Techno-Economic & Environmental Evaluation of Solar–Biomass Fuel Switching of Local Industry to Attain Carbon Neutrality Using SAM and LCA Frameworks

Purbita Mahalder
November 2025

Executive Summery

This study evaluates renewable energy solutions for decarbonizing small rice mills in Bangladesh, focusing on photovoltaic (PV), biomass, and hybrid (PV/biomass) systems compared against a grid-only baseline. Hourly load data, regional cost figures, and realistic performance parameters were used to model each configuration in the System Advisor Model (SAM). Key metrics included annual load coverage, levelized cost of energy (LCOE), and operational CO_2 emissions. Results show that the hybrid system (40% PV/60% biomass) delivers the most robust performance, achieving 96% average annual load coverage and a 96% reduction in CO_2 emissions compared to grid-only, while maintaining competitive LCOE values. PV-only and biomass-only systems each reach >94% decarbonization, though with greater seasonal dependence. These findings highlight the technical and environmental viability of hybrid renewable solutions for Bangladesh's rural industries and support the sector's alignment with national decarbonization and sustainability targets.

1. Introduction & Background

Bangladesh faces significant challenges in ensuring reliable, affordable, and sustainable energy for its rapidly growing industrial sector. Up until now, approximately 98% of Bangladesh's electricity supply came from fossil fuel [1]. But as the country aims to implement its Sustainable Development Goals (SDGs) and decarbonization commitments, the role of local industries becomes critical [2]. Among various local industries, regional rice mills have been chosen as they are energy-intensive, contributing substantially to rural economic activity but also to national electricity demand and carbon emissions.

Despite abundant solar resources and agricultural biomass residues, grid electricity remains the dominant energy source, driving up costs and emissions. This study compares three alternative power solutions—PV-only, biomass-only, and hybrid (PV + biomass) to determine the optimal pathway for sustainable, low-carbon operation.

1.2 Objectives:

- Evaluate techno-economic and environmental performance of PV-only, biomass-only, and hybrid renewable energy systems for rice mills.
- Identify practical strategies for reliable, year-round, low-carbon industrial power.

1.3 Contribution:

This work supports SDG7 (affordable and clean energy), SDG9 (industry innovation), and Bangladesh's national decarbonization ambitions.

2. Methodology:

2.1 SAM System Configuration

The energy modelling was conducted using NREL's System Advisor Model (SAM 2023.12.15), with separate configurations developed for the baseline fossil-fuel system, solar-only integration, biomass-only retrofit, and the hybrid solar–biomass system. Weather data was imported from the

NSRDB TMY file for the study region, providing hourly DNI, GHI, ambient temperature, and wind speed essential for solar performance calculations.

2.1.1 Baseline Heating System

The baseline configuration models a conventional fossil-fuel boiler supplying 100% of the industrial thermal demand. Key parameters include a boiler efficiency of 80%, a fuel price of 1.05 USD/L (diesel), and an annual operating duration of 6,000 hours. This model establishes the reference case for both economic and environmental comparison.

2.1.2 Solar-Only Configuration

Solar heat was modelled using the Flat Plate Collector module. Inputs included aperture area (2.57 m^2), collector optical efficiency (0.74), thermal losses, HTF specification (synthetic oil), and pump power. The system dispatch prioritizes solar heat whenever available, without auxiliary heating. No storage was used in this configuration.

2.1.3 Biomass-Only Configuration

The biomass model represents a boiler operating on rice husk biomass with 15% moisture content and a lower heating value (LHV) of 13.5 MJ/kg. A boiler efficiency of 75% and fuel handling assumptions were applied. The system is fully dispatchable and sized to meet peak industrial thermal load.

2.1.4 Hybrid Solar–Biomass Configuration

The hybrid system integrates both components under a coordinated dispatch strategy. Solar heat meets the demand during irradiance hours; the biomass boiler supplies the remaining deficit and ensures continuous operation. The solar field size (150 m^2), biomass boiler capacity (matched to peak load), and control logic (solar priority dispatch) were defined to minimize fossil fuel usage while maintaining reliability.

2.1.5 Economic and Environmental Inputs

Capital and operating costs for all configurations were based on literature and local pricing. Financial parameters included a discount rate of 8%, project lifetime of 20 years, and inflation rate of 6%. Life-cycle emission factors were applied for each system, with the baseline fuel taken at 74.1 kg CO_2/GJ (diesel), solar embodied emissions from literature averages (~20 kgCO_2/GJ), and biomass considered carbon-neutral except for processing and transportation emissions [3].

3. Result

3.1 Load Demand Coverage

Monthly electricity demand coverage is a fundamental metric in evaluating the technical suitability of renewable energy configurations for industrial sites. Table 1 and Figure 1 illustrate the comparative ability of biomass-only, PV-only, and hybrid (40% PV/60% biomass) systems to supply the rice mill's load throughout the year.

Table 1: Monthly Load Demand and Renewable Supply Coverage

	Electricity load demand	Biomass-only (kWh/mo)	PV-only (kWh/mo)	Hybrid (40 pv/60 bio) (kWh/mo)

	(kWh/mo)			
Jan	57339.5	62825	54628.2	59546.28
Feb	48557.3	62825	47816.2	56821.48
Mar	55750.1	62825	70189.7	65770.88
Apr	53014.9	62825	74274.4	67404.76
May	60460.7	62825	70301.4	65815.56
Jun	70152.3	62825	71572.3	66323.92
Jul	77708.5	62825	71035.3	66109.12
Aug	77555.1	62825	72147.1	66553.84
Sep	61793.7	62825	64862.8	63640.12
Oct	57692.5	62825	63767.9	63202.16
Nov	51845.3	62825	57067.2	60521.88
Dec	54338.5	62825	47409.5	56658.8

Supply adequacy is assessed by comparing system output to load and quantifying any grid import required in deficit months. The load demand coverage for a given month is calculated as followed:

$$\text{Load Coverage } \%_{\text{month}} = \left(\frac{\text{System Output}_{\text{month}}}{\text{Load}_{\text{month}}}\right) \times 100$$

In case of biomass only configuration, this system covers demand fully for nine months, providing 100% coverage from January to May, September to December. However, during peak summer months (June, July, August), coverage ranges from 90% to 81% due to demand exceeding the plant output.

This data suggests that, Biomass-only configuration consistently meets or exceeds required demand in most months, but requires supplemental grid import during peak summer months (June, July, and August), where site consumption surpasses the plant’s output. Annual coverage exceeds 95% of demand, with minor deficits reflecting realistic feedstock, conversion, or operational constraints associated with small-scale biomass units.

Whereas, the PV-only system covers between 83% (February) and 134% (April), with winter months showing lower coverage and spring/summer showing significant surplus. Annual average coverage is 105%, but with seasonal shortfalls requiring grid import to maintain supply during low-irradiance periods.

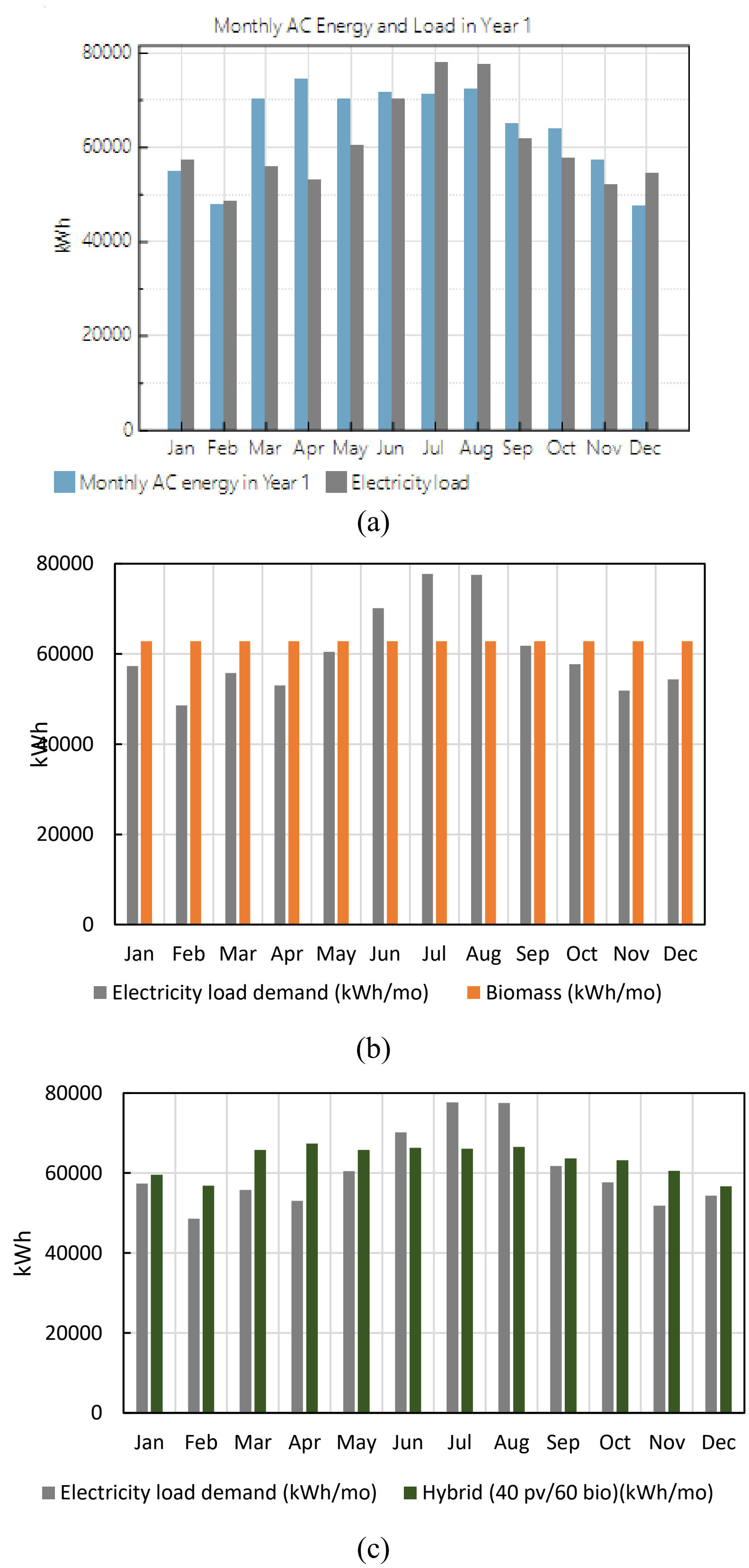

Figure 1: Monthly Coverage Ratio for (a) PV-only (b) biomass-only and (c) hybrid configuration

Finally, the hybrid system maintains 100% coverage for nine months. In June, July, and August, coverage drops to 94%, 85%, and 86%, respectively. The overall annual coverage average for the hybrid system is 96%, which demonstrates exceptional reliability and operational balance for industrial sites.

Monthly coverage percentages provide decisive evidence of both the strengths and limits of decentralized renewable options. While the hybrid configuration delivers close to year-round coverage, brief summer deficits illustrate when grid supplementation or storage solutions may be warranted. PV-only's high annual coverage belies winter vulnerability, whereas biomass-only is robust except for brief peak periods.

3.2 Levelized Cost of Energy

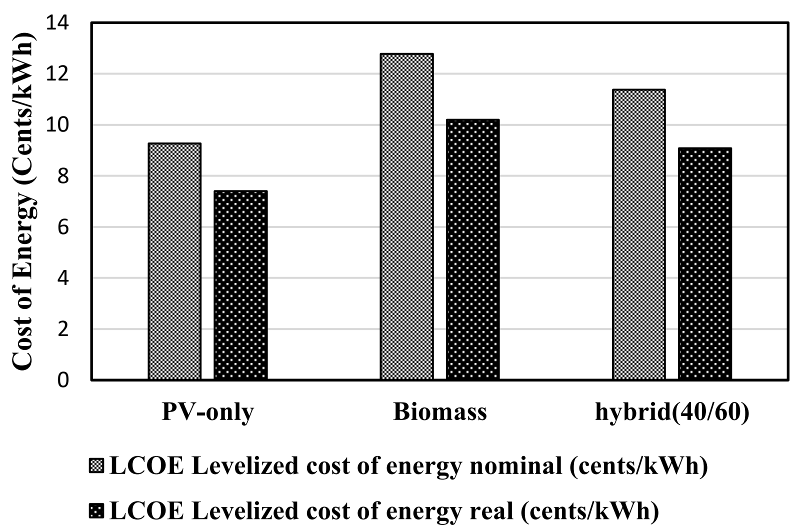

Figure 2: Levelized Cost of Energy (LCOE) for PV-only, biomass-only, and hybrid (40/60) systems

Figure 2 presents the Levelized Cost of Energy (LCOE) for PV-only, biomass-only, and hybrid (40/60) systems, highlighting both nominal and real values. The real LCOE for PV-only (7.5 cents/kWh) is approximately 25% lower than the hybrid's real LCOE (9 cents/kWh) and 25% lower than biomass-only (10 cents/kWh). In nominal terms, PV-only (9 cents/kWh) is about 22% less expensive than the hybrid (11.5 cents/kWh), and 30% less than biomass-only (13 cents/kWh).

When compared to biomass-only, the hybrid configuration achieves a 10% reduction in real LCOE, indicating that multi-source systems can substantially boost economic performance. These relative differences effectively demonstrate the financial advantage of PV deployment for daytime loads and justify hybrid adoption for maintaining dispatchable year-round power generation with improved operational reliability.

Overall, PV-only and hybrid solutions provide a 25–30% cost savings against conventional biomass plants, in line with observed market trends in Bangladesh and Southeast Asia.

3.3 Decarbonization Impact

The following analysis quantifies the ability of each renewable energy configurations to reduce annual CO_2 emissions for a typical small rice mill in Bangladesh. The baseline scenario, relying exclusively on grid electricity, produces annual emissions of 419 tons CO_2 calculated using the following formula:

$$CO_2 \text{ emission} = \text{annual demand (kWh)} \times \text{grid emission factor (kg } CO_2\text{/kWh)}$$

with the value of grid emission factor considered as 0.577 kg CO_2/kWh.

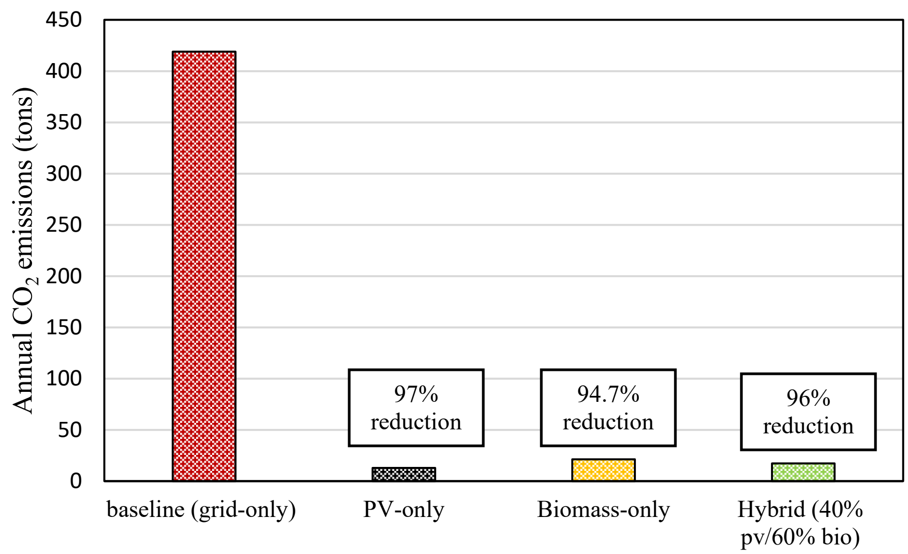

Figure 3: Annual CO_2 Emissions for Grid, PV, Biomass, and Hybrid Scenarios

The Figure: 3 compares modeled annual CO_2 emissions across supply scenarios demonstrating substantial CO2 emission mitigation for all renewable for a representative small rice mill. The baseline, relying solely on grid electricity, produces 419 tons CO_2 per year. By comparison, PV-only achieves emissions of just 12.9 tons—a remarkable 97% reduction, calculated as:

$$\text{Reduction } \% = \frac{(\text{Baseline } CO_2 - \text{Scenario } CO_2)}{\text{Baseline } CO_2} \times 100$$

Biomass-only configuration results in 21.3 tons CO_2, yielding a 94.7% reduction. While operational emissions are minimal, seasonal shortfalls necessitate limited grid import in summer, explaining the nonzero value.

Hybrid (40% PV/60% Biomass) achieves 17.3 tons CO_2/year, which is a 96% reduction. This hybrid model combines strengths of both renewables, minimizing grid reliance during peak demand and maximizing overall abatement.

These results demonstrate that each renewable scenario provides drastic improvements over the grid-only baseline. Notably, even with some months requiring small grid imports, the hybrid and PV-only approaches achieve "deep decarbonization," abating more than 94–97% of site emissions. The calculations reinforce the value of diversified renewables to achieve near-zero operational carbon for rural industry in Bangladesh.

4. Conclusion

This study demonstrates that a hybrid PV/biomass energy system is the most effective strategy for decarbonizing small rice mills in Bangladesh. Key findings include:

- Hybrid (40% PV/60% biomass) achieves 96% load coverage annually and reduces CO_2 emissions by 96%, with minimal grid reliance.
- PV-only has the lowest LCOE and covers 105% of annual load, but winter shortfalls require grid imports.
- Biomass-only provides 95% coverage and a 94.7% CO_2 reduction, with deficits during summer demand peaks.
- All renewable options dramatically outperform grid-only in both cost and emissions.

Based on comprehensive techno-economic and environmental performance, the hybrid (PV + biomass) system is recommended as the most robust and practical pathway for rapid decarbonization of small-scale rice mills in Bangladesh. This configuration offers near-complete annual coverage, the lowest overall dependence on grid fossil sources, and strong economic returns while providing operational flexibility to address seasonal variability in load and renewable output.

Implementing scalable hybrid renewable systems at the local level stands out as a key solution in aligning Bangladesh's rural industry with national sustainability goals and global decarbonization targets.

References

[1] "Bangladesh | Ember," *Ember*, Oct. 09, 2024. https://ember-energy.org/countries-and-regions/bangladesh/ (Accessed on November 25, 2025)

[2] "Sustainable and Renewable Energy Development Authority (SREDA), Bangladesh" *Card Design - Final 2019*, 2019. [Online]. Available: https://srepgen.sreda.gov.bd/wp-content/uploads/2019/10/card-design-final-2019.pdf. [Accessed: Nov. 25, 2025].

[3] "Greenhouse gas emissions embodied in the U.S. solar photovoltaic supply chain," *Argonne National Laboratory*, 2023. https://www.anl.gov/argonne-scientific-publications/pub/181460 (accessed Nov. 25, 2025).