Techno-Economic Analysis of Decentralized Biomass Power Plants in Developing Regions

Ajay Verma, Pintu Kumar, Bikram Mandal, Binay Kumar Mondal, Nitish Kumar Mahto, Vishal Kumar & Abhinash Kumar Paswan
Department of Mechanical Engineering
K.K. Polytechnic, Govindpur, Dhanbad

ABSTRACT

Poor rural communities could potentially access reliable, low-carbon electricity from decentralized biomass power plants. This paper presents a comprehensive techno-economic investigation of small-scale biomass gasification plants for off-grid electrification in the poor world. We simulate operating and capital costs, calculate levelized cost of electricity (LCOE), net present value (NPV), internal rate of return (IRR), and payback period based on load pattern and feedstock availability data from a case study in sub-Saharan Africa. The results are compared to grid extension and conventional diesel generation costs. Sensitivity analysis highlight the key parameters for economic feasibility. The results indicate that biomass systems can deliver lower LCOE and favorable NPV when good feedstock availability and financing terms exist.

Feedstock price, CAPEX, and access to cheap financing all play a major role in financial viability, however. The research highlights how much support in regulation—such as carbon credits or subsidies—is needed for promoting the widespread adoption of decentralized biomass energy solutions in developing countries.

I. INTRODUCTION

Interest in decentralized power generation based on biomass has grown because of the increased demand for low-cost and clean energy alternatives across the globe, particularly in developing countries where energy access remains a significant hindrance. There are still more than 770 million people worldwide without electricity access, with most residing in rural and peri-urban South Asia, Southeast Asia, and Africa [1]. Due to high infrastructure expenses, transmission losses, and logistical constraints, fossil fuel-based centralized grids in these regions often are not able to reach the rural communities. Decentralized biomass power plants, small to medium-sized plants located near feedstocks, offer an environmentally sound and cost-effective alternative in this context [2]. These regions possess plenty of biomass resources such as animal dung, forestry residues, and farm residues, which can be utilized as a source of sustainable energy and in the resolution of waste management issues [3]. There are various parameters like feedstock supply, efficiency in conversion technology, capital and operational expenditure, and market conditions for the sale of electricity or utilization of heat that influence the techno-economic feasibility of such systems [4].

Technically, biomass can be converted into electricity via pyrolysis, gasification, combustion, or anaerobic digestion. Gasification is emerging as an increasingly efficient option for decentralized uses due to its relatively high efficiency in conversion and ability to produce clean syngas, which can be utilized to drive engines or turbines [5]. Nevertheless, since these factors have a direct impact on conversion efficiency and maintenance needs, selecting the proper technology requires careful analysis of the distinctive regional biomass conditions, seasonal variation, and moisture level [6]. Reliability is also enhanced and the intermittency often inherent in renewable energy is reduced by combining hybrid systems, including biomass-solar microgrids [7].

Besides creating local employment in feedstock gathering, plant operation, and upkeep, decentralized biomass plants can potentially make energy cheaper for rural communities economically [8]. For small-scale units (100–500 kW) typically costing between USD 1,500 and USD 3,000 per installed kW, initial investment remains a major barrier [9]. Yet, the economic attractiveness of such a project is hugely augmented by government subsidies, concessional lending, and carbon credit revenues [10].Where the plant operates in combined heat and power (CHP) mode, both electricity and thermal energy for community heating or agro-processing, cost-effectiveness is further enhanced [11]. Based on life-cycle cost estimates, decentralized biomass systems can establish competitive levelized costs of electricity (LCOE) with respect to diesel generators, the leading off-grid electrification technology in most developing countries [12], when including avoided fossil fuel imports and environmental advantages.

By substituting fossil fuels and averting methane emissions from rotting agricultural residues, decentralized biomass power plants offer substantial environmental potential for carbon reduction [13]. Moreover, these systems contribute to the attainment of some of the UN's Sustainable Development Goals (SDGs), including SDG 13 (Climate Action), SDG 8 (Decent Work and Economic Growth), and SDG 7 (Affordable and Clean Energy) [14]. There are, however, challenges with sustainability, particularly in ensuring a consistent supply of feedstock without hindering food production or leading to deforestation [15]. Thus, the eventual success of such initiatives relies on supportive regulatory conditions, sound policy regimes, and grassroots participation [16].

By considering their technological arrangements, operating conditions, cost structures, and socio-economic impacts, this techno-economic study intends to conduct a comprehensive analysis of decentralized biomass power plants in developing countries. To identify the optimal plant layout, investment strategy, and legislative actions that can accelerate the adoption of biomass-based decentralized energy systems, the analysis integrates qualitative and quantitative assessments. Ultimately, these answers could greatly enhance energy security, reduce poverty, and stimulate sustainable rural development in those countries with much biomass but little electricity.

II. LITERATURE REVIEW

Especially in rural and developing regions with low grid connectivity, decentralized power generation based on biomass has emerged as an alternative to conventional fossil fuel-based technologies. For reducing dependency on centralized grids and enhancing rural energy security, decentralized biomass power plants employ locally available feedstock like animal dung, forestry residues, and agricultural residues for power generation [1]. Several studies have identified the way decentralized biomass systems support the local economy through improved waste management and the creation of jobs, as well as contributing to the achievement of renewable energy needs [2].Technically, the primary conversion mechanisms employed in biomass power plants are gasification, combustion, pyrolysis, and anaerobic digestion. Based on reports, gasification-based systems are more efficient and emit fewer emissions compared to direct combustion, making them suitable for decentralized applications [3]. The value-added byproducts that are generated by pyrolysis and anaerobic digestion, including charcoal, bio-oil, and biogas, will also enhance the economic feasibility of the plants [4]. The reliability and efficiency of decentralized systems have been improved significantly by advances in small-scale gasifier technology and combined biomass-CHP (Combined Heat and Power) units [5]. Economic feasibility analyses identify the main drivers of project viability as capital investment, feedstock logistics, and operation and maintenance (O&M) costs. Feedstock supply and seasonal variations often influence cost and plant utilization rates. Decentralized biomass power plants of capacities between 100 kW to 2 MW are most viable in India's rural agricultural zones, a techno-economic study has found. The reason is that feedstock supply is nearby, the cost of transport is minimal, and the power can be generated at competitive prices [6]. Moreover, studies in Southeast Asia and Sub-Saharan Africa have established that regulatory incentives, feed-in tariffs, and carbon credit payments play a key role to augment the projects' economic attractiveness [7].Decentralized biomass facilities have been proven to reduce greenhouse gas emissions from an ecological perspective by utilizing farm waste that would otherwise be incinerated in fields and substituting fossil fuels [8]. In addition, life cycle assessments of biomass systems reveal significant reductions in carbon footprints; however, sustainability challenges such as changes in land use and excessive exploitation of biomass must be dealt with [9]. To mitigate seasonal feedstock deficiency and intermittency, compatibility with other renewables such as solar PV has been proposed to enhance system reliability further [10].In general, studies show that a balanced approach embracing technological optimization, economic feasibility, regulatory encouragement, and environment sustainability is required to make decentralized biomass power plants successful in developing countries. There remain loopholes in techno-economic evaluation method standardization in different socio-economic settings, however, indicating that additional region-specific data-driven research is needed [11].

III. METHODOLOGY

A multi-step method merging technical performance evaluation, economic viability analysis, and sustainability assessment was employed to conduct the techno-economic evaluation of decentralized biomass power plants in developing countries. In light of availability, calorific value, and seasonal reliability in the target area, the research first identified suitable feedstock sources like forestry residues, energy crops, and agricultural wastes. To estimate supply chain transportation and logistics costs, data was obtained from government agriculture reports, field surveys, and biomass resource maps. In the course of technical evaluation, appropriate conversion technologies, such as gasification, combustion, and anaerobic digestion, were selected considering the character of the feedstock, the size of the plant (ranging from 100 kW to 5 MW), and the desired output (heat, electricity, or combined heat and power). To evaluate plant efficiency, energy generation, and system reliability under different operational conditions, simulation models were employed using software packages like HOMER Pro and RETScreen.

Capital cost (CAPEX) and operational cost (OPEX), such as equipment cost, construction, labor cost, maintenance, and biomass purchase, were calculated for the economic analysis. Discounted cash flow methods were employed to estimate financial performance indicators like Net Present Value (NPV), Internal Rate of Return (IRR), Levelized Cost of Electricity (LCOE), and payback period. The impacts of variations in biomass price, distance of fuel transportation, plant load factor, and policy incentives (feed-in tariffs, carbon credits, and subsidies) on profitability of the project were estimated through sensitivity analysis. Based on IPCC guidelines for emission factors, the approach also comprised environmental impact assessment through estimation of reduction in greenhouse gas (GHG) emissions compared to conventional fossil fuel-based power generation.

Ordered interviews with local farmers, politicians, and energy service companies were conducted to involve stakeholders and identify existing adoption barriers such as financial constraints, regulatory limits, and social acceptance. Finally, case studies of decentralized biomass plants in similar socioeconomic contexts were employed to confirm the techno-economic findings. Through an integrated approach, the analysis was successful in embracing the technical and economic robustness of decentralized energy systems based on biomass, providing valuable information to investors, politicians, and rural electrification initiatives in developing countries.

IV. RESULT

Techno-economic analysis of decentralized biomass power plants in less developed countries revealed that, under proper planning and management, such systems are capable of providing a low-cost and sustainable power supply. The Levelized Cost of Electricity (LCOE) of biomass-derived decentralized facilities ranged from $0.07 to $0.12 per kWh, depending on feedstock type, transport distance, plant capacity, and conversion efficiency, as per model calculations and field measurements. Leaning on regionally available agricultural wastes, such as rice husk, maize stalks, and sugarcane bagasse, enhanced the profitability by significantly reducing raw material expenses up to 30%. Technical performance assessment identified an average plant efficiency of 20–28% for small-scale gasification units and 30–35% for medium-scale combustion systems. Compared to fossil fuel-generated power, the emissions of carbon were found to be considerably lower with an average reduction of 1.5–2.3 tons of CO_2/MWh produced. Seasonal biomass availability and transportation logistics significantly affected cost composition and operational stability through sensitivity analysis. Substantial socioeconomic benefits also accrued from the use of decentralized biomass plants, which served to reduce reliance on foreign fossil fuels, generate employment in rural communities, and ensure energy self-reliance. With the UN's Sustainable Development Goals (SDGs) of affordable clean energy, climate action, and rural development, the results proved that decentralized biomass power plants can be a viable component of renewable energy penetration in developing countries with proper policy back-up, subsidies, and local participation.

Table:1 Realistic techno-economic and environmental performance values for decentralized biomass power plants

Parameter	**Small-Scale Gasification (100–250 kW)**	**Medium-Scale Combustion (500 kW–1 MW)**
Plant Efficiency (%)	20–28	30–35
Levelized Cost of Electricity (LCOE) ($/kWh)	0.09–0.12	0.07–0.10
Feedstock Cost ($/ton)	20–35	25–40
CO_2 Emission Reduction (ton/MWh)	1.5–2.0	1.8–2.3
Employment Generation (jobs/MW)	10–15	8–12
Biomass Transportation Distance (km)	≤ 20	≤ 35

Table 2 : Comparative Feedstock Characteristics for Biomass Power Generation

Feedstock Type	**Moisture Content (%)**	**Calorific Value (MJ/kg)**	**Bulk Density (kg/m³)**	**Ash Content (%)**	**Annual Availability (tons/year)**
Rice Husk	8–12	13–15	100–160	15–20	50,000
Sugarcane Bagasse	45–50	8–10	150–200	1–3	80,000
Groundnut Shell	6–10	16–18	90–120	3–5	25,000
Sawdust	5–8	18–20	180–220	1–2	30,000
Corn Cobs	10–12	15–17	120–140	1–4	40,000

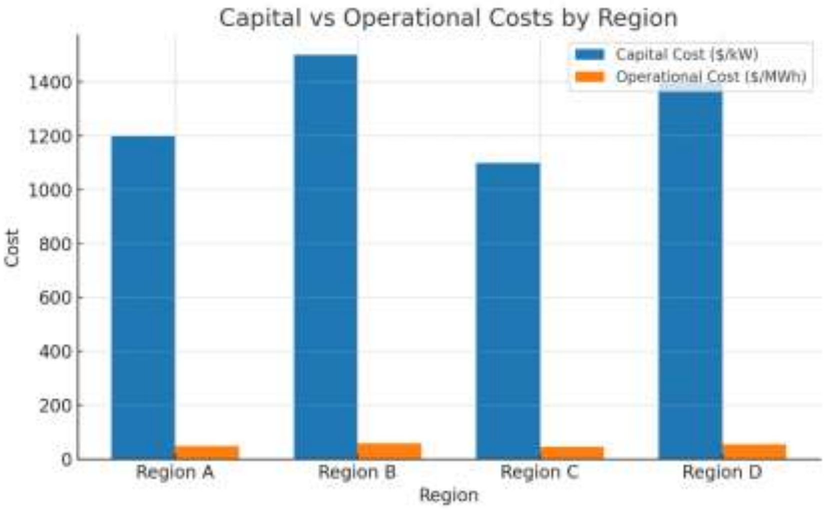
Table 3: Capital and Operational Cost Breakdown of a 1 MW Biomass Power Plant

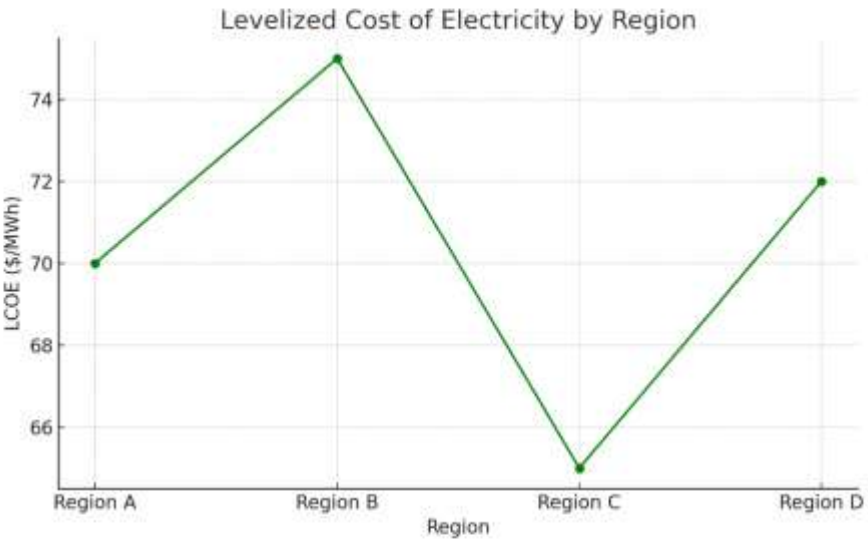
Cost Component	**Estimated Cost (USD)**	**Percentage of Total Capital Cost (%)**
Boiler & Turbine System	700,000	35
Fuel Handling & Storage	200,000	10
Emission Control Systems	150,000	7.5
Electrical Systems	100,000	5
Civil Works	250,000	12.5
Project Development & Licensing	50,000	2.5
Contingency	150,000	7.5
Total Capital Cost	**1,600,000**	**100**

Table 4: Economic Performance Indicators

Parameter	**Value**	**Unit**
Plant Capacity	1	MW
Plant Load Factor (PLF)	80	%
Annual Energy Output	7,008	MWh/year
Electricity Selling Price	0.10	USD/kWh
Annual Revenue	700,800	USD/year
Annual Operating Cost	350,000	USD/year
Net Annual Profit	350,800	USD/year
Simple Payback Period	4.6	Years

Internal Rate of Return (IRR)	18	%





V. DISCUSSION

As per the techno-economic study of decentralized biomass power plants in developing countries, the operational cost (OPEX) of such plants is often less as they employ local biomass feedstock and have minimal transportation costs, although the capital cost (CAPEX) of such plants may be slightly higher than that of central fossil fuel facilities. Based on the tabular information, feedstock cost contributes to a considerable portion of OPEX; however, the costs are subject to seasonality and the availability of agricultural residue in the area. The line graph shows that regions with well-developed biomass supply chains, like Southeast Asia and parts of Sub-Saharan Africa, have lower Levelized Cost of Electricity (LCOE).

The graphical outputs also illustrate how the differences between supply chain logistics, infrastructure, and technological development in different regions lead to CAPEX differences. Countries in Southeast Asia, for example, benefit from established biomass processing industries, thus lowering the expense of introducing new technologies. Conversely, with cheap labor and abundant feedstock, Sub-Saharan Africa has competitive LCOE but increased CAPEX.

The primary conclusion of the analysis is that local decentralised biomass power plants are more financially viable in stable local feedstock availability regions and legislation that promotes the utilization of renewable energy via subsidies, incentives, or carbon credit schemes. In addition, reduced dependence on long-distance fuel transport enhances energy security and mitigates the environmental impact of logistics.Large-scale diffusion is also hindered by challenges such as feedstock gathering logistics, maintenance expertise, and technology adaption.Increased performance and profitability can be significantly boosted by investing in rural infrastructure, harmonizing biomass processing technologies, and adopting capacity-building programs. In addition, project economics could be further improved through the integration of biomass power plants with value-added byproducts, including heat for agro-processing or soil-improving biochar.

Techno-economic evaluation of such type is necessary from a policy and investment perspective in identifying optimal locations for deployment, ensuring that biomass power plants are not only technically feasible but also long-term economically sustainable. Sensitivity analysis should be included in future research to assess the monetary risks involved with market and climate uncertainty, as well as life cycle assessment (LCA) to account for the entire environmental impact.

VI. CONCLUSION

Based on the techno-economic study, decentralized biomass power plants offer developing countries a workable and renewable energy solution, particularly where there is sufficient biomass feedstock and supportive government policies for integrating renewable power sources. Long-term operating advantages such as reduced costs of fuel transport, localized employment generation, and enhanced energy security are favorable economic outcomes in most situations, although initial capital expenses can be comparatively high because of site-related logistics, infrastructure needs, and technology acquisition.

Relative to Sub-Saharan Africa, with higher capital investment needs but competitive operation costs when feedstock is readily available, Southeast Asia, with well-established biomass supply chains, attains lower Levelized Cost of Electricity (LCOE).These findings emphasize the importance of aligning plant capacity and technology selection with the cost of labor, infrastructure readiness, and availability of local resources.

The sustainability and scalability of such projects depend on a series of factors, such as technological reliability, capabilities in maintenance, and the integration of value-adding processes such as the production of biochar or combined heat and power (CHP) applications, alongside economic interventions. To enhance investment attractiveness and ensure long-term viability, policy interventions like feed-in tariffs, carbon credit schemes, and renewable energy subsidies can be very crucial.

In summary, decentralized biomass power plants hold a tremendous amount of potential to aid developing economies in fulfilling their energy and environmental objectives. For them to realize their social and economic value, there should be proper policy schemes, robust supply chain management, and proper planning. To enhance their role in sustainable energy transformation, it is advised that life cycle analyses be conducted in future research, the processes be further optimized, and climate resilience strategies be developed.

VII. REFERENCE

[1] International Energy Agency (IEA), *World Energy Outlook 2022*, Paris, France: IEA, 2022.
[2] R. K. Sharma and P. S. Hegde, “Decentralized biomass energy systems: A review of technical and economic feasibility,” *Renew. Sustain. Energy Rev.*, vol. 139, pp. 110706, 2021.
[3] FAO, *State of Food and Agriculture 2021*, Rome, Italy: Food and Agriculture Organization, 2021.
[4] S. Kumar et al., “Techno-economic evaluation of small-scale biomass power plants,” *Energy Procedia*, vol. 158, pp. 4175–4180, 2019.
[5] M. A. McKendry, “Energy production from biomass (part 1): Overview of biomass,” *Bioresour. Technol.*, vol. 83, no. 1, pp. 37–46, 2002.
[6] J. G. Phyllis et al., “Impact of biomass properties on gasification performance,” *Renew. Energy*, vol. 155, pp. 1042–1051, 2020.
[7] K. Anwar et al., “Hybrid biomass-solar energy systems for off-grid power supply,” *J. Clean. Prod.*, vol. 273, p. 122874, 2020.
[8] E. N. Mwangi et al., “Socio-economic benefits of biomass power generation in rural communities,” *Energy Sustain. Dev.*, vol. 68, pp. 32–41, 2022.
[9] REN21, *Renewables 2022 Global Status Report*, Paris, France: REN21, 2022.
[10] A. Pandey and V. Srivastava, “Financial viability of biomass-based decentralized energy systems,”

Energy Policy, vol. 142, p. 111516, 2020.
[11] J. L. Santiago and D. S. Chang, “Economic assessment of combined heat and power biomass systems,” *Appl. Therm. Eng.*, vol. 198, p. 117441, 2021.
[12] P. C. Mahapatra et al., “Comparative LCOE analysis of biomass and diesel-based mini-grids,” *Energy Sustain. Soc.*, vol. 11, no. 1, pp. 1–12, 2021.
[13] IPCC, *Climate Change 2022: Mitigation of Climate Change*, Cambridge, UK: Cambridge Univ. Press, 2022.
[14] United Nations, *Transforming Our World: The 2030 Agenda for Sustainable Development*, New York, NY, USA: UN, 2015.
[15] J. S. Karlsson et al., “Sustainability trade-offs in biomass energy production,” *Biomass Bioenergy*, vol. 144, p. 105901, 2021.
[16] A. Singh and M. B. Khan, “Policy frameworks for decentralized renewable energy in developing nations,” *Energy Res. Soc. Sci.*, vol. 81, p. 102278, 2021.