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Original Research Article

Techno-Economic and Environmental Assessment of a Hybrid Biogas–Solar PV System for Sustainable Rural Energy Supply

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ABSTRACT

Decentralized renewable energy systems can provide a promising pathway for improving energy access in rural regions with limited grid reliability. This study conducts a techno-economic and environmental assessment of a household-scale hybrid energy system integrating a 1.65 kWp solar photovoltaic (PV) array with a fixed-dome biogas digester. System performance was evaluated using one year of field data and a 20-year economic model. At an 8% discount rate, the system requires an initial investment of USD 1,227. It yields annual savings of USD 321.45, resulting in a net present value of USD 1,707.3, an internal rate of return of 23%, and a discounted payback period of four years. The hybrid configuration achieves a net reduction of approximately 2.16 tCO_2e yr^{-1}. Results demonstrate that integrating PV and biogas improves economic viability and energy reliability, offering a sustainable solution for decentralized rural energy supply.

KEYWORDS

Hybrid renewable energy system, Solar PV, Biogas digestion, Techno-economic analysis, Energy reliability, Greenhouse-gas mitigation.

INTRODUCTION

Bangladesh, like many developing economies, faces persistent energy challenges driven by rapidly growing demand, heavy dependence on fossil fuels, and increasing exposure to global price volatility. National electricity demand increased by approximately 7% in 2024 due to heat-driven consumption growth, while fossil fuels continue to dominate the national and global primary energy mix [1]. Recent geopolitical disruptions, such as the Russia–Ukraine conflict, have further destabilized energy markets and intensified fuel price uncertainty worldwide [2]. Fossil fuel combustion and industrial activities accounted for more than 75% of global greenhouse gas (GHG) emissions and nearly 90% of carbon dioxide emissions in 2024 [3]. Despite these pressures, per-capita energy consumption in Bangladesh remains only about 14% of the global average [4], and declining domestic natural gas reserves are increasing reliance on imported fuels, thereby heightening energy insecurity.

To expand electricity access in rural areas, Bangladesh has implemented the world's largest Solar Home System (SHS) programme, providing basic electricity services to millions of off-grid households [5]. While the programme has substantially improved lighting and appliance access, most rural households still depend on liquefied petroleum gas (LPG) or traditional biomass for cooking, contributing to indoor air pollution and continued GHG emissions. At the same time, Bangladesh possesses abundant organic waste resources, supported by a large livestock population and extensive poultry production, which present significant opportunities for decentralized biogas generation. In parallel, unused rooftop space in rural dwellings offers considerable potential for small-scale solar photovoltaic (PV) deployment. The integration of biogas and solar PV technologies therefore, represents a promising hybrid solution for decentralized, low-carbon household energy supply.

A growing body of literature has investigated the technical and economic feasibility of standalone and hybrid renewable energy systems for off-grid and grid-constrained contexts. Household-level biogas adoption studies report tangible economic benefits for users, primarily through reduced fuel expenditures [6]. Several techno-economic studies have examined the feasibility of hybrid renewable energy systems for rural electrification. Vahdatpour et al. [7] evaluated off-grid hybrid configurations across multiple climatic regions and confirmed their technical viability under varying resource conditions. Chowdhury et al. [8] conducted a detailed techno-economic assessment of a photovoltaic–biomass system in Bangladesh, demonstrating improved cost-effectiveness compared to standalone configurations. Ahmed et al. [9] further highlighted the suitability of hybrid solar–biomass systems for electrification in isolated rural communities.

At the household scale, biogas technology has received considerable attention as a decentralized energy solution. Salam et al. [10] identified key performance limitations and adoption challenges through a household survey, while Rahman et al. [11] demonstrated favorable economic outcomes for biogas and solar home systems. In a broader policy and deployment context, Asif and Barua [12] examined large-scale renewable energy dissemination programs in Bangladesh, highlighting institutional and implementation aspects. Complementary techno-economic analyses by Okedu and Al-hashmi [13] and Rad et al. [14] further compared system costs and configurations across different contexts, while Peirow et al. [15] emphasized reliability considerations in hybrid system design. The environmental context relevant to system deployment in Chattogram was provided by Majumder et al. [16].

Beyond household-scale applications, the feasibility of hybrid systems has been explored across a range of technical and geographical contexts. Kumaravel and Ashok [17] optimized a biomass–solar–pico-hydel configuration for remote electrification, demonstrating the importance of resource complementarity. Akbulut et al. [18] investigated feedstock management strategies to enhance biogas production efficiency. Economic and design evaluations of biogas systems were further developed by Adeoti et al. [19] and Kandpal et al. [20], while Petrillo et al. [21] incorporated life-cycle assessment and cost analysis into the evaluation of hybrid systems. Rubab and Kandpal [22] additionally proposed a structured methodology for financial assessment of biogas technologies. More recent research has focused on system optimization and performance enhancement. Mohammad et al. [23] applied response surface methodology to improve photovoltaic system performance, whereas Hasan et al. [24] developed an advanced energy management strategy to enhance the operational efficiency of hybrid renewable systems.

Despite these advances, several limitations remain in the existing literature. Many studies rely predominantly on simulation outputs, generalized cost assumptions, or short-term performance estimates, with limited use of field-validated operational data at the household scale. In addition, comprehensive assessments that simultaneously integrate real-world system monitoring, detailed component-level techno-economic cash-flow analysis, and full life-cycle GHG accounting—including fugitive methane emissions from biogas systems—remain scarce, particularly within the Bangladeshi context. As a result, the long-term financial robustness and environmental performance of hybrid biogas–PV systems under realistic operating conditions are not yet well established.

To address these gaps, this study presents a field-based techno-economic and environmental assessment of a household-scale hybrid solar PV–biogas system deployed in rural Bangladesh. The main contributions of this work are threefold:

(i) Generation of an empirically grounded dataset capturing seasonal PV and biogas performance under real operating conditions;

(ii) Integration of detailed life-cycle GHG accounting with component-level techno-economic modelling using locally representative cost parameters; and

(iii) Sensitivity-based evaluation and policy-relevant discussion of key factors influencing the economic viability of hybrid renewable systems in rural settings.

The remainder of the paper is organized as follows: Section 2 describes the study site, system configuration, and assessment methodologies; Section 3 presents the results and sensitivity analyses; and Section 4 discusses the implications for decentralized energy planning and concludes the study.

MATERIALS AND METHODS

This section describes the study site, system configuration, monitoring protocol, and analytical procedures used to assess the technical, environmental, and economic performance of a household-scale solar–biogas hybrid system in rural Chattogram, Bangladesh. The total system methodology is shown in a flow chart (Figure 1).

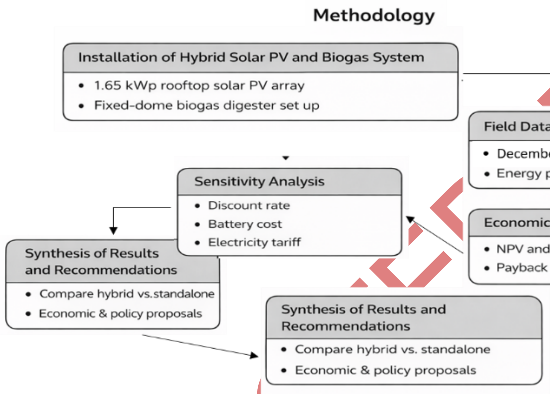


Figure 1. Research methodology for hybrid systems analysis

Study Site and Climatic Conditions

Field investigations were conducted at a rural household in Chattogram, Bangladesh (Figure 2), characterized by a tropical monsoon climate. The household represents a typical rural Bangladeshi family of 6 members, engaged mainly in agriculture and informal labor, which reflects common socio-economic conditions in rural Bangladesh.

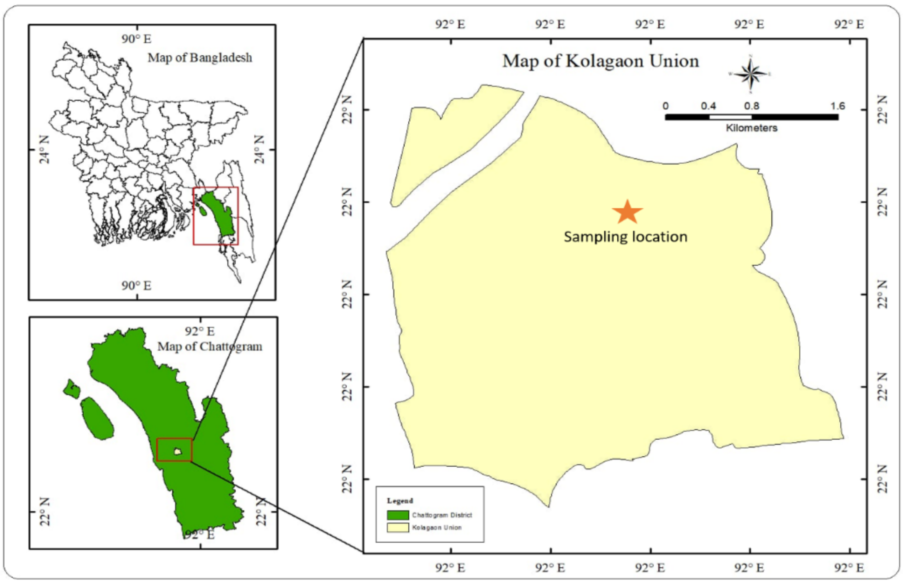


Figure 2. The geographic coordinate maps of Bangladesh and Chattogram are also included on the left, and the sample collection location is on the right.

Long-term climatic data (2014–2023) obtained from NASA POWER and PVGIS indicate an average global horizontal irradiance of 6.18 kWh/m²-d, direct normal irradiance of 5.0 kWh/m²-d, sunshine duration of 7.5–9 h, mean ambient temperature of approximately 31.9 °C, and relative humidity up to 80% during the monsoon season [16][25].

Hybrid System Architecture

The system consists of two subsystems operating in parallel:

1. Solar PV subsystem: A 1.65 kWp rooftop PV array (three 550 Wp Longi LR5-72HPH-550M modules), mounted at a fixed tilt angle of approximately 23°, corresponding to the existing rooftop inclination and optimize annual insolation (Figure 3). For Chattogram (latitude ~22.3°N), the optimal annual tilt angle is typically in the range of 20°–25°.The system includes a PV ION SP-2.0 inverter (2 kW rated) and three 12 V, 150 Ah lead-acid batteries (Rahimafrooz). Component nominal specifications are summarized in Table 1.

Table 1. Detailed specifications of the solar panel, inverter, and battery.

SL	Name	Specification
01	Monocrystalline Silicon Solar Panel	1. Brand: Longi, Model: LR5-72HPH-550M G2
		2. Power Range: 540~550W
		3. V_{max}: 41.95V, V_{oc}: 49.80V
		4. I_{sc}: 13.99 Amp, I_{max}: 13.12 Amp
		5. Module Efficiency: 21.3%
02	Hybrid Inverter	1. Model: PV ION SP-2.0
		2. Brand: ION
		3. Rated Power & Input voltage: 2000W 220VAC
		4. $\eta_{MPPT(peak)}$:98%, $\eta_{Inverter(peak)}$: 94%
		5. Transfer/ switching time: 10mS
03.	Battery	1. Model: Rahimafrooz 1TB 150 ah Tabular Battery.
		2. Volt: 12 V, Plate: 21, 150AH

Figure 3. Solar panel setup

2. Biogas subsystem: A fixed-dome digester fed with mixed organic waste (cow dung, poultry litter, kitchen scraps). The produced biogas is used for cooking; digestate is collected for agricultural use. The resulting biogas is a methane-rich gas containing 50–75% methane, 25–50% carbon dioxide, and 0–10% nitrogen and hydrogen.

The hybrid configuration is intended for off-grid or grid-constrained rural households. The system is designed for autonomous operation and low maintenance. A schematic diagram of the integrated system is provided in Figure 4.

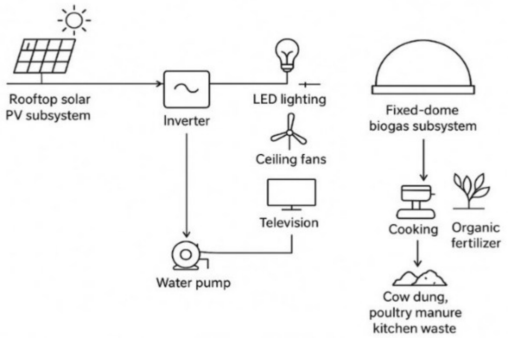


Figure 4. Schematic diagram of the integrated system

PV System Monitoring and Performance Analysis

The electrical load profile was developed based on measured household consumption and appliance-level verification at the study site. A one-month pre-installation survey (November 2024) was conducted to record appliance ratings, daily operating hours, and irrigation pump usage through direct observation and short-term plug-in energy meter measurements. These data were used to construct representative seasonal demand profiles reflecting typical rural operation patterns. The resulting mean daily energy demand ranged from 1.90 kWh/d in winter (November–February) to 5.74 kWh/d in summer (March–October), as detailed in Table 2. Seasonal variation primarily reflects extended fan operation during warmer months.

The PV system capacity (1.65 kWp) was selected based on the measured household electricity demand. Using the site-specific average solar resource (6.18 kWh/m²-d) and typical system performance factors, the selected capacity is expected to generate approximately 5.0–5.5 kWh/d, which closely matches peak seasonal demand while exceeding average annual demand.

An overall system performance ratio (PR) of 75–80% was adopted to account for inverter, wiring, and temperature-related losses. PV performance was monitored using a Huawei SmartLogger 3000A01EU, recording AC energy output, module temperature, ambient temperature, and plane-of-array irradiance. Data were aggregated daily and monthly for the period December 2024 – November 2025 to capture seasonal variability.

Usable rooftop area was computed as:

$$A_{usable} = A_{roof} - A_{obstructions} - A_{safety} \quad (1)$$

Where, A_{safety} accounts for a 5–10% margin for access and maintenance. The total measured roof area was 46.8 m². After excluding 6.5 m² of permanent obstructions (including

Table 2. Seasonal load profile of a rural household

Appliance	Type	Quantity	Power Rating (W)	Hours/Day	Total Daily Energy (Wh)
Summer Load (March–October)					
LED Lights	AC	6	20	6	720
Ceiling Fans	AC	4	80	12	3,840
Television	AC	1	200	4	800
Water Pump (0.5 HP)	AC	1	375	1	375
Total Daily Energy (Summer)					5,735 Wh = 5.74 kWh
Winter Load (November–February)					
LED Lights	AC	6	20	6	720
Television	AC	1	200	4	800
Water Pump (0.5 HP)	AC	1	375	1	375
Total Daily Energy (Winter)					1,895 Wh = 1.9 kWh

a water storage tank and ventilation shafts) and reserving a 7% safety margin, the resulting usable area was 37.0 m². The installed 1.65 kWp PV array (three 550 Wp modules; total footprint ≈ 7.74 m²) occupies approximately 21% of the usable space, confirming clear spatial feasibility. Only south-facing sections with appropriate tilt and minimal shading were selected. Installation complied with manufacturer specifications and local electrical standards.

Biogas System Design and Operation

The biogas system was designed for household-scale operation using mixed livestock manure and domestic organic waste available at the study site. Feedstock availability was verified through on-site livestock inventory and short-term weighing over a two-week observation period prior to system commissioning. The household maintains three stall-fed cows and ten poultry birds year-round, typical of rural smallholder practice in Chattogram. Average fresh dung production was measured at 11–12 kg/(cow-d), resulting in approximately 33–36 kg/d of cow dung. Poultry litter contribution averaged 0.10–0.11 kg/(bird-d) (1.0–1.1 kg/d total), while kitchen waste generation was approximately 0.4–0.5 kg/d for a 4–6 member household. The resulting total feedstock input ranged between 34.5–37.5 kg/d, diluted at a 1:1 ratio to produce ~75 L/d of slurry. The digester was designed for mesophilic operation under local climatic conditions. Although typical hydraulic retention times (HRT) for tropical digesters range between 35–50 days, a conservative HRT of 55 days was selected to ensure process stability during cooler winter months (18–22 °C) [23], when microbial activity declines and digestion slows. The required working volume was therefore calculated as:

$$V_d = \text{Daily slurry input (L)} \times RT = 75 \times 55 = 4125\ \text{L} = 4.125\ \text{m}^3 \qquad (1)$$

After accounting for a 10% allowance for gas space and operational variability, the total digester volume was fixed at 4.5 m³, consistent with established household-scale fixed-dome systems in South Asia. A dome-type gas holder with a nominal capacity of 1.5 m³ was integrated to buffer daily gas production and stabilize delivery pressure. The digester structure was constructed as a fixed-dome masonry unit with reinforced concrete sealing to minimize leakage. A schematic overview of the biogas system is provided in Figure 5.

Environmental parameters and GHG accounting

<u>Emission accounting framework:</u> The greenhouse gas (GHG) mitigation potential of the proposed solar–biogas hybrid system was quantified by estimating avoided CO_2-equivalent (CO_2e) emissions relative to conventional grid electricity and fossil-based cooking fuels. The assessment followed the Intergovernmental Panel on Climate Change (IPCC) 2019 Refinement to the 2006 Guidelines [26], using emission factors representative of Bangladesh [27], with all results expressed on a 100-year global warming potential (GWP_{100}) basis.

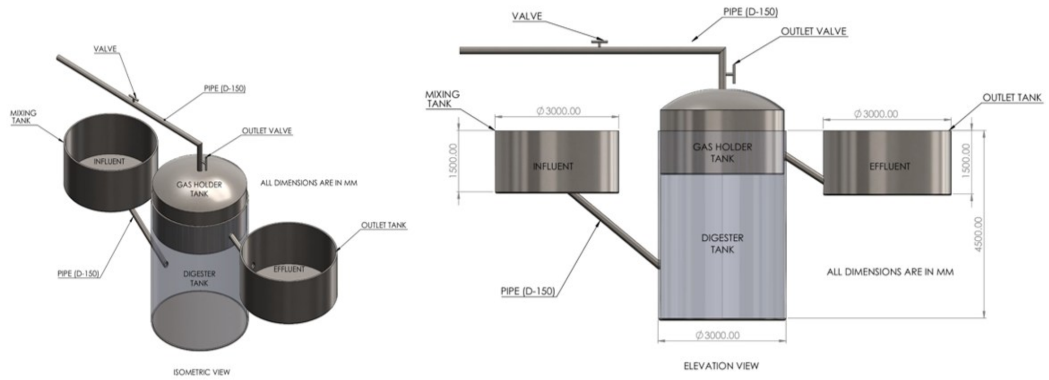


Figure 5. Schematic diagram of a total biogas system.

Avoided emissions from the solar PV subsystem were calculated from the annual electricity generation and the national grid emission factor, as expressed in Equation (3):

$$ER_{PV} = E_{PV} \times EF_{grid} \quad (3)$$

Where EF_{grid} was taken as 0.67 kg CO_2e/kWh, reflecting the average grid mix in Bangladesh [28]. Similarly, Biogas mitigation was estimated from displaced cooking fuels:

$$ER_{BG} = V_{BG} \times H_v \times EF_{fuel} \quad (4)$$

Where displaced fuels include LPG and traditional firewood. CO_2 emissions from firewood combustion were treated as biogenic and excluded, consistent with IPCC methodology [29]; however, associated non-CO_2 emissions (CH_4 and N_2O) were included using default emission factors [30]. Therefore, their influence on total mitigation results is acknowledged as a source of uncertainty. Potential offsets due to methane leakage from the digester and gas distribution system were included as:

$$ER_{CH_4} = V_{CH_4,\, fug} \times \rho_{CH4} \times GWP_{CH_4} \quad (5)$$

Where methane leakage was assumed to be 3% of total biogas production, consistent with reported values for small-scale fixed-dome digesters in South Asia [6][31], $\rho CH4 = 0.716$ kg m^{-3}, and $GWP_{CH_4} = 28$ [21]. This value lies within the 1–5% range typically reported for small-scale masonry digesters under routine maintenance conditions. The net annual GHG reduction from the hybrid system was therefore calculated as:

$$ER_{total} = ER_{PV} + ER_{BG} - ER_{CH4} \quad (6)$$

<u>Waste Management Impact:</u> The waste management impact of the biogas subsystem was evaluated based on the quantity of organic waste treated, biogas production, and digestate generation. Daily feedstock input consisted of mixed household and livestock waste, which was anaerobically digested under controlled conditions. The resulting digestate was considered a recoverable by-product with potential for nutrient recycling. Environmental benefits were assessed in terms of avoided uncontrolled decomposition and associated emissions, using literature-based emission factors.

Economic Parameters

<u>Capital and Operating Costs and Annual Fuel Cost Savings:</u> The economic evaluation was based on capital expenditure (CAPEX), annual operating expenditure (OPEX), and fuel cost savings for both PV and biogas subsystems. CAPEX included PV modules, batteries, inverter, and balance-of-system components, as well as digester construction and gas-handling infrastructure. Cost inputs were derived from prevailing market prices in Bangladesh

Annual OPEX was estimated as a fixed percentage of CAPEX, representing routine maintenance and minor repairs. Annual savings were calculated from avoided LPG consumption, grid electricity use, and diesel fuel, using local energy prices. Net annual savings were used as input for subsequent economic indicators.

<u>Economic Performance Indicators:</u> Standard financial metrics, including payback period, net present value (NPV), benefit–cost ratio (BCR), and internal rate of return (IRR), were applied following established methodologies [32] [33].

$$\text{Net annual cash flow} = \text{Annual fuel savings} - \text{Annual OPEX} \quad (7)$$

The simple (undiscounted) payback period ($T_{payback}$) was calculated as:

$$T_{payback} = \frac{\text{CAPEX}}{\text{Net annual cash flow}} \quad (8)$$

According to [6], the economic lifespan of fixed dome biogas plants is up to 15 years. However, many other studies suggest the biogas dome can operate for up to 20 years [34][35][36]. The NPV was calculated over a 20-year project life using a discount rate of 08%, as follows:

$$NPV(r) = -\,CAPEX + \sum_{t=1}^{20} \frac{\text{Net annual cash flow}}{(1+r)^t} \quad (9)$$

Owners use benefit-cost analysis as a financial estimator to determine whether a project is feasible. The BCR formula is as follows:

$$BCR = \frac{\sum_{t=1}^{n} \frac{B_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{C_t}{(1+r)^t}} \quad (10)$$

The appeal of the investment was assessed by comparing IRRs with market loan rates. IRR rates above 10% were regarded as financially compelling, especially when government subsidies were available. It can be stated as follows:

$$NPV(r)=0; \quad NPV = \sum_{t=1}^{n} \frac{CF_t}{(1+IRR)^t} - I_0 \quad (11)$$

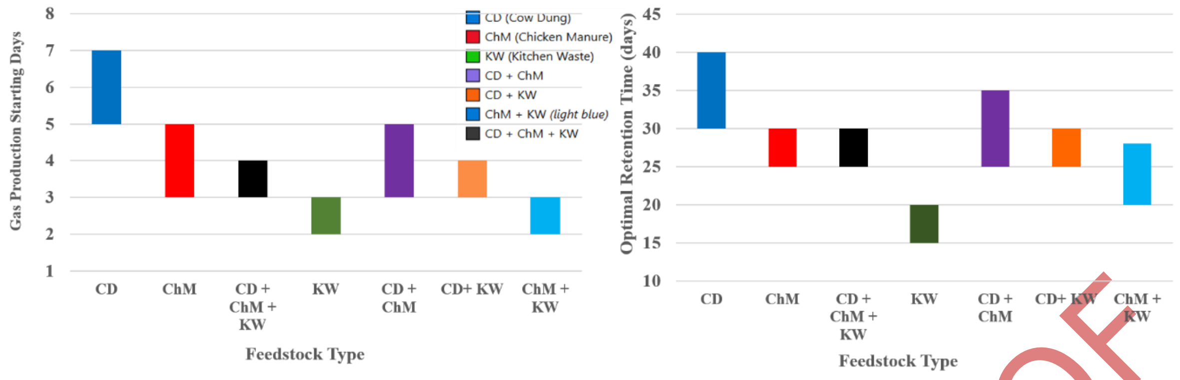
RESULTS AND DISCUSSION

Energy Output of the Hybrid Biogas–Solar PV System

Field monitoring from December to June demonstrated clear seasonal dynamics in both the biogas and solar PV subsystems, driven by variations in ambient temperature and solar irradiance typical of coastal Bangladesh. The integrated system exhibited strong reliability and complementary energy outputs—thermal energy from biogas and electrical energy from solar PV—ensuring year-round household energy supply.

Biogas Subsystem Performance: The biogas subsystem operated reliably using mixed organic feedstock consisting of livestock manure and household kitchen waste. Feedstock digestion characteristics, including gas initiation time and hydraulic retention period, were monitored during the one-year operational period of this study and are summarized in Fig. 6.

Kitchen waste showed the fastest digestion response, with gas initiation within 2–3 days and retention periods of 15–20 days due to its high biodegradability. In contrast, cow dung required longer stabilization (5–7 days) and retention times (30–40 days) because of its higher lignocellulosic content. Chicken manure exhibited intermediate behavior. Co-digestion of these substrates reduced start-up time and improved digestion kinetics compared with monodigestion by balancing the carbon–nitrogen ratio and increasing the availability of easily degradable organic matter.



(a) (b)

Figure 6. Biogas feedstock characteristics and digestion performance; Figure 6(a) Biogas production starting days; and Figure 6(b) Optimal retention time.

Table 3. Daily biogas production under field conditions

Month	Season	Avg Temp (°C)	Retention Time (days)	Biogas Yield (m^3/day)
December	Winter	18–21	35–40	1.60
January	Winter	18–22	35–40	1.60
February	Late Winter	24–26	32–37	1.90
March	Pre-Summer	27–30	28–35	2.00
April	Summer	33–37	25–30	2.20
May	Summer	35–39	26–32	2.20
June	Rainy Season	32–35	27–33	2.00
July	Monsoon	29–31	28–34	1.95
August	Monsoon	29–31	28–34	1.90
September	Late Monsoon	29–32	27–32	2.00
October	Post-Monsoon	27–30	28–35	2.05
November	Late Autumn	24–27	30–36	1.75

Seasonal variation in biogas yield (daily) was observed under field conditions during the monitoring period (Table 3**).** Gas production increased from winter to early summer as ambient temperature approached the mesophilic digestion range (28–38 °C), enhancing methanogenic activity. Average daily biogas output varied from approximately 1.60 m^3 during cooler winter months to about 2.2 m^3 in summer, reflecting the temperature sensitivity of anaerobic digestion. Despite these seasonal fluctuations, the digester maintained continuous gas production throughout the year due to the mixed-feed strategy, which improved carbon–nitrogen balance and buffering capacity. Similar seasonal performance patterns in small-scale digesters operating under tropical climates have also been reported in rural Bangladesh [31][37].

Biogas typical methane content of 50–70%, the calorific value of biogas is approximately 20–23 MJ/m^3 [38]. Based on the measured biogas production of 1.60–2.2 m^3/d, the corresponding energy potential is estimated to be 32–50 MJ/d (8.9–14.0 kWh/d).

<u>Solar PV Subsystem Performance:</u> The solar PV subsystem exhibited pronounced seasonal variation in energy output, with higher specific yields during pre-summer and summer months due to increased solar irradiance and extended daylight hours. The measured average daily specific yield of 5.0 kWh/kW-d is consistent with the national average range of 4.6–5.0

Table 4. Monthly solar PV electricity production.

Month	Avg irradiation (kWh/m^2-d)	Daily specific yield (kWh/kW-d) = Irr × PR	System daily output (kWh/d)	Monthly kWh
December	3.7	2.886	4.33	134.2
January	3.9	3.042	4.56	141.4
February	4.3	3.588	5.38	155.7
March	5.3	4.134	6.20	192.1
April	5.6	4.368	6.55	196.5
May	5.1	3.978	5.97	185.1
June	4.1	3.432	5.15	150.6
July	4.0	3.120	4.68	148.1
August	3.8	3.042	4.56	139.4
September	4.3	3.432	5.15	154.4
October	4.9	3.822	5.73	177.6
November	4.2	3.276	4.91	151.4
Total (Dec–Nov)		—	—	1,920.5 kWh

kWh/kW-d for Bangladesh [39], indicating representative system performance. Monthly electricity production increased from 134.2 kWh in December to a peak of 196.5 kWh in April, corresponding to the period of highest solar irradiance in Bangladesh (Table 4). Output gradually declined from June to August (150.6–139.4 kWh) due to increased cloudcover and atmospheric moisture associated with the monsoon season. Electricity generation recovered during the post-monsoon months of September and October, reaching 177.6 kWh in October, before decreasing again in November (151.4 kWh) as winter solar irradiation declined.

Over the twelve-month monitoring period, the PV subsystem generated a total of 1,920.5 kWh, corresponding to an average monthly production of approximately 160 kWh. Periodic module cleaning and appropriate tilt selection were implemented to limit performance losses associated with dust accumulation and seasonal environmental factors.

The observed electricity generation was sufficient to supply the household's core electrical demands, including lighting, ventilation, and small appliances, thereby substantially reducing dependence on grid electricity. Moreover, PV generation exceeds load during peak solar hours, indicating the presence of surplus energy due to limited storage capacity. If grid connection is available, this excess could be exported, improving system utilization and increasing annual savings. However, this option depends on local net metering policies and was not included in the present economic analysis.

<u>System Reliability and Load Matching:</u> The integrated solar–biogas system demonstrated effective load matching and high operational reliability across daily demand cycles. As shown in Figure 7, daytime electrical loads, dominated by irrigation and auxiliary appliance use, were primarily met through direct solar PV generation, while excess solar energy generated during peak irradiation hours was stored in the battery bank and utilized during evening and nighttime periods when PV generation was unavailable.

The system employed three 150 Ah batteries, providing a combined nominal storage capacity of approximately 5.4 kWh. Considering a recommended 50% depth of discharge, the usable storage capacity was approximately 2.7 kWh, which corresponds closely to the household's typical evening and night-time electricity demand dominated by lighting, fan operation, and small appliances. Based on the measured load distribution and PV generation profile, the battery system supplied approximately 70–80% of nocturnal electrical demand, while the remaining portion was occasionally met by residual PV generation during early evening hours.

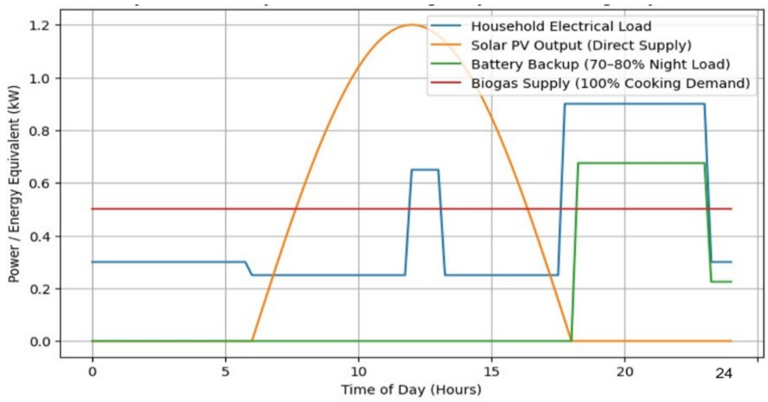


Figure 7. Load Matching

Thermal energy requirements for cooking were fully met by the biogas subsystem throughout the day, ensuring continuous service independent of solar availability. Based on the baseline LPG consumption of approximately 144 kg/year (Table 8), the corresponding thermal demand is estimated at ~5.0 kWh/day. In comparison, the measured biogas production (1.60–2.2 m³/day) provides approximately 8.9–14.0 kWh/day, confirming that the system sufficiently meets household cooking energy requirements. This functional decoupling of electrical and thermal energy supply enhanced overall system resilience under variable weather conditions. The coordinated operation of PV generation, energy storage, and biogas production resulted in an estimated ≈ 95% household load coverage. Comparable reliability improvements in hybrid renewable systems have been reported in previous studies [34][35].

Environmental Parameter

Emission Reduction (GHG): The hybrid solar–biogas system demonstrated significant mitigation potential under field conditions. Table 5 summarizes the quantified emission reductions from both subsystems and the offset due to fugitive methane leakage. All values are expressed in CO_2-equivalent (CO_2e) terms on a 100-year GWP basis [36].The assumed methane leakage rate (3%) introduces uncertainty in the net GHG reduction estimates, as actual emissions may vary depending on digester condition and operation.

The combined configuration reduced CO_2e emissions by 25-30% (2.16 tCO_2e/yr), demonstrating the system's potential for decentralized decarbonization, with comparable hybrid emission savings reported [34][35].

Waste Management Impact: The biogas subsystem significantly improved organic waste management by anaerobically treating approximately 37.5 kg/d of mixed biodegradable waste, thereby preventing open dumping and uncontrolled decomposition—major sources of methane emissions and local pollution (Table 6). In addition to renewable energy recovery, the

Table 5. Annual greenhouse gas reduction from the hybrid system

Component	Activity Data	Emission Factor (kg CO_2e/unit)	GHG Reduction (kg CO_2e/yr)
Solar PV subsystem	1,920.5 kWh/yr electricity	0.67 kg CO_2e/kWh [28]	1286.7
Biogas subsystem	≈ 1.9 m³/d × 365 = 693 m³/yr biogas	6.0 kWh/m³ × 0.234 kg CO_2e/kWh [26]	973
Fugitive CH_4 emissions	3 % of total biogas (methane ≈ 60 %)	GWP_{100} = 28 kg CO_2e/kg CH_4	−92.6
Total Net Reduction			2167.07 kg CO_2e/yr

Table 6. Waste Conversion and Environmental Benefits of the Biogas System

Parameter	Typical Value	Environmental Benefit	Reference
Daily feedstock input	~37.5 kg (mixed organic waste)	Avoids open dumping of organic waste	[36]
Biogas yield	1.60–2.2 m³/d	Reduces CH_4 from unmanaged waste	[40]
Digestate output	~25–30 kg/d	Provides stabilized biofertilizer; returns macro-nutrients (N, P, K) to soil.	[36]
Vermicompost potential (post-digestate treatment)	~40–60% mass conversion	Improves nutrient bioavailability, reduces phytotoxicity, and enhances soil microbial activity	[41]
Avoided CH_4 emissions	≈ 20–25 kg CO_2e/m	Mitigates GHG release from landfills	[36]
Waste utilization efficiency	>85% organic conversion	Promotes circular waste management	[42]

digestion process generated a stabilized nutrient-rich digestate, enabling beneficial reuse rather than disposal.

Following anaerobic stabilization, the solid fraction of the digestate can be further processed through vermicomposting, producing high-quality organic fertilizer while supporting nutrient recycling and soil health improvement. Overall, the hybrid system supports a waste–energy–nutrient circular pathway, contributing to landfill diversion and climate mitigation objectives

Economic Parameters

Capital and Operating Costs: The techno-economic assessment indicates that the proposed hybrid solar–biogas configuration represents a financially viable decentralized energy solution under prevailing market conditions (2024–2025). The total initial capital investment includes photovoltaic (PV) modules, batteries, inverter, charge controller, balance-of-system (BOS) components, and installation, together with the biogas digester structure, gas-handling system, and associated civil works.

As summarized in Table 7, the aggregate capital expenditure (CAPEX) of the complete hybrid system was estimated at USD 1,227, after accounting for a 30% battery subsidy applied to the PV subsystem. The adjusted PV subsystem investment was USD 879, representing approximately 72% of total CAPEX, primarily due to the cost intensity of storage and power electronics. The biogas unit required USD 348, reflecting its relatively low material and fabrication complexity of fixed-dome digesters commonly used in rural South Asia.

Table 7. Capital and annual operating costs of the total hybrid system

Item	Unit cost ($)	Qty	Subtotal ($)
For Solar			
550 W panel	111	3	333
150 Ah, 12V battery	133	3	399
Battery subsidy (30%) (applied to battery subtotal)			−120
2 kW Hybrid Inverter	193	1	193
BOS & installation	—	—	74
PV CAPEX (before subsidy)	—	—	999
Total annual OPEX (straight average)	—	—	15
PV CAPEX (after battery subsidy)			879
For Biogas			
Civil Work (digester construction, slurry pit 1.5 m³, gas holder, Inlet & outlet tanks, PVC piping & fittings)			296
Two-burner stove + pressure regulator + safety fittings			30
Labor & installation (masonry, plumbing, commissioning)			22
Total CAPEX			348

TOTAL CAPEX (PV + Biogas)	1227
Annual routine O&M (1.5% CAPEX)	18
Capital Recovery Factor (CRF)	0.1019
Annualized CAPEX (1,227 × 0.1019)	125
Total Equivalent Annual Cost (EAC)	143

A project lifetime of 20 years was assumed [43]. Component lifespans were considered as 5 years for lead-acid batteries and 10 years for the inverter, consistent with regional operating conditions [44]. Battery replacement, therefore, represents the most significant lifecycle cost component of the PV subsystem. Routine operation and maintenance (O&M), including inspection, minor servicing, and periodic system checks, was conservatively estimated at 1.5% of total CAPEX (approximately USD 18/yr), in line with empirical findings for decentralized hybrid systems in tropical regions [45][46]. The economic evaluation incorporates capital recovery using a discount rate of 8%, resulting in a capital recovery factor (CRF) of 0.1019.

Although the PV subsystem alone exhibits relatively high upfront investment due to battery storage requirements, integration with the biogas subsystem improves the overall economic performance by simultaneously providing electricity and cooking energy. This hybrid configuration reduces dependence on grid electricity and LPG consumption, thereby improving lifecycle economic performance compared with single-technology systems.

Annual Fuel Cost Savings: Table 8 summarizes the annual fuel cost savings achieved through the integration of the biogas and solar PV systems. The biogas unit fully meets the household cooking demand, eliminating the yearly LPG expenditure. At the same time, the solar PV system supplies most of the day & nighttime electrical load, reducing grid dependency by approximately 70%. Additionally, the utilization of biogas and solar power for irrigation has completely displaced diesel consumption. The combined effect of these transitions yields an estimated annual savings of USD 321.45, highlighting the system's strong potential to lower recurring fuel costs and enhance long-term economic sustainability for rural households.

Economic Performance Analysis: The long-term financial viability of the proposed hybrid solar–biogas system was evaluated over a 20-year project lifetime using an 8% discount rate, consistent with economic assessments commonly applied in decentralized renewable energy studies in developing economies [32]. The key techno-economic indicators are summarized in Table 09.

The PV subsystem shows moderate economic viability under subsidized conditions, with an NPV of USD 764.6, IRR of 17%, and discounted payback period of 6.8 years. However, under the no-subsidy scenario, CAPEX increases to USD 999, reducing the NPV to USD 645.4 and IRR to 15%, while extending the discounted payback period to 8.4 years. This indicates that PV system performance is highly sensitive to battery cost support.

Table 8. Annual fuel cost savings

Energy Source	Unit	Baseline Usage	Unit Cost	Annual Baseline Cost	Reduction (%)	Annual Savings	Remarks
LPG (Cooking)	kg/year (1kg= 0.54 m^3)	144 (≈12 kg/month) [47]	$ 0.97/kg	$ 139	100	$ 139	Complete substitution by biogas for cooking
Grid Electricity	kWh/year	1500	$ 0.089/kWh	$ 133.5	70	$ 93.45	Solar PV supplies the majority of the load
Diesel (Irrigation)	L/year	100	$ 0.89/L	$ 89	100	$ 89	Solar pump eliminates diesel use
Total	—	—	—	$ 361.5	—	$ 321.45	—

Table 9. Economic performance indicators of the hybrid biogas–solar PV system

System	Total CAPEX ($)	Annual O&M ($)	Annual Savings ($)	Net Annual Cashflow ($)	NPV (20 yrs, 8%) ($)	IRR (%)	Simple Payback (yrs)	Discounted Payback (yrs)
PV subsystem (without subsidy)	999	15	182.45	167.45	645.4	15	6.0	8.4
PV subsystem (with subsidy)	879	15	182.45	167.45	764.6	17	5.25	6.8
Biogas subsystem	348	5.2	139	133.8	966.7	37	2.60	2.9
Combined (PV with subsidy + biogas) system	1,227	22.5	321.45	298.95	1,707.3	22	4.11	4.2

In contrast, the biogas subsystem exhibits stronger economic performance. The digester system achieves a positive NPV of USD 966.7 and a comparatively high IRR of about 37%, with a simple payback period of approximately 2.6 years. These favorable results primarily arise from the direct substitution of LPG consumption, low operational costs, and stable availability of organic feedstock.

When both technologies are integrated, the hybrid configuration provides the most favorable overall economic outcome. The combined system yields an NPV of approximately USD 1,707.3 and an IRR of about 22%, with a discounted payback period of roughly 4.2 years. The improved economic performance reflects the complementary interaction between the two subsystems: solar PV supplies daytime electricity demand while the biogas unit offsets cooking fuel expenses, thereby increasing total annual savings and stabilizing household energy expenditures.

Overall, the results indicate that technology integration significantly enhances financial viability compared with stand-alone systems. The hybrid solar–biogas approach therefore represents a practical and economically sustainable pathway for decentralized energy supply in rural households.

<u>Sensitivity Analysis:</u> To evaluate the robustness of the system performance, both economic and technical sensitivities were examined. The analysis considers key economic parameters as well as system sizing constraints that influence overall energy supply reliability.

1. <u>Economic sensitivity</u>**:** A one-at-a-time sensitivity analysis was conducted for the three parameters that most strongly influence decentralized renewable energy economics: the discount rate, battery replacement cost, and grid electricity tariff. Each parameter was varied within plausible ranges derived from regional energy market conditions while holding other variables constant. Table 10 summarizes the variation ranges and corresponding impacts.

The results indicate that increases in grid electricity tariffs significantly improve the economic attractiveness of decentralized renewable systems by increasing avoided electricity expenditures. Conversely, higher battery costs moderately reduce system profitability due to the need for periodic replacement, while higher discount rates reduce long-term economic returns. From a policy perspective, these findings suggest that capital subsidies for storage technologies, stable tariff structures, and concessional financing mechanisms can substantially enhance investment feasibility

Table 10. Sensitivity ranges and NPV in economic analysis

Parameter	Base Value	Variation Range	NPV ($)
Discount rate	8%	5–12%	2,180 - 1,210
Battery replacement cost	$399	±30%	1,480 - 1,920
Grid electricity tariff	$0.089/kWh	±25%	2,030 - 1,360

2. Technical sensitivity of system sizing: Field observations indicate that, although the PV subsystem produces surplus energy during peak daytime hours, the system does not fully meet total household electricity demand. This mismatch is primarily attributed to the limited storage capacity of the battery system rather than insufficient PV generation.

The installed battery bank provides approximately 2.7 kWh of usable storage, which is comparable to typical evening and nighttime demand; however, it becomes insufficient during extended usage and low-irradiance conditions, resulting in partial unmet load. This indicates that system performance is constrained by storage capacity rather than generation capacity under the current configuration. These findings highlight the importance of balanced system sizing between PV generation and battery storage for achieving a reliable household energy supply.

DISCUSSION

This study evaluated the technical and economic feasibility of a household-scale hybrid solar PV–biogas energy system under real operating conditions in rural Bangladesh. The findings demonstrate that the effectiveness of the hybrid configuration arises from functional complementarity between electricity and thermal energy subsystems, rather than from the performance of individual technologies alone [48].

Complementary System Performance

The measured results demonstrate that the PV and biogas subsystems operate independently while addressing different household energy demands. The PV system generated a total of 1,920.5 kWh/yr, with peak production occurring during high-irradiance months (March–May), whereas biogas production ranged from 1.60 to 2.2 m^3/d depending on ambient temperature and digestion conditions (Table 3 and Table 4).

Rather than directly compensating for each other, the two subsystems contribute to overall system reliability by serving distinct energy functions. For instance, reduced PV output during monsoon months (June–August), when electricity generation declined to 139–150 kWh/m, did not affect cooking energy availability because biogas production remained relatively stable (1.9–2.0 m^3/d). This indicates that system reliability is achieved through functional diversification of energy supply, rather than direct operational coupling between subsystems [49].

Economic Implications of Hybridization

The economic results highlight the differing contributions of each subsystem. The biogas system achieved a higher economic return (IRR ≈ 37%, payback ≈ 2.6 years) due to complete substitution of LPG consumption and low operating costs. In contrast, the PV system showed moderate performance (IRR ≈ 17%, payback ≈ 5.25 years), primarily due to higher capital costs associated with battery storage.

However, integration significantly improves overall financial performance. The combined system achieved an NPV of USD 1,707.3 and an IRR of ~22%, with a discounted payback period of ~4.2 years. This improvement arises from aggregation of multiple energy savings streams (electricity, LPG, and diesel), which increases total annual cash flow (USD 298.95/yr) and reduces financial risk compared to reliance on a single energy source. Thus, the benefit of hybridization is not due to physical interaction between subsystems, but due to economic synergy through diversified cost savings.

Environmental Performance and Practical Implications

The hybrid system achieved a net emission reduction of approximately 2.16 tCO_2e/yr, with contributions from both PV electricity generation (1,286.7 kg CO_2e/yr) and biogas utilization (973 kg CO_2e/yr), partially offset by methane leakage (−92.6 kg CO_2e/yr). These results demonstrate that combining renewable electricity generation with waste-to-energy conversion provides a measurable environmental benefit under real operating conditions.

In addition, the system processes approximately 37.5 kg/d of organic waste, contributing to improved local waste management and reducing uncontrolled methane emissions. This integrated energy–waste approach is particularly relevant for rural regions with abundant biomass resources and limited waste management infrastructure

Implications for Multi-Household Systems

A key limitation of this study is its focus on a single household, which restricts direct generalization of economic performance. At a community scale, system performance is expected to improve due to economies of scale and resource aggregation. For instance, a shared biogas digester can reduce capital cost per unit of gas production while improving thermal stability and digestion efficiency, potentially lowering the payback period compared to the ~2.6 years observed at household level.

Similarly, shared PV or mini-grid configurations can reduce per-household investment in inverters and storage, while aggregated demand profiles may improve battery utilization and reduce required storage capacity. However, these benefits depend on effective system design, including distribution infrastructure and coordinated operation. Therefore, while community-scale systems offer improved economic potential, their performance is contingent on appropriate management and implementation frameworks.

Policy Implications

The results highlight that battery cost is the primary constraint on PV system viability, as identified in the sensitivity analysis. Targeted subsidies or concessional financing for battery replacement would therefore significantly improve lifecycle economics.

In contrast, the strong economic performance of the biogas subsystem (IRR ≈ 37%) suggests that policy efforts should prioritize scaling biogas deployment**,** particularly through community-level digesters to exploit economies of scale. Additionally, the sensitivity of system profitability to electricity tariffs indicates that tariff rationalization or net metering mechanisms could enhance the competitiveness of decentralized PV systems. Overall, integrated policy approaches that support both PV and biogas technologies are likely to yield greater economic and environmental benefits than single-technology interventions.

Study Limitations and Future Research

Several limitations should be acknowledged. First, this study is based on one year of field-monitored data; longer-term observations would improve the robustness of performance and economic projections, particularly under extreme climatic conditions. Second, the economic analysis assumes fixed component lifetimes and replacement intervals, particularly for batteries, which can vary depending on operational practices and environmental conditions. Third, the study evaluates a single-household system, and therefore, scaling effects associated with larger community-based installations were not examined. Fourth, the reliance on literature-based estimates for fugitive methane emissions rather than direct field measurements. However, actual emissions can vary depending on construction quality, maintenance practices, and operating conditions. As methane has a high global warming potential, even small deviations in leakage rates can significantly influence net GHG reduction estimates. Future research should investigate multi-household hybrid systems, alternative battery technologies, long-term operational datasets to further refine techno-economic assessments and in-situ quantification of methane leakage to improve the accuracy of greenhouse gas mitigation assessments.

Implications for Rural Energy Systems

The findings suggest that hybrid PV–biogas systems can provide a practical decentralized energy solution by simultaneously addressing electricity demand, cooking energy needs, and organic waste management. In regions with unreliable grid access or rising fuel costs, such systems can reduce dependence on centralized energy infrastructure while improving household energy security. The complementary technical performance and favorable economic indicators observed in this study suggest that such hybrid systems can play an important role in supporting sustainable rural energy transitions, particularly in regions with abundant solar resources and readily available organic feedstock.

CONCLUSION

This study evaluated the technical, economic, and environmental performance of a household-scale hybrid solar PV–biogas energy system under real operating conditions in rural Bangladesh. The results show that integrating rooftop PV with a fixed-dome biogas digester can effectively provide both electricity and cooking energy while utilizing locally available organic waste. The system achieved a positive net present value, an internal rate of return of 22%, and a discounted payback period of approximately four years, while reducing greenhouse gas emissions by about 2.16 tCO_2e per year.

Although the standalone PV subsystem remains economically limited under current electricity tariffs, its integration with biogas improves overall financial performance and energy reliability. This demonstrates the value of combining complementary renewable technologies for decentralized household energy supply.

However, the findings are based on a single household case study, and system performance may vary depending on factors such as organic waste availability, roof area for PV installation, and local energy prices. Future research should therefore focus on long-term monitoring and multi-site studies to better assess scalability and broader applicability.

Overall, hybrid solar PV–biogas systems show strong potential as a decentralized and sustainable energy solution for rural households in Bangladesh.

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NOMENCLATURE

Symbols

- BCR – Benefit–Cost Ratio
- CAPEX – Capital expenditure (USD)
- CF_t – Net cash flow in year *t* (USD/yr)
- CRF – Capital recovery factor
- C_t – Cost in year *t* (USD)
- B_t – Benefit in year *t* (USD)
- DCF_t – Discounted cash flow in year *t* (USD/yr)
- EAC – Equivalent annual cost (USD/yr)
- GWP – Global warming potential
- IRR – Internal rate of return (%)
- I_0 – Initial investment cost (USD)
- NPV – Net present value (USD)
- OPEX – Operating expenditure (USD/yr)
- r – Discount rate
- t – Time (year)

- T_{pay}back – Payback period (years)

REFERENCES

[1] Energy and sustainability, *Energy Institute*, 2025. [Online]. Available: https://www.energyinst.org/statistical-review, [Accessed: 04- December-2025].

[2] M. Sun, X. Cao, X. Liu, T. Cao, and Q. Zhu, The Russia-Ukraine conflict, soaring international energy prices, and implications for global economic policies, *Heliyon*, vol. 10, no. 16, p. e34712, 2024, https://doi.org/10.1016/j.heliyon.2024.e34712.

[3] Causes and Effects of Climate Change in Education, vol. 11, no. S2-Feb, pp. 65–68, 2024. [Online]. Available: https://www.un.org/en/climatechange/science/causes-effects-climate-change#:~:text=Producing food causes emissions of,from packaging and distributing food. [Accessed: 04- December-2025].

[4] H. Unit, Energy Scenario, Bangladesh, 2024. [Online]. Available: www.hcu.org.bd. [Accessed: 06- December-2025].

[5] Bangladesh Solar Home Systems Provide Clean Energy for 20 million People, *The world bank*, 2024. [Online]. Available: https://www.worldbank.org/en/news/press-release/2021/04/07/bangladesh-solar-home-systems-provide-clean-energy-for-20-million-people. [Accessed: 06- December-2025]

[6] D. Bedana, M. Kamruzzaman, M. J. Rana, B. A. A. Mustafi, and R. K. Talukder, Financial and functionality analysis of a biogas plant in Bangladesh, *Heliyon*, vol. 8, no. 9, 2022, https://doi.org/10.1016/j.heliyon.2022.e10727.

[7] S. Vahdatpour, S. Behzadfar, L. Siampour, E. Veisi, and M. Jahangiri, Evaluation of Off-grid Hybrid Renewable Systems in the Four Climate Regions of Iran, *J. Renew. Energy Environ.*, vol. 4, no. 1, pp. 61–70, 2017, https://doi.org/10.30501/jree.2017.70107.

[8] N. Chowdhury, C. A. Hossain, M. Longo, and W. Yaïci, Feasibility and cost analysis of photovoltaic-biomass hybrid energy system in off-grid areas of Bangladesh, *Sustain.*, vol. 12, no. 4, 2020, https://doi.org/10.3390/su12041568.

[9] M. R. Ahmed, S. R. Hazra, M. M. Rahman, and R. J. Bhuiyan, Solar-Biomass Hybrid System; Proposal for Rural Electrification in Bangladesh, *Electr. Electron. Eng. An Int. J.*, vol. 4, no. 1, pp. 1–11, 2015, https://doi.org/10.14810/elelij.2015.4101.

[10] S. Salam, R. Parveen, S. M. Nasim Azad, and M. A. Salam, Understanding the Performance of Domestic Biodigesters in Bangladesh: A Study from Household Level Survey, *Bus. Manag. Stud.*, vol. 6, no. 2, p. 27, 2020, https://doi.org/10.11114/bms.v6i2.4869.

[11] M. M. Rahman, M. F. Hasan, A. Saat, and M. A. Wahid, Economics of biogas plants and solar home systems: For household energy applications, *J. Adv. Res. Fluid Mech. Therm. Sci.*, vol. 33, no. 1, pp. 14–26, 2017.

[12] M. Asif and D. Barua, Salient features of the Grameen Shakti renewable energy program," *Renew. Sustain. Energy Rev.*, vol. 15, no. 9, pp. 5063–5067, 2011, https://doi.org/10.1016/j.rser.2011.07.050.

[13] K. E. Okedu and M. Al-hashmi, Assessment of the Cost of various Renewable Energy Systems to Provide Power for a Small Community: Case of Bukha, Oman, *Int. J. Smart grid*, no. March, 2018, https://doi.org/10.20508/ijsmartgrid.v2i3.17.g17.

[14] M. A. V. Rad, R. Ghasempour, P. Rahdan, S. Mousavi, and M. Arastounia, Techno-economic analysis of a hybrid power system based on the cost-effective hydrogen production method for rural electrification, a case study in Iran, *Energy*, vol. 190, 2020, https://doi.org/10.1016/j.energy.2019.116421.

[15] S. Peirow, F. Razi Astaraei, A. A. Saifoddin Asl, and H. Yousefi, Sustainable Backup Power Supply of a Hospital by Designing a Hybrid Renewable Energy System, *J. Renew. Energy Environ.*, vol. 9, no. 4, pp. 48–63, 2022, https://doi.org/10.30501/jree.2022.304704.1257.

[16] A. K. Majumder, A. Al Nayeem, M. N. A. Patoary, and W. S. Carter, Temporal variation of ambient particulate matter in Chattogram City, Bangladesh, *J. Air Pollut. Heal.*, vol. 5, no. 1, pp. 33–42, 2020, https://doi.org/10.18502/japh.v5i1.2857.

[17] S. Kumaravel and S. Ashok, An optimal stand-alone biomass/solar-PV/pico-hydel hybrid energy system for remote rural area electrification of isolated village in western-ghats region of India, *Int. J. Green Energy*, vol. 9, no. 5, pp. 398–408, 2012, https://doi.org/10.1080/15435075.2011.621487.

[18] A. Akbulut, R. Kose, and A. Akbulut, Technical and economic assessments of biogas production in a family size digester utilizing different feedstock rotations: Döğer case study, *Int. J. Green Energy*, vol. 11, no. 2, pp. 113–128, 2014, https://doi.org/10.1080/15435075.2012.752374.

[19] O. Adeoti, M. O. Ilori, T. O. Oyebisi, and L. O. Adekoya, Engineering design and economic evaluation of a family-sized biogas project in Nigeria, *Technovation*, vol. 20, no. 2, pp. 103–108, 2000, https://doi.org/10.1016/S0166-4972(99)00105-4.

[20] T. C. Kandpal, B. Joshi, and C. S. Sinha, Economics of family sized biogas plants in India, *Energy Convers. Manag.*, vol. 32, no. 2, pp. 101–113, 1991, https://doi.org/10.1016/0196-8904(91)90150-H.

[21] A. Petrillo, F. De Felice, E. Jannelli, C. Autorino, M. Minutillo, and A. Lubrano, Life cycle assessment (LCA) and life cycle cost (LCC) analysis model for a stand-alone hybrid renewable energy system, *Renew. Energy*, vol. 95, pp. 337–355, 2016, https://doi.org/10.1016/j.renene.2016.04.027.

[22] S. Rubab and T. C. Kandpal, A methodology for financial evaluation of biogas technology in India, vol. 9534, no. September, pp. 10–23, 2018, https://doi.org/10.1016/0961-9534(95)00051-8.

[23] A. T. Mohammad, M. A. Al-Obaidi, H. J. Dakkama, and H. Y. Bahlol, Modelling and Optimisation of Solar Photovoltaic Power Using Response Surface Methodology, *J. Sustain. Dev. Energy, Water Environ. Syst.*, vol. 12, no. 4, pp. 1–16, 2024, https://doi.org/10.13044/j.sdewes.d12.0519.

[24] M. N. Hasan, M. A. Rahman, M. F. Ishraque, K. Ahmad, S. A. Shezan, and M. S. Ahmed, An Improved Energy Management Strategy for Hybrid Power Systems Using Dual Predator Optimization, *J. Sustain. Dev. Energy, Water Environ. Syst.*, vol. 13, no. 3, pp. 1–20, 2025, https://doi.org/10.13044/j.sdewes.d13.0586.

[25] M. I. Miskat, P. Sarker, H. Chowdhury, T. Chowdhury, and S. Rahman, Current Scenario of Solar Energy Applications in Bangladesh: Techno-Economic Perspective, Policy Implementation, and Possibility of the Integration of Artificial Intelligence, *Energies*, *16*(3), 1494, 2023, https://doi.org/10.3390/en16031494.

[26] M. L. Gitarskiy, The Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, *Fundam. Appl. Climatol.*, vol. 2, pp. 5–13, 2019, https://doi.org/10.21513/0207-2564-2019-2-05-13.

[27] A. M. Tiasha and S. Roy, Green Jobs and the Renewable Energy Transition in Bangladesh, vol. 1 April, 2025. [Accessed: 14-January-2026].

[28] International Energy Agency, CO_2 Emissions in 2023, *Int. Energy Agency*, vol. 24, p. 22, 2023, [Online]. Available: www.iea.org.[Accessed: 05- February-2026]

[29] 2006 IPCC National Greenhouse Gas Inventories, Institute for Global Environmental Strategies (IGES), Hayama, Japan, 2006. [Accessed: 25- January-2026].

[30] National Greenhouse Gas (GHG) Inventory Process and Lessons Learned, 2006 IPCC Guidelines for National Greenhouse Gas Inventories vol. 1, chap. 1, sec. 1.4, [Online]. Available:http://mrv.eis.gov.bd/media/media_upload/reports/1699241585783_1_Brouchure_GHG_Inventory_Process_Final_Output.pdf. [Accessed: 06- January-2026].

[31] K. N. Islam, T. Sarker, F. Taghizadeh-Hesary, A. C. Atri, and M. S. Alam, Renewable energy generation from livestock waste for a sustainable circular economy in Bangladesh, *Renew. Sustain. Energy Rev.*, vol. 139, no. November 2020, p. 110695,

2021, https://doi.org/10.1016/j.rser.2020.110695.

[32] T. F. Torries, Evaluating Mineral Projects: Applications and Misconceptions, 1998.

[33] M. Kamruzzaman, S. Islam, and M. J. Rana, Financial and factor demand analysis of broiler production in Bangladesh, *Heliyon*, vol. 7, no. 5, p. e07152, 2021, https://doi.org/10.1016/j.heliyon.2021.e07152.

[34] C. Li, L. He, Y. Cao, G. Xiao, W. Zhang, X. Liu, Z. Yu, Yi.Tan, and J. Zhou, Carbon emission reduction potential of rural energy in China, *Renew. Sustain. Energy Rev.*, vol. 29, pp. 254–262, 2014, https://doi.org/10.1016/j.rser.2013.08.073.

[35] M. K. Islam, N. M. S. Hassan, M. G. Rasul, K. Emami, and A. A. Chowdhury, "Life cycle environmental assessment of hybrid renewable energy system," *E3S Web Conf.*, vol. 545, 2024, https://doi.org/10.1051/e3sconf/202454501001.

[36] S. K. Khanal, Anaerobic Biotechnology for Bioenergy Production: Principles and Applications, *Anaerob. Biotechnol. Bioenergy Prod. Princ. Appl.*, pp. 1–301, 2009, https://doi.org/10.1002/9780813804545.

[37] M. F. I. Al Imam, M. Z. H. Khan, M. a. R. Sarkar, and S. M. Ali, Development of Biogas Processing from Cow dung , Poultry waste , and Water, *Int. J. Nat. Appl. Sci.*, vol. 2, no. 1, pp. 13–17, 2013.

[38] T. Bond and M. R. Templeton, Energy for Sustainable Development History and future of domestic biogas plants in the developing world, *Energy Sustain. Dev.*, vol. 15, no. 4, pp. 347–354, 2011, https://doi.org/10.1016/j.esd.2011.09.003.

[39] M. S. H. Lipu, M. Shazib Uddin, and M. A. R. Miah, A feasibility study of solar-wind-diesel hybrid system in rural and remote areas of Bangladesh, *Int. J. Renew. Energy Res.*, vol. 3, no. 4, pp. 892–900, 2013.

[40] J. Penman, M. Gytarsky, T. Hiraishi, W. Irving, and T. Krug, 2006 IPCC - Guidelines for National Greenhouse Gas Inventories, *Directrices para los Inventar. Nac. GEI*, vol. 5, p. 12, 2006, [Online]. Available: http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html, [Accessed: 27-January-2026].

[41] D. Crutchik, G. Rodríguez-Valdecantos, G. Bustos, J. Bravo, B. González, and C. Pabón-Pereira, Vermiproductivity, maturation and microbiological changes derived from the use of liquid anaerobic digestate during the vermicomposting of market waste, *Water Sci. Technol.*, vol. 82, no. 9, pp. 1781–1794, 2020, https://doi.org/10.2166/wst.2020.427.

[42] P. Mosharraf, M. S. Zahan, D. K. Das, and S. Chowdhury, Biogas Potentiality Through Waste Management in Bangladesh, *J. Renew. Energy Environ.*, vol. 7, no. 4, pp. 44–49, 2020, https://doi.org/10.30501/jree.2020.222856.1089.

[43] M. A. Case, P. Lodge, and H. Chung, The Long-Term Usage of an Off-Grid Photovoltaic System with a Lithium-Ion Battery-Based Energy Storage System on High Mountains: A Case Study in Paiyun Lodge on Mt. Jade in Taiwan, 10, 202, 2024, https://doi.org/10.3390/ batteries10060202.

[44] M. Cazel, What to Know About AGM Battery Vs. Lead Acid Battery, *AAA Connect*, 2025. [Online]. Available: https://www.acg.aaa.com/connect/blogs/4c/auto/agm-battery-vs-lead-acid-battery#:~:text=Cost & Lifespan: AGM batteries cost,typical 3–5 year lifespan, [Accessed: 17-February-2026].

[45] S. Hossain, I. N. Fahim, A. Ahmed, A. M. Arika, and S. Rahman, Techno-Economic Analysis of Solar/Wind/Biogas Hybrid Renewable Energy System in Bangladesh Using Metaheuristic Algorithms, *2023 1st Int. Conf. Adv. Electr. Electron. Comput. Intell. ICAEECI 2023*, 2023, https://doi.org/10.1109/ICAEECI58247.2023.10370989.

[46] M. F. H. Mojumder, T. Islam, P. Chowdhury, M. Hasan, N. A. Takia, N. Chowdhury, O. Farrok, Techno-economic and environmental analysis of hybrid energy systems for remote areas: A sustainable case study in Bangladesh, *Energy Convers. Manag. X*, vol. 23, no. July, p. 100664, 2024, https://doi.org/10.1016/j.ecmx.2024.100664.

[47] LPG Industry In Bangladesh - An Insider's Insight, [Online]. Available:

https://knowledgeridge.com/expert-views/lpg-industry-in-bangladesh-an-insiders-insight/2021. [Accessed: 10-February-2026].

[48] C. Roldán-Porta, C. Roldán-Blay, D. Dasí-Crespo, and G. Escrivá-Escrivá, Optimising a Biogas and Photovoltaic Hybrid System for Sustainable Power Supply in Rural Areas, *Appl. Sci.*, vol. 13, no. 4, 2023, https://doi.org/10.3390/app13042155.

[49] B. F. Silinto, C. van der Laag Yamu, C. Zuidema, and A. P. C. Faaij, Hybrid renewable energy systems for rural electrification in developing countries: A review on energy system models and spatial explicit modelling tools, *Renew. Sustain. Energy Rev.*, vol. 207, no. September 2024, 2025, https://doi.org/10.1016/j.rser.2024.114916.