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RESEARCH ARTICLE

Biogas vs. Pipeline Gas in Rural Energy Transitions: A Comparative Sustainability Assessment Using Multi-Criteria Decision Analysis (MCDA)

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Abstract: Rural energy transitions in Bangladesh are central to achieving Sustainable Development Goal 7, yet policymakers face difficult trade-offs across environmental, economic, social, and technical dimensions. This study conducts a comparative sustainability assessment of biogas and pipeline gas using a Multi-Criteria Decision Analysis (MCDA) framework combining Analytic Hierarchy Process (AHP) weighting with TOPSIS ranking. Primary data were collected via a structured household survey (n = 120) in rural Cumilla, complemented by expert pairwise comparisons to derive criteria weights. AHP prioritized environmental (0.4658) and social (0.2771) criteria over economic (0.1611) and technical (0.0960) considerations (Consistency Ratio = 0.0115). TOPSIS results ranked pipeline gas as the more sustainable option overall (score = 1.000), while biogas scored lower (0.000). Dimension-wise analysis showed small differences in environmental and technical performance, but a marked advantage for pipeline gas in social acceptability and economic feasibility. Findings indicate that while biogas offers clear environmental benefits and circular-economy synergies, adoption barriers—upfront costs, maintenance burdens, and variable user experience—limit perceived sustainability. Policy priorities include targeted biogas subsidies, user training and maintenance services, and context-specific hybrid models integrating biogas where resources allow and pipeline gas where infrastructure is viable.

Keywords: Biogas; Pipeline gas; MCDA; AHP–TOPSIS; Rural Bangladesh; Sustainable energy; SDG 7; Energy transition

1. Introduction

The efforts towards clean energy in rural Bangladesh represent one of the most critical realizations of Sustainable Development Goal 7 (SDG 7), which aims to ensure universal access to affordable, reliable, sustainable, and modern energy. Bangladesh has made significant progress through renewable energy initiatives—particularly solar home systems and biogas technologies—achieving notable advances in rural electrification. Solar home system (SHS) ownership positively affects electricity consumption in remote areas, contributing to economic development in territories beyond conventional grid access (Hasan, 2023). SHSs have reduced energy costs and improved living standards in areas where approximately 30% of rural homes are connected to grid power (Debnath et al., 2023). Biogas technology offers an additional dimension of rural energy supply, converting farm and organic waste into energy while addressing waste management challenges (Wasi et al., 2024). Biogas systems reduce reliance on conventional biomass fuels, which contribute to deforestation and energy poverty (Hassan et al., 2013).

Bangladesh's dependence on natural gas as a primary power source has intensified interest in diversifying the energy mix through pipeline network expansion and integration with renewable alternatives including biogas (Ahmed et al., 2015; Islam et al., 2014). The comparative sustainability assessment of these two energy sources—biogas and pipeline gas—requires a multi-dimensional framework that can systematically weigh environmental, economic, social, and technical trade-offs. Multi-Criteria Decision Analysis (MCDA) methods, particularly the combination of AHP for criteria weighting and TOPSIS for alternative ranking, have proven effective for transparent, context-aware energy decision-making (Waas et al., 2014; Shaaban et al., 2018).

Study Objectives and Research Questions

The general objective of this study is to conduct a comparative sustainability assessment of biogas and pipeline gas as rural energy sources in Bangladesh using MCDA, focusing on environmental, economic, social, and technical dimensions. Specific objectives include: (1) evaluating environmental sustainability of each energy source; (2) assessing economic feasibility and cost-effectiveness; (3) investigating social acceptability and health-related benefits; (4) comparing technical reliability and infrastructure readiness; and (5) applying AHP and TOPSIS for sustainability ranking.

The primary research question asks: Which rural energy source—biogas or pipeline gas—offers greater overall sustainability in the context of rural Bangladesh as measured by MCDA? Secondary questions examine environmental impacts, cost and affordability dynamics, community perceptions, infrastructural challenges, and the effectiveness of MCDA in ranking the two alternatives for evidence-based policy decisions.

2. Literature Review

The concept of rural household energy transition in developing countries reveals complex social, economic, and infrastructural dynamics in the shift toward cleaner energy sources. The energy ladder hypothesis demonstrates a shift toward more refined fuels with ascending household income (Goswami et al., 2017; Timilsina et al., 2023), though this process is non-uniform and characterized by significant disparities across income groups and regions (Haq et al., 2024). Biogas digesters improve livelihoods in rural communities by saving energy costs, reducing reliance on wood fuel, and supplying organic manure (Berhe et al., 2017). Technical advances in biogas have confirmed its economic viability for cheap cooking and heat production in rural settings (Wang et al., 2020; Raja & Wazir, 2017). Combined pipeline and domestic biogas investments can provide rural populations with access to both renewable and conventional energy options (Salleh et al., 2016; Hamid & Blanchard, 2018).

Sustainability evaluation frameworks for rural energy systems must integrate environmental, financial, and social indices (Waas et al., 2014). MCDA tools have been utilized effectively to compare energy systems and support resource allocation decisions (Schröder et al., 2018; Shaaban et al., 2018). Participatory stakeholder assessments enhance relevance and applicability by raising acceptance and improving the quality of decision-making in rural settings (Coelho et al., 2010). The gap in comparative lifecycle sustainability analysis of biogas and pipeline gas, and the challenges of integrating these two energy forms into coherent policy, represent the primary research lacunae this study addresses (Tonrangklang et al., 2022; Zhao et al., 2023).

3. Conceptual Framework

Four sustainability constructs are assessed: **Environmental Sustainability** (greenhouse gas emissions, deforestation, pollution, renewable resource utilization; Waas et al., 2014; Sharma & Bandyopadhyay, 2023); **Economic Sustainability** (affordability, lifecycle costs, income generation potential; Wang et al., 2020; Raja & Wazir, 2017); **Social Sustainability** (public health impacts, energy access equity, gender burden, community acceptance; Mensah & Adu, 2015; Faizan & Thakur, 2019); and **Technical Sustainability** (reliability, infrastructure readiness, maintenance capacity, scalability; Hossain et al., 2023; Zhao et al., 2023). The dependent variable is the overall TOPSIS sustainability ranking score, derived from AHP-weighted independent variables grouped across these four dimensions.

4. Methodology

4.1 Research Design and Study Area

This study adopted a comparative cross-sectional research design using a quantitative approach integrated with MCDA. The study was conducted in Cumilla District, located in south-eastern Bangladesh, selected for its high rural population density, co-existence of pipeline gas connections and small-scale biogas installations, active NGO-led renewable energy initiatives, and diversity in socioeconomic backgrounds and energy-use behaviors. The study focused specifically on rural unions in Cumilla Sadar South and Lalmai Upazilas.

4.2 Sampling and Data Collection

Stratified random sampling ensured balanced representation from households using biogas (n = 60) and pipeline gas (n = 60), for a total of 120 households. Purposive sampling identified key informants including local leaders, energy technicians, and NGO representatives. A structured questionnaire was administered face-to-face by trained enumerators fluent in Bangla. Sections covering environmental, economic, social, and technical assessment used a 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree). Interviews lasted approximately 25–30 minutes per household. The questionnaire was pre-tested with 10 participants in a neighboring union.

4.3 MCDA Implementation

AHP was applied for criteria weighting through expert and user pairwise comparisons across the four sustainability dimensions. Normalized scores from household responses were aggregated and compared between biogas and pipeline gas using TOPSIS. Content validity was ensured through expert review by energy professionals from SREDA and BRAC. Reliability was tested through Cronbach's alpha (>0.7 for all dimension-specific scale items). The Consistency Ratio (CR = 0.0115) confirmed logical consistency in AHP judgment matrices (threshold: CR < 0.1).

5. Results

5.1 AHP Criteria Weights

Table 1 presents the AHP-derived weights for the four sustainability dimensions. Environmental sustainability received the highest weight (0.4658), followed by social (0.2771), economic (0.1611), and technical (0.0960). These weights reflect expert judgment that environmental and social considerations should dominate the comparative assessment in the rural Bangladeshi context.

Table 1. *AHP Criteria Weights and Interpretation*

Sustainability Dimension	AHP Weight	Interpretation
Environmental	0.4658	Most important — renewable and low-emission considerations dominate
Social	0.2771	Second priority — health, gender burden, community acceptance
Economic	0.1611	Third priority — cost, affordability, local job creation
Technical	0.0960	Least weighted — infrastructure, reliability, scalability

Note. CR = 0.0115, confirming consistency (CR < 0.10 threshold met).

5.2 TOPSIS Ranking

Table 2 presents the TOPSIS sustainability ranking results. Pipeline gas ranked as the more sustainable alternative with a TOPSIS score of 1.000, while biogas scored 0.000. Pipeline gas outperformed biogas across all four sustainability dimensions, with the most notable advantage in the social dimension (3.39 vs. 2.94). Environmental and technical dimension scores were comparable between the two alternatives.

Table 2. *TOPSIS-Based Sustainability Ranking Results*

Fuel Type	Environmental	Economic	Social	Technical	TOPSIS Score
Biogas	3.01	3.06	2.94	3.11	0.000
Pipeline Gas	3.06	3.15	3.39	3.18	1.000

Note. TOPSIS score range: 0 (least sustainable) to 1 (most sustainable). Dimension scores are mean Likert ratings (1–5 scale).

5.3 Comparative Analysis by Sustainability Dimension

Table 3 presents the dimension-wise comparative analysis with mean scores, standard deviations, and interpretive notes. The greatest divergence between the two energy sources was in the social dimension (pipeline gas M = 3.39, SD = 0.71; biogas M = 2.94, SD = 1.07). The high variability for biogas (SD = 1.07) indicates inconsistent user experiences, particularly among women who bear disproportionate maintenance burdens. Environmental and technical dimensions showed minimal gaps, while the economic dimension slightly favored pipeline gas due to government subsidy structures and lower operational complexity.

Table 3. *Comparative Analysis by Sustainability Dimension*

Dimension	Pipeline Gas	Biogas	Gap	Interpretation
Environmental	Pipeline Gas: 3.06 (SD 0.80)	Biogas: 3.01 (SD 0.84)	Small gap	Both rated similarly; users prefer pipeline gas for reduced indoor smoke
Economic	Pipeline Gas: 3.15 (SD 0.86)	Biogas: 3.06 (SD 0.83)	Minor gap	Pipeline gas benefits from government subsidies and stable monthly costs
Social	Pipeline Gas: 3.39 (SD 0.71)	Biogas: 2.94 (SD 1.07)	Largest gap	Pipeline gas rated consistently safer and easier to use; biogas shows high variability
Technical	Pipeline Gas: 3.18 (SD 0.87)	Biogas: 3.11 (SD 0.84)	Minimal gap	Both similar; pipeline gas slightly more reliable and stable

6. Discussion

6.1 Interpretation of MCDA Rankings

The MCDA framework yields a clear preference for pipeline gas over biogas as a sustainable rural energy solution. Despite biogas being traditionally promoted as a low-carbon, renewable alternative, this study demonstrates that its real-world adoption and perceived benefits are not yet sufficiently strong to rival pipeline gas in users' assessments. This reflects not only the technologies themselves but also the systemic infrastructure support, reliability, associated costs, and social acceptability in everyday use. Pipeline gas enjoys favorable perception due to consistent service delivery, government-backed subsidies, and infrastructural convenience. These findings are consistent with literature on energy transition in developing countries, where socioeconomic factors—income, education, infrastructure access—primarily drive household energy choices (Haq et al., 2024; Goswami et al., 2017).

6.2 Social and Economic Dimensions

Social sustainability recorded the greatest gap between alternatives. Biogas systems require daily engagement—biomass feedstock management, technical maintenance, and troubleshooting—that places a disproportionately large burden on women and older household members, reducing usability and acceptability (Shabnam & Girling, 2022; Ashraf et al., 2019). The high variability in biogas social scores (SD = 1.07) points to inequities in access and experience, with households possessing better education or livestock availability benefiting more. The economic dimension showed a slight advantage for pipeline gas due to national subsidies and centralized infrastructure, despite biogas's theoretical cost-effectiveness from locally produced fuel. Upfront installation costs, recurring maintenance, and feedstock collection were the main economic impediments reported by biogas users (Wang et al., 2020; Raja & Wazir, 2017).

6.3 Policy Implications

These findings call for a multi-pronged rural energy policy. First, river nomadic communities and rural households should be formally recognized in disaster risk reduction and climate adaptation frameworks with explicit psychosocial support provisions. Second, targeted subsidies for biogas installation in rural areas—particularly for low-income and female-headed families—are needed, alongside microfinance partnerships and pay-as-you-go schemes. Third, behavior change campaigns, local youth and women trained as 'biogas champions,' and demonstration projects in each Union Parishad can normalize biogas usage. Fourth, hybrid energy models—biogas as primary source with pipeline gas as seasonal backup, or biogas-grid integration—offer resilience and flexibility by respecting local resource constraints while pursuing sustainable outcomes.

7. Conclusion

This study conducted a comparative sustainability assessment of biogas and pipeline gas in rural Bangladesh using the AHP–TOPSIS MCDA framework. Among 120 rural respondents, pipeline gas ranked highest in TOPSIS sustainability scoring (1.000), primarily due to strengths in social acceptability, economic feasibility, and technical reliability. Biogas, while environmentally aligned with circular economy principles, ranked lower (0.000) due to constraints in cost, maintenance burden, and social adoption barriers. The AHP weights confirmed the primacy of environmental and social considerations in rural household decision-making. Findings contribute empirical evidence from Bangladesh to SDG 7 energy access strategies, offering nuanced insights into household preferences and system trade-offs. Future research should explore longitudinal analyses, life-cycle environmental assessments, and the effectiveness of hybrid policy interventions combining biogas incentives with pipeline gas infrastructure investment.

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