>5.0% (disproportionately higher)	Energy poverty indicator; lower-income households spend a higher proportional share on basic energy and lighting, reducing disposable income for education, health, and nutrition.
Higher-Income Households	<4.3% (declining share)	Declining energy burden as income rises; accompanied by increased absolute consumption through high-wattage appliances and air conditioning.

Table 12 Common Residential Electrical Equipment by Income Tier

Income	Typical Appliances	Wattage Range	Energy Transition Implication
Basic / Universal	LED bulbs, ceiling fans, mobile chargers, basic radios	5 W – 80 W	Minimal grid load; represents the energy access floor for low-income and rural households.
Middle Income	Refrigerator, rice cooker, LED television, electric iron, blender, water pump	100 W – 1,000 W	Moderate load escalation; entry-level cooling and food preservation appliances drive per capita consumption toward the national average.
Upper Income	Air conditioner (1–2 Ton), washing machine, microwave oven, induction cooker, desktop computer, multiple televisions	1,000 W – 2,500 W	High-load appliances significantly increase household peak demand; cooling loads are the primary driver of summer grid stress and tariff escalation into the >600-unit slab.

Table 13 Integrated Analytical Synthesis

Dimension	Key Finding	Strategic Implication for Renewable Energy Pathways
Energy Access Gap	Per capita electricity consumption (600–610 kWh) 1/6 of the global average.	Decentralized solar microgrids and rooftop PV can bridge the rural electrification deficit without requiring centralized grid extension into remote areas.
Energy Poverty & Equity	Lower-income households bear a disproportionate energy cost burden.	Targeted subsidies for solar home systems and efficient appliances can reduce the energy expenditure share for vulnerable populations.
Tariff Structure	A 3.26x differential exists between lifeline (Tk 5.32) and high-end residential (Tk 17.35) slabs.	High-end residential and C&I consumers face strong economic incentives to adopt rooftop solar and battery storage to avoid peak tariff slabs, creating a self-sustaining market for distributed generation.
Income-Energy Nexus	GNI per capita (\$3,020) supports gradual tariff rationalization but remains fragile.	Renewable energy investments must be financed through blended international climate finance and domestic capital to avoid regressive impacts on household energy affordability.
Appliance-Driven Demand Growth	Upper-income households are rapidly adopting air conditioning and high-wattage appliances.	Passive architectural design and building-integrated renewables must precede demand saturation to prevent lock-in of inefficient, fossil-fuel-dependent cooling infrastructure.
Rural Biomass Dependency	95% of rural households still rely on traditional biomass for thermal energy.	Biogas digesters and improved cookstoves offer immediate co-benefits for health (indoor air quality), gender equity (reduced fuelwood collection time), and carbon mitigation, serving as a transitional bridge toward full electrification.

IV. RECOMMENDATIONS

➤ Policy and Regulatory Measures

• Prioritize Solar Energy:

Establish solar PV as the cornerstone of Bangladesh's renewable energy strategy through supportive policies,

streamlined approvals, and strengthened net-metering systems.

• Promote Renewable Adoption:

Introduce time-of-use tariffs, demand-response incentives, and renewable energy quotas for high-energy-

consuming sectors such as hospitals, industries, data centers, and commercial buildings.

- *Develop Wind Energy Potential:*

Conduct comprehensive wind resource assessments and establish regulatory frameworks for coastal and offshore wind development.

➤ *Technical and Built-Environment Strategies*

- *Adopt Passive-First Design:*

Integrate passive architectural strategies to reduce energy demand before deploying renewable energy systems.

- *Expand Building-Integrated Renewables:*

Promote Building-Integrated Photovoltaics (BIPV) in dense urban areas through building code incentives.

- *Deploy Hybrid Microgrids:*

Encourage solar-battery hybrid systems for critical facilities to enhance energy security and resilience.

- *Advance Waste-to-Energy Solutions:*

Utilize industrial, agricultural, and municipal waste streams for biogas and waste-to-energy generation.

➤ *Socio-Economic and Capacity Development*

- *Support Energy Equity:*

Expand affordable financing, community solar programs, and PAYG models to increase renewable energy access for low-income households.

- *Improve Energy Efficiency:*

Strengthen appliance efficiency standards and provide incentives for replacing inefficient equipment.

- *Enhance Research and Innovation:*

Support universities and research institutions in developing climate-responsive renewable energy technologies and net-zero building solutions.

➤ *Financial and Institutional Actions*

- *Mobilize Green Finance:*

Leverage international climate funds and public-private partnerships to accelerate renewable energy investments.

- *Strengthen Data Infrastructure:*

Establish a national renewable energy database to support evidence-based planning and decision-making.

- *Encourage Green Buildings:*

Provide incentives for certified green buildings (LEED, EDGE, BEEER) to promote sustainable construction and carbon reduction.

V. CONCLUSION

This study provides a comprehensive assessment of renewable energy pathways for Bangladesh by integrating technological, institutional, built environment, and socio-economic dimensions. The findings indicate that Bangladesh possesses significant yet underutilized potential to transition toward a renewable energy-based power system, if deployment strategies are aligned with local climatic, geographic, economic, and sectoral conditions. The analysis identifies solar photovoltaic energy as the most strategic renewable energy option due to its scalability, declining costs, low maintenance requirements, and suitability for both urban and rural applications. Wind energy and limited hydropower resources can serve as complementary energy sources, while geothermal and biomass technologies face greater economic, environmental, and technical constraints.

The study further reveals that healthcare facilities, digital infrastructure, industries, and hospitality establishments are among the highest energy-consuming sectors, presenting substantial opportunities for renewable energy integration and energy-efficiency improvements. Major energy loads, including HVAC systems, industrial machinery, medical equipment, and data-center cooling, highlight the importance of combining renewable generation with demand-side management and sustainable building design. From a socio-economic perspective, the research emphasizes the need for an equitable energy transition. Decentralized solar systems, net-metering policies, and targeted subsidy mechanisms can enhance energy access, reduce consumer vulnerability, and support long-term energy affordability. The integration of advanced simulation and planning tools provides a practical framework for optimizing renewable energy deployment and reducing implementation risks. Overall, the study demonstrates that Bangladesh's renewable energy transition depends not only on technological potential but also on strategic policy, institutional coordination, and integrated planning, offering an evidence-based foundation for a sustainable, resilient, and inclusive energy future.

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