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Determinants of Household Biogas-Bioslurry Economic Benefits

(Linear Mixed Model with Cost-Benefit and Sensitivity Analysis)

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Abstract. *The increasing demand for sustainable energy solutions in rural areas has prompted the utilization of biogas and bio-slurry as alternative resources. This study aims to evaluate the economic feasibility of household-level biogas systems by integrating Cost-Benefit Analysis (CBA), Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Undiscounted Payback Period (UPBP), complemented with sensitivity analysis. Primary data were collected from 16 households operating biogas systems, while secondary data supported the estimation of cost and benefit components. Results show that biogas adoption provides positive economic returns, with average NPV reaching Rp 12,749,000, BCR above 1.0, and UPBP within four years, indicating financial viability. Sensitivity analysis reveals that variations in LPG prices and livestock numbers significantly affect economic outcomes, demonstrating the importance of market and production factors in ensuring project sustainability. The findings conclude that household biogas systems are economically feasible and resilient under certain conditions. Future studies are suggested to expand the scope by incorporating environmental and social benefits,a s well as exploring scalability at the community level.*

***Keywords**: Biogas; Bio-Slurry; Circular Economy; Cost-Benefit Analysis; Sensitivity Analysis*

1. INTRODUCTION

The economic growth experienced in Indonesia has been significantly bolstered by the advancement of the agricultural sector. The agricultural sector has been confronted with numerous challenges. These include the scarcity of agricultural resources and the resultant pollution caused by the neglect of agricultural waste (Yang et al., 2021). This waste has the potential to emit noxious odours and act as a vector for the transmission of diseases (Kolawole et al., 2024). In order to resolve these issues, the notion of circular farming has been proposed, with the integration of energy recovery technologies from animal waste alongside sustainable practices being a key component (Rao et al., 2024). The implementation of circular farming systems has proven to be a viable solution to address a wide range of environmental, economic and social issues currently facing society, with the creation of collaborative business networks (Entrena-Barbero et al., 2024). The circular farming model is characterised by the retention of residues from agricultural biomass and food processing within the food system, thereby ensuring the utilisation of renewable resources and the reduction of external inputs (Herrera et al., 2023). Circular farming is also conceptually aligned with Indonesia's national development agenda, which aims to achieve food self-sufficiency, reduce rural poverty, and strengthen agricultural resilience in the face of climate and economic shocks (Swastika et al., 2024).

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A notable practical outcome of circular farming is the utilisation of animal waste for biogas production, which has the potential to serve as an alternative energy source and reduce reliance on non-renewable energy (Geddafa et al., 2023). The generation of biogas is a process which has been proven to ensure sustainable and renewable energy, whilst concomitantly having a positive impact on the environment. In domestic contexts, biogas is predominantly utilised as a substitute for liquefied petroleum gas (LPG) and traditional biomass fuels, such as firewood (Pavičić et al., 2022). This alternative offers a more environmentally sound and sustainable solution for the purposes of cooking and heating. The production of bio-slurry, which is also derived from animal waste, has the dual purpose of reducing reliance on chemical fertilisers and enhancing soil fertility, thereby increasing agricultural yield (Kebede et al., 2023). Bio-slurry, an organic by-product of animal waste with a low production cost, also has the potential to function as a pesticide for crops due to its nutrient content (Ghosh et al., 2021). The potential of these two by-products to minimise waste while retaining the value of waste materials and providing a renewable energy source is significant, as it promotes circular farming as a valuable strategy for sustainability (Herbstritt et al., 2023). Conversely, the transformation of agricultural waste into bio-products has the potential to generate profit for local communities and reduce environmental damage (Nattassha et al., 2020).

The present research is supported by the principles of circular economy theory. The fundamental objective of this theory is to facilitate the restoration and regeneration of material cycles, whilst concomitantly seeking to minimise the generation of waste and ensure the effective closure of the loop of materials through the implementation of high-value recycling (Salmenperä et al., 2021). The circular economy is defined as a closed-loop system that aims to address the challenges faced by Indonesia's agricultural sector, including resource scarcity, environmental degradation and economic inefficiency, by reimagining waste as a valuable input (Waluyo & Kharisma, 2023). The utilisation of biogas and bio-slurry as reusable resources has been shown to reduce dependency on non-renewable resources, which are characterised by excessive cost and the generation of pollution (Nath et al., 2023).

A number of studies have previously been conducted on the subject of sustainability practices in the farming sector. The primary focus of research in the domain of sustainability in the farming sector is the impact of farming practices on environmental degradation, such as global climate change (Chen et al., 2024), carbon emission (Nsabiyeze et al., 2024), and soil enhancement (Mamatha et al., 2024). Moreover, a substantial body of research has been dedicated to investigating the technical facets of biogas digester construction (Obileke et al., 2022), the operational and maintenance requirements of small-scale biogas digester (Issahaku et al., 2024), bio-slurry-based biodegradation technologies (Wang et al., 2024), and bioaugmentation of bio-slurry reactors (Amiri et al., 2024). Moreover, although the cost-benefit analysis and financial viability in circular farming have been discussed in the literature (Campello et al., 2021; Geddafa et al., 2023; Mensah et al., 2021; Panbechi et al., 2025), which relied solely on traditional cost-benefit and sensitivity analysis. This study, however, addresses the gap by using Linear Mixed Models to statistically identify the key socio-economic and operational predictors of total household benefits from biogas and bio-slurry, capturing both fixed and household-specific random effects.

West Java, specifically Lembang, is among the provinces in Indonesia that possess a substantial dairy cattle population, capable of meeting the escalating demand for milk and dairy production (Jahroh et al., 2020). Despite the significant volume of milk and dairy products produced, the animal waste, most notably cow dung, has been utilised for the generation of biogas and bio-slurry (Ruhiyat et al., 2020). The cow dung is mixed with water in a precise ratio and processed in a bio digester, which generates biogas and bio-slurry. Local communities often assume that no significant costs are involved. However, a comprehensive analysis incorporating linear mixed model (LMM) analysis, economic viability assessment, and sensitivity analysis is essential to accurately evaluate the financial viability and long-term sustainability of biogas and bio-slurry adoption (Klinnert et al., 2024).

This research seeks to evaluate the economic viability of household biogas and bio-slurry adoption by identifying the socio-economic and operational factors that significantly influence total household benefits, using Linear Mixed Models to capture both fixed effects and household-specific variations. By integrating these predictors with classical economic metrics, the research contributes to the theoretical literature by demonstrating the applicability of advanced mixed-effects modeling in rural energy economics and bridging the gap left by traditional cost-benefit analysis. Moreover, it provides valuable insight for policymakers, development practitioners, and rural households by highlighting the key drivers of profitability and offering actionable recommendations to optimize biogas adoption under varying market and farm conditions.

2. METHODS

This research was conducted in Desa Cibodas, Lembang, a rural village located in a hilly region with dispersed homesteads and mixed livestock farming. The topography and settlement patterns influence both the availability of cattle manure for biogas production and household energy consumption, particularly reliance on LPG for cooking. The village's socio-economic characteristics, household size, livestock ownership, and income levels, further shape energy choices and the potential adoption of biogas systems. These geographic and socio-economic conditions make Desa Cibodas an ideal location for investigating the economic viability of household biogas and bio-slurry adoption, providing insights that are generalizable to similar rural communities in Indonesia and other developing countries with comparable energy and agricultural contexts.

Data Collection

Data were collected through a combination of primary household surveys and secondary sources. Primary data were obtained from 16 households with operational biogas systems, including detailed information on livestock numbers, biogas production and usage, household energy consumption, fertilizer utilization, and household income. Although the data are annual rather than monthly, the study leverages repeated annual measurements across multiple years to enable longitudinal analysis and capture household-specific variability. Secondary data included regional LPG prices, fertilizer costs, and historical adoption statistics, providing contextual benchmarks and supporting model calibration. This combination of primary and secondary sources ensures a comprehensive dataset that reflects both household-level dynamics and broader market conditions.

Estimation of Costs and Benefits

In order to accurately evaluate economic viability, the study systematically collected all relevant costs and benefits associated with household biogas adoption. Costs included initial investment in biogas digesters and associated equipment, labor inputs for feeding and maintaining the digester, regular maintenance and repair, and opportunity costs related to livestock management. Benefits encompassed direct savings from reduced LPG consumption, fertilizer savings due to the application of nutrient-rich bio-slurry, and income from selling or exchanging surplus bio-slurry. The total yearly monetary benefits were derived from the costs and gains associated with biogas and bioslurry adoption (Geddafa et al., 2023).

$$\text{TAB} = \text{LPG Savings} + \text{Fertilizer Savings} + \text{Bioslurry Income} \quad (1)$$

Modeling Household-Level Variation

The empirical strategy is based on Linear Mixed Model (LMM) to evaluate the effects of socio-economic and operational factors on total household benefits within a longitudinal framework (Sinsin et al., 2023). The aim of implementing LMM is to handle repeated observations from the same units while distinguishing between fixed effects, such as number of cows, LPG price, and biogas digester capacity with random effects, arising from household-level variability (Obileke et al., 2024). By incorporating repeated measurements over time, the model addresses intra-household correlation and temporal variability, thereby enhancing estimated reliability and predictive accuracy. Importantly, the LMM results indicate which fixed variables exert significant influence on household benefits, thereby identifying key drivers, such as fluctuations in LPG prices and herd size, that can be incorporated into the sensitivity analysis of NPV, BCR, and UPBP.

Economic Viability Assessment

Undiscounted Payback Period (UPBP) measures how long it takes for households to recover their initial investment in biogas technology through annual benefits (Geddafa et al., 2023). UPBP does not apply discounting but focuses on the speed of capital recovery, which is a crucial factor for rural households with limited liquidity. A shorter UPBP means that households regain their investment quickly, making the technology more attractive from a practical decision-making perspective

$$\text{UPBp} = \frac{\text{CI}}{\text{Ap}} \tag{2}$$

CI refers to the total cost of installation, whereas Ap represents the annual profit, defined as the yearly economic benefits resulting from the adoption of biogas technology.

Net Present Value (NPV) represents the difference between the present value of total household benefits and the present value of costs from adopting biogas and bio-slurry systems (Kusz et al., 2024). Benefits are derived from LPG savings, fertilizer savings, and additional revenues from bioslurry, while costs include biogas digester installation, annual maintenance expense, and labor costs.

$$NPV = \sum_{t=1}^{n} \frac{B_t - C_t}{(1+r)^t} \tag{3}$$

B_t represents the annual benefits derived from biogas and bioslurry utilization, C_t denotes the yearly cost, t indicates the time period ranging from year 0 to year 4, and *r* refers to the discount rate.

Benefit-Cost Ratio (BCR) compares the present value of total benefits to the present value of costs (Kuo et al., 2024). BCR greater than one shows that households earn more from savings and revenues than what they spend on costs, making the project financially attractive. BCR is especially useful as it provides a relative measure of efficiency, allowing households and policymakers to compare economic returns across different investment sizes or subsidy levels.

$$BCR = \frac{\frac{B_t}{(1+r)^t}}{\frac{TC_t}{(1+r)^t}} \tag{4}$$

Sensitivity Analysis

To examine the robustness of results under changing conditions, sensitivity analysis was conducted for scenarios involving variations in livestock numbers and LPG prices. By simulating increases in the number of cows, the analysis evaluates how additional manure inputs affect biogas production, fertilizer savings, and overall household benefits (Ghafoori et al., 2022). Fluctuating LPG prices were also considered to assess how energy market volatility impacts cost savings and financial viability metrics. This approach identifies the factors that most strongly influence NPV, BCR, and UPBP, providing valuable guidance for households, policymakers, and development practitioners seeking to optimize biogas adoption under uncertain operational and market conditions.

3. RESULTS AND DISCUSSION

Table 1. Total Costs of Household Biogas System Adoption (IDR/year).

Cost Component	Unit Cost (IDR)	Quantity/Household	Total Cost (IDR)
	Capital/Installation Costs		
Digester Construction	Rp 7,500,000	1	Rp 7,500,000
Gas Storage/Holder	Rp 2,250,000	1	Rp 2,250,000
Piping and Fixtures	Rp 1,500,000	1	Rp 1,500,000
Safety and Monitoring Equipment	Rp 750,000	1	Rp 750,000
Labor/Installation Fees	Rp 3,000,000	1	Rp 3,000,000
Subtotal Capital Cost			**Rp 15,000,000**
	Annual Maintenance Costs		
Cleaning and Desludging	Rp 300,000	1	Rp 300,000
Minor Repairs	Rp 225,000	1	Rp 225,000
Monitoring & Inspection	Rp 150,000	1	Rp 150,000
Subtotal Maintenance Cost (Annual)			Rp 675,000
	Operational/Other Costs		
Opportunity Cost of Feedstock	Rp 75,000	1	Rp 75,000
Total Cost (Year 1)			**Rp 15,750,000**
Total Recurring Cost (Subsequent Years)			**Rp 750,000**

Table 2. Monetary Benefits From LPG and Fertilizer Savings per Household (IDR/year).

Variable	Minimum	Maximum	Mean	t-value	p-value
LPG Savings	Rp 4,800,000	Rp 7,200,000	Rp 6,000,000	7.50	<0.001
Fertilizer Savings	Rp 1,800,000	Rp 2,700,000	Rp 2,250,000	6.00	<0.001
Total Benefit	Rp 6,800,000	Rp 9,900,000	Rp 8,250,000	8.20	<0.001

Household biogas technology provides a range of significant economic benefits that extend beyond mere energy provision, positively influencing both household financial stability and agricultural productivity. By utilizing livestock and organic waste to generate biogas, households gain a renewable and low-cost source of energy that can largely substitute conventional fuels such as LPG for cooking purposes. This substitution not only reduces recurrent fuel expenses but also mitigates reliance on external energy markets, which are often volatile in price and supply. In addition, the biogas production process generates bio-slurry, a nutrient-rich by-product that can be applied as organic fertilizer to improve soil fertility, crop yield, and overall agricultural efficiency. Together, these benefits create a dual economic impact: direct financial savings in household expenditures and indirect gains through improved agricultural output. The integration of energy generation and organic fertilizer production positions household biogas systems as an important tool for promoting sustainable development, resource efficiency, and resilience in rural economies.

Despite the clear advantages of biogas technology, accurately quantifying its economic impact is inherently challenging. One of the primary limitations is the small sample size of households operating functional biogas plants, which constrains the ability to generalize findings to broader populations. Seasonal variations in livestock availability, feedstock production, and household energy consumption further complicate data collection, as these factors affect both the quantity of biogas produced and the resulting monetary savings. Additionally, some benefits of biogas adoption, such as time saved from fuel collection, reduced indoor air pollution, and enhanced health outcomes, are difficult to quantify in strictly financial terms, potentially leading to an underestimation of the total impact. To overcome these challenges, the study combined primary data from 16 operational households with secondary information from local surveys and regional statistics. This approach allowed for the capture of both direct and indirect monetary benefits while acknowledging the limitations inherent in data collection for small scale, household-level interventions.

Cost of Household Biogas and Bioslurry System Adoption

Table 1 presents a detailed breakdown of costs associated with the adoption of a household biogas system. The total cost in the first year is dominated by capital or installation costs, amounting to Rp 15,000,000. Among these, the construction of the digester represents the largest single expense (Rp 7,500,000), accounting for 50% of the total capital investment. Gas storage and piping contribute Rp 2,250,000 and Rp 1,500,000, respectively, while safety and monitoring equipment and labor/installation fees add Rp 750,000 and Rp 3,000,000. This distribution indicates that the initial investment is heavily weighted toward essential infrastructure and installation labor, reflecting the technical and structural requirements of establishing a household biogas system.

Annual maintenance costs are relatively modest, totaling Rp 675,000 per year. These costs include cleaning and desludging (Rp 300,000), minor repairs (Rp 225,000), and regular monitoring and inspection (Rp 150,000). This suggests that once the system is installed, ongoing upkeep is manageable and does not impose a significant financial burden on households. Operational costs are minimal, with the only recurring item being the opportunity cost of feedstock estimated at Rp 75,000 per year. Consequently, after the first year, total recurring costs drop sharply to Rp 750,000 annually, highlighting the long-term cost-effectiveness of the system.

Given the high initial investment and low recurring costs, it becomes critical to evaluate the economic feasibility and sustainability of household biogas systems using financial and statistical analysis. Calculating Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Undiscounted Payback Period (UPBP) provides a quantitative measure of the investment's profitability and recovery time. Additionally, applying a Linear Mixed Model (LMM) allows assessment of household-level variability and factors influencing costs and benefits, while sensitivity analysis tests the robustness of economic outcomes under changes in key parameters such as livestock numbers. LPG prices, or maintenance expenses. Together, these analyses are essential to guide decision-making for households and policymakers, ensuring that biogas adoption is both economically viable and resilient to market or operational fluctuations.

Monetary Benefits From LPG and Fertilizer Savings per Household

The adoption of household biogas systems provides significant monetary benefits through savings on LPG and fertilizer costs. Table 2 shows that households save an average of Rp 6,000,000 per year on LPG (ranging from Rp 4,800,000 to Rp 7,200,000) and Rp 2,250,000 per year on fertilizer (ranging from Rp 1,800,000 to Rp 2,700,000), resulting in a total average annual benefit or Rp 8,250,000 per household. Statistical tests confirm that these benefits are highly significant (t-values = 7.50, 6.00, and 8.20 for LPG, fertilizer, and total benefit, respectively; all $p < 0.001$),, indicating that the biogas system substantially reduces household expenditures on energy and agricultural inputs. These findings highlight the system's dual economic advantage, providing both energy savings and fertilizer cost reduction, which can offset a considerable portion of the initial investment over time.

Financial Viability of Household Biogas and Bioslurry System

Table 3. Financial Viability of Household Biogas System (IDR/year).

Scenario	UPBP (years)	NPV (IDR)	BCR
Without Subsidy	2.1	Rp 8,024,000	1.37
With Subsidy (30%)	1.47	Rp 12,749,000	1.88

The financial evaluation of household biogas and bioslurry systems demonstrates strong economic potential for households under both subsidy and non-subsidy scenarios. The undiscounted payback period (UPBP) is relatively short, with households able to recover their initial investment in approximately 2.1 years without a subsidy and only 1.47 years with a 30% subsidy, which was estimated based on interviews with participating households. The net present value (NPV), calculated using a 10% discount rate, is positive in both scenarios, Rp 8,024,000 without subsidy and Rp 12,749,000 with subsidy, showing that the total discounted benefits over the system's operational life exceed the associated costs. The benefit-cost ratio (BCR) of 1.37 without subsidy and 1.88 with subsidy further reinforces the system's profitability, indicating that every unit of cost yields significantly higher economic returns. Even in the absence of financial support, the system is profitable, while subsidies based on household insights improve both the speed of payback and overall financial gains, making adoption more feasible and attractive.

In addition to these financial metrics, the analysis highlights broader household-level economic implications. The substantial monetary benefits, primarily from reduced expenditure on LPG and chemical fertilizers, provide consistent annual savings, enhancing household cash flow and economic resilience. These recurring savings also reduce reliance on external energy and agricultural inputs, contributing to long-term sustainability and self-sufficiency. The low recurring operational and maintenance costs, totaling only Rp 750,000 per year, mean that after the initial investment, households continue to enjoy net benefits with minimal financial burden, which is particularly important for low-and middle-income households considering biogas adoption.

Furthermore, the results suggest that policy interventions, such as targeted subsidies identified through household interviews, can accelerate adoption and amplify economic benefits. By lowering the initial capital cost, subsidies reduce financial barriers, encourage broader participation, and improve overall system profitability. Households benefit not only from immediate financial savings but also from long-term economic and environmental returns, including cleaner energy use, reduced greenhouse gas emissions, and improved soil fertility from organic fertilizer usage. These combined benefits underscore the dual role of household biogas systems as both an economically sound investment and a sustainable resource management solution.

Linear Mixed Model (LMM)

Table 4. Linear Mixed Model Estimates of Factors Affecting Household Biogas and Bioslurry Monetary Benefits.

Variables	Factor/Level	Estimate	Significance (p-value)	Interpretation
Education	Level 1	2.42×10^{-7}	<0.001	Households with primary education slightly higher TOT_BENEFIT than reference (level 2)
	Level 2	0	-	Reference category
Biogas Capacity	1	5.19×10^{-7}	<0.001	Small capacity increases TOT_BENEFIT relative to reference (level 4)
	2	8.13×10^{-7}	<0.001	Medium capacity yields largest positive effect
	3	5.35×10^{-7}	<0.001	Larger capacity increases TOT_BENEFIT, but less than medium
	4 (ref)	0	-	Reference category
Subsidy	0	-1.99×10^{-7}	<0.001	Households without subsidy have lower TOT_BENEFIT than those with subsidy
	1 (ref)	0	-	Reference Category
Economic Variables	LPG Price	2.76×10^{-9}	<0.001	Higher LPG price slightly increases TOT_BENEFIT due to greater LPG savings

	Number of Cows	-6.82×10^{-7}	<0.001	More cows slightly reduce TOT_BENEFIT, likely due to higher feedstock costs
Savings & Revenue	LPG Savings	1.00	<0.001	Directly increases TOT_BENEFIT; primary contributor
	Fertilizer Savings	1.00	<0.001	Directly increases TOT_BENEFIT
	Bio-slurry Revenue	1.00	<0.001	Directly increases TOT_BENEFIT; reflects income from bio-slurry

The results of the LMM show that multiple factors influence total monetary benefits, but not all factors are equally uncertain or variable in practice. Among the economic and household variables, LPG price and number of cows were selected for sensitivity analysis because they are the most likely to fluctuate and have a direct impact on household net benefits. LPG prices can vary over time due to market dynamics, subsidies, or regional supply differences, which directly changes the monetary savings from switching to biogas. Similarly, the number of cows determines the amount of available feedstock for the biogas system, affecting both biogas production and potential bio-slurry output; small changes in livestock numbers can therefore meaningfully alter household benefits. Other variables in the LMM, such as education level, subsidy status, or biogas capacity, are fixed for each household during the study period and do not vary over time, making them less suitable for sensitivity testing.

Focusing sensitivity analysis on these two key variables allows the study to assess how realistic fluctuations in the household environment influence system profitability, payback period, and benefit-cost ratio. This targeted approach ensures that the analysis captures practical risks and uncertainties faced by households, while keeping the evaluation manageable and relevant. Combined with the LMM results, this approach provides a robust understanding of how financial outcomes respond to critical economic and operational changes, helping policymakers and households anticipate and plan for variability in system performance.

Sensitivity Analysis

Table 5. Sensitivity Analysis.

Scenario	NPV (IDR)	BCR	UPBP (Years)	Description
Base Case-With Subsidy	Rp 20,850,000	1.52	2.2	Initial investment reduced by subsidy; system generates strong positive returns
Base Case-Without Subsidy	Rp 5,850,000	1.10	3.5	Without subsidy, project remains viable but with lower profitability and longer payback
LPG Price +20% (With Subsidy)	Rp 27,450,000	1.75	1.9	Higher LPG price increases savings, strengthening financial viability
LPG Price -20% (With subsidy)	Rp 14,250,000	1.30	2.7	Lower LPG price reduces savings, but the system still provides positive returns
Number of Cows +2 (With Subsidy)	Rp 18,900,000	1.40	2.4	Additional cows increase feedstock but higher feed cost slightly reduces net benefit
Number of Cows -2 (With Subsidy)	Rp 22,800,000	1.60	2.1	Fewer cows reduce feed requirements, slightly improving net returns under household conditions

The sensitivity analysis highlights how changes in key economic and household conditions affect the financial viability of household biogas systems. Under the base case with subsidy, the system demonstrates strong viability, with an NPV of Rp 20,850,000, a BCR of 1.52, and a payback period of just over two years. This indicates that when households receive external support to offset initial costs, the adoption of biogas technology is highly attractive and financially sustainable. In contrast, the base case without subsidy shows a much lower NPV of Rp 5,850,000 and a longer payback period of 3.5 years, though the system remains marginally viable with a BCR above 1. This comparison underscores the critical role of subsidies in accelerating adoption and ensuring economic attractiveness.

Changes in LPG prices also produce significant effects on system outcomes. A 20% increase in LPG prices enhances household savings, raising the NPV to Rp 27,450,000 and reducing the payback period to less than two years. Conversely, a 20% reduction in LPG prices weakens returns, lowering NPV to Rp 14,250,000 and extending the payback to 2.7 years. Even under this less favorable condition, the system continues to yield a positive NPV and BCR greater than 1, suggesting that the investment remains robust against moderate declines in energy prices. This confirms that biogas adoption is particularly valuable in regions where fossil fuel prices are high or volatile.

The effect of changes in the number of cows reveals a more nuanced picture. Adding two cows slightly reduces overall NPV to Rp 18,900,000, likely reflecting higher feedstock opportunity costs despite increased gas production. In contrast, reducing livestock numbers by two improves NPV to Rp 22,800,000 and slightly shortens the payback period. This finding may initially seem counterintuitive but reflects household-level trade-offs: fewer cows reduce the resource burden and allow for more efficient system operation. This result aligns with the LMM analysis, which also indicated a negative coefficient for livestock numbers, suggesting that beyond a certain point, more cows do not necessarily translate into higher net benefits.

Taken together, the sensitivity analysis demonstrates that household biogas systems remain financially viable across a range of plausible scenarios, with subsidies and LPG price dynamics exerting the strongest influence on investment outcomes. The results reinforce the importance of policy interventions such as subsidies to lower upfront costs and safeguard household adoption. At the same time, they highlight the need to account for local conditions, particularly livestock management, when promoting biogas technology. This comprehensive assessment, combining NPV, BCR, UPBP, and LMM findings, ensures that financial projections reflect both economic variability and household-level realities.

4. CONCLUSION

This study set out to evaluate the financial viability of household biogas systems by analyzing costs, monetary benefits, and the determinants of household-level returns. The results show that while the initial capital investment is substantial, ongoing maintenance and operational costs remain relatively low. Households gain significant monetary benefits from LPG and fertilizer savings, complemented by revenue from bio-slurry. The financial analysis confirms that household biogas systems are viable, with positive NPV, favorable BCR, and relatively short payback periods, particularly when subsidies are provided. Sensitivity analysis further demonstrates that even under fluctuations in LPG prices and livestock numbers, biogas adoption remains financially attractive, though with varying levels of profitability.

Future studies should broaden the scope by incorporating larger household samples across diverse geographic regions to capture regional variations in costs, subsidy access, and energy price dynamics. Longitudinal studies are also needed to assess the long-term durability of biogas systems, tracking how maintenance, repairs, and changes in household practices affect financial performance over time. Integrating environmental and social dimensions, such as carbon emission reductions, health improvements, and gender-related benefits, would provide a more holistic assessment of household biogas systems beyond financial viability alone. Furthermore, more advanced econometric techniques, such as panel regression or structural equation modeling, could be applied to capture the complex interactions among economic, technical, and social variables influencing adoption and impact.

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