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DECENTRALIZED BIOMETHANE INJECTION AND ORGANIC FERTILIZER RECOVERY: ECONOMIC AND ENVIRONMENTAL EVIDENCE FROM RURAL PUNJAB, PAKISTAN

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Abstract

This paper assesses the financial and environmental sustainability of the decentralized village-level biogas systems that inject the purified biomethane into the Pakistani natural gas grid and produce livestock waste organic fertilizer. In rural Punjab, having very dense farm stock animals and unsaturated organic waste, the study develops a deterministic economic-environmental model that incorporates energy generation, fertilizer recovery and emission of greenhouse gases reduction. According to findings, a typical biogas unit with the size of the village of 10, 000 people is expected to generate approximately 247 m3 of grid-quality biomethane and four tons of organic fertilizer daily if it is fed on 10,000 kg of livestock dung per day. The financial analysis shows that it has a good commercial viability and the internal rate of return is above 25 percent and the net present value is positive at more than a decade. Environmental evaluation displays a significant amount of methane reduction, equating to the saving of approximately 277 metric tons of CO 2 -equivalent emission every year. Comparative evaluation shows that biomethane provides energy at a much reduced cost per kilowatt-hour as compared to imported liquefied natural gas (LNG), and enhances energy security, rural monetary gain, and lessening of emissions. The sensitivity analysis ensures that the viability of the entire system is solid under a large variety of conditions both technical and in the market. The results indicate that decentralized biomethane systems are an affordable and scalable policy to decrease the LNG reliance, foster sustainable farming, and boost efforts to climate change and energy transition in Pakistan.

Keywords: Decentralized biogas; Biomethane injection; Renewable gas; LNG substitution; Organic fertilizer; Livestock waste; Energy security; Climate mitigation; Pakistan
JEL Classification: Q42; Q12; Q16; Q54; Q56

1. Introduction

The issue facing Pakistan agricultural and energy sectors is the increasing reliance on imported energy, environmental management degradation and underutilization of rural biomass. The agriculture sector relies on livestock farming that makes up more than 60% of the value added in the sector and generates massive volumes of organic waste, along with Punjab State, rural (Government of Pakistan, 2023). Unless there is the high quality waste-to-resource systems, this biomass produces methane and contaminates the environment rather than recycles. Further, in Pakistan, the domestic energy consumption continues to be largely dependent on the imported liquefied natural gas (LNG), which undermines the fiscal balance of the country and puts the country at risk of the global price volatility (IEA, 2021).

The biogas systems could be decentralized, which proves to be really interesting because on the one hand, it addresses the energy scarcity, on the other hand, it solves the environmental challenges and agricultural problems. According to the previous research, decentralized renewable energy is capable of enhancing energy accessibility in rural areas, enhancing resilience, and reducing dependency on centralized networks based on fossil-fuel sources (Bhattacharyya, 2013; Munir et al., 2018). Livestock manure is converted to renewable methane using the biogas technology and to organic fertilizer in the form of digestate, a circular agriculture (Wakeel et al., 2023).

The question guiding this study is the following: Could village-based biogas units that inject purified biomethane into the national grid and produce organic fertilizer lead to economic and environmental benefits in the rural Punjab? The issue is important since LNG imports impose a burden on the balance of payment of Pakistan and increase the prices of fertilizers thereby increasing costs incurred by farmers and damaging the soil (Government of Pakistan, 2023; UNDP Pakistan, 2022). A system, which substitutes imported energy and reduces reliance on synthetic fertilizers, would not only appropriate several externalities, but would also provide individual and collective payoffs.

Although previous studies assess the bio-gas potential and energy output by modelling (Borges et al., 2021; Nehra and Jain, 2023) and analyze the technical aspects of injecting renewable gas into the country grid (Keogh et al., 2022), there are very few papers that evaluate energy substitution, fertilizer recovery, financial feasibility, and environmental benefit on a single economic basis in Pakistan.

In order to close this gap, this paper constructs a deterministic economical-environmental model of assessing decentralized biogas systems in rural Punjab. The results point to the financial viability of village scale units, the significant reduction in greenhouse-gas emissions, and the relative affordability of these types of units as an alternative source of imported LNG. These findings highlight the importance of decentralized biogas as a strategic instrument of sustainable energy transition, rural development and mitigation of the climate conditions in Pakistan.

2. Literature Review

The implementation of biogas technologies in the rural economy has found its way into the academic and policymaking communities due to its ability to address energy deficits, reduce environmental losses, and facilitate environmentally friendly farming. One of the clean and renewable alternatives available to the traditional fuel sources, such as firewood, kerosene and fossil fuel, particularly in the developing countries, is the biogas, an anaerobic end result of the digestion process of organic waste, including livestock manure (Surendra et al., 2014). Besides power, biogas systems produce digestate - a highly nutritive byproduct of various biomass that can partially serve as the substitute to chemical fertilizers, since the combination of renewable energy and sustainable agriculture is achieved.

Emerging literature highlights the enhanced access to electricity by rural areas due to decentralized energy systems. The implementation of off-grid and community-based renewable energy is socially positive and technically viable with Bhattacharyya (2013) demonstrating that the technology is effective in South Asia. Decentralized systems enhance resiliency, reduce transmission losses, and enable local owners. Similar conclusions are made by Karekezi et al. (2002), who state that renewable technologies may flourish in the rural areas after they are consistent with the local socio-economic factors. In both, current difficulties (as documented) relate to funding constraints, flaky institutions and unpredictability in policy, which are detrimental to mass adoption.

In as much as bio-gas has its promise, it has serious challenges that hinder its uptake. Nehra and Jain, who have conducted a study about the potential of biogas based on the livestock manure in India (2023) have evaluated cultural resistance, lack of proper maintenance, and lack of economic incentives as the major obstacles. These are of concern to Pakistan where other socio-institutional problems are prevailing. Wakeel et al. evaluate the resources of biogas in Pakistan and determine that despite the potential being huge, solar and wind have dominated the agenda set by policy makers. In turn, biogas is not reflected in renewable energy plans of nations, although it would be suitable in rural areas and in livestock-intensive settings.

Less empirical studies have been done about Pakistan. In their work, Munir et al. (2018) investigate rural energy solutions and highlight the fact that biogas plants managed by a community can increase the access to energy and rural development in Punjab. They emphasize on methane recovery importance and appropriate utilization of biogas slurry. Nevertheless, their analysis is overwhelmed by description and does not entail a strict quantitative assessment of economic viability, that is, large-scale grid integration, or market prospects of organic fertilizer using digestates. Accordingly, there is no proper research on the economics of decentralized biogas systems. Although the energy literature has been able to move forward, studies on sustainable agriculture have developed an interest on how organic compounds can alleviate adverse externalities associated with intensive use of chemical fertilizers. Ghafoor et al. (2010) demonstrate that biogas system productions (digestate) enhance soil fertility, soil structure and reduce the use of artificial fertilizers, including urea and DAP. The results indicate some important agronomic and environmental advantages. Nonetheless, few articles measure the wider economic effects of fertilizer recovery particularly with regards to farm level saving of money, generation of revenue and the longer term productivity of soil. This disparity is even keener on small scale biogas activities in the South Asian farming systems.

In a modeling approach, the current studies have yielded advanced models used to evaluate the possibilities of renewable energy and performance of the systems. Borges et al. (2021) model biogas potential on biomass sources by system modeling and an overview of technical and economic models that introduce biogenic gas into natural gas grids are presented by Keogh et al. (2022). The contributions are significant how to integrate an energy system and compatibility of the infrastructure. They, however, tend to disconnect the agricultural aspect and view biogas as an energy source instead of considering it as a two-output system, which yields a fuel and a fertilizer.

In general, the literature is inclined to analyze biogas in disaggregated terms: access to energy, technical viability, and the benefits of fertilizers or policy obstacles. A comprehensive economic analysis of the whole lifecycle of the village level biogas systems, such as, waste collection and anaerobic digestion, methane purification, gas grid injection, fertilizer recovery, and environmental externalities is still almost non-existent, particularly in Pakistan.

This paper will bridge that gap by creating an extensive economic and environmental modelling concept that is specific to rural Punjab. By assessing the energy substitution, fertilizer production, financial, and mitigating greenhouse gas jointly, the paper adds to the literature of decentralized renewable energy system and climate-smart agriculture. By doing that it connects the biogas solutions on a local level to the larger national goals of energy security, rural development and environmental sustainability.

3. Methodology

The deterministic economic and environmental model employed in this research is to assess the technical feasibility, financial viability and climate mitigation of village-based biogas systems (decentralized) in rural Punjab, Pakistan. The methodology takes into consideration agricultural economics, energy economics as well as environmental valuation concepts to embrace the entire production chain of biogas systems- collection of livestock waste, anaerobic digestion, biomethane purification, gas grid injection and recovery of organic fertilizer. Deterministic method sets policy-relevant standards within representative operating situations as opposed to stochastic modeling of farm-level behaviour, which is the best practice in assessing renewable energy feasibility.

The example village of a representative village is taken to be the unit of analysis since this village is densely populated with livestock enough to drive a community-based biogas facility. Livestock dung is an input that is seen as productive giving two joint products of purified biomethane and organic fertilizer rich in nutrients. The basic relationship of production is defined as a linear biogas output formula:

$$B_i = \eta_d \, D_i$$

Where, B_i being the total biogas output (m³/day), D_i the amount of livestock dung processed (kg/day), and eta d being the biogas conversion efficiency (m³/kg). The biological process of anaerobic digestion is captured in this relationship and is at the backbone of the production estimates found in Table 1 that includes dung input per day, yield of biogas, overall biogas yield, quantity of methane content and quantity of purified methane.

Since raw biogas can only be used as a purified methane product, purified biomethane product is obtained as type of usable methane output:

$$M_i = \phi_m \, B_i$$

Where, $M_i$becomes usable methane output (m³/day) and the rate of methane content ratio of the biogas is denoted asϕ_m. This definition is essential to make sure that the potential energy is not overrated because non-combustible gases are not taken into account. The predicted concentration of methane is the reflection of conventional performance of livestock-based digesters and directly informs the estimates of purified methane as listed in **Table 1**:

In order to evaluate energy substitution potential, purified methane is converted to LNG equivalent units by use of the equation:

$$E_i = \frac{M_i}{\psi_{\text{LNG}}}$$

Where, E_i is LNG-equivalent energy (kg/day) and, ψ_{LNG} is the conversion factor between methane volume and LNG mass. This step would allow comparing locally produced renewable energy with the imported fossil energy. The subsequent equivalent is the basis of the analysis of the LNG biogas comparison provided in **Table 6** that compares the energy content, prices, and the cost per kilowatt-hour.

Fertilizer production is assumed to be proportional to dung input: F i = 0.006 D i, with fertilizer production, F i, and the yield coefficient of fertilizer, 0.006. This connection represents nutrient recovery of anaerobic digestion and forms the basis of estimates of fertilizer production in Table 2. Table 2 gives the conversion rates and daily fertilizer production, daily market prices and related revenue, having connection between biological processes and economic result.

Organic fertilizer production is modeled as a proportional byproduct of dung input. Daily fertilizer output is given by:

$$F_i = \alpha_f \, D_i$$

Where, with fertilizer production F_i, and the yield coefficient of fertilizer α_f. This connection represents nutrient recovery of anaerobic digestion and forms the basis of estimates of fertilizer production in **Table 2**. Table 2 gives the conversion rates and daily fertilizer production, daily market prices and related revenue, having connection between biological processes and economic result. Organic fertilizer production is modeled as a proportional byproduct of dung input.

The sum of the energy and fertilizer price determines the total daily revenues in the biogas system. Daily fertilizer output is given by:

$$R_i = P_m M_i + P_f F_i$$

Where, P_m is the controlled price of methane per cubic meter, and P_f is the price of organic fertilizer on the market per kilogram. This is an expression of revenue based on which the financial indicators described in **Table 3** can be summarized. Net profit in one year is calculated by subtracting operating and maintenance expenses and viability of long-term investments is determined by use of conventional capital budgeting indices.

NPV is calculated as:

$$\text{NPV} = \sum_{t=1}^{T} \frac{\pi_t}{(1+r)^t} - I_0$$

Where, $\pi_t$denotes net profit in year t, $r$is the real discount rate, $T$is the project lifespan, and $I_0$is initial capital expenditure. The Internal Rate of Return (IRR) is calculated by the rate of discount, which will provide a value that gives a value of NPV=0. Table 3 reports these indicators, which are applied to determine the economic appeal of the decentralized biogas systems at the baseline assumptions.

The environmental benefits are measured using an estimate of avoided methane emissions of untreated livestock waste. The daily methane avoidance is transformed to the carbon dioxide equivalents by the following formula:

$$\text{CO}_{2e,i} = \text{CH}_{4,i} \times \text{GWP}_{\text{CH}_4}$$

where $\text{CH}_{4,i}$denotes avoided methane emissions (kg/day) and $\text{GWP}_{\text{CH}_4}$is the global warming potential of methane. The formulation connects the results of treatment of biological waste (environmental) to outcomes of climate mitigation and directly reflects the indicators of the environment provided in Table 4, such as daily and annual savings in CO 2 equivalent.

In order to determine the strength of the work in new technical and market conditions, sensitivity analysis checks realistic values of the main parameters. These include biogas yield (η_d), methane concentration (ϕ_m), methane price (P_m), fertilizer price (P_f), and the discount rate (r). These limits represent variations in the feedstock quality, digester performance, market values and financing. The bounds have been enumerated in **Table 5** indicating the way the economic and environmental outcomes respond.

They are different in biogas yield, methane concentration, methane price, fertilizer price and the discount rate. Due to the deterministic nature of the model, policy scenarios can be compared without any extra complexity. Manipulation of behavioral responses allows us to identify the impacts of technical factors, prices and policy instruments. The results can be generalized to other similar districts by focusing on individual villages. Combined all these factors render the model to be applicable in investment planning, subsidy design, and the evaluation of the biogas role in the energy and agriculture plan in Pakistan.

4. Results

The below section presents the simulation output of a village-size biogas system in the rural Punjab. We discuss six metrics technical output, fertilizer recovery, financial performance, environmental benefits, sensitivity to changes in parameters and comparison with imported LNG. They are illustrated in the form of tables.

4.1 Biogas and Biomethane Production

All the calculations were displayed in table 1 given the performance of the system under base line assumptions. The ratio of 10,000 kg of livestock dung fed per day yields 380 m^3 of raw biogas. The purified bio methane produced is 247 m^3/day with a methane content of 65%. The numbers prove that even small units can be used to produce grid-quality methane using local livestock waste.

Table 1: Biogas Production Metrics

Parameter	Value
Daily dung input	10,000 kg
Biogas yield per kg of dung	0.038 m^3/kg
Total biogas output	380 m^3/day
Methane content	65%
Purified methane output	247 m^3/day

4.2 Organic Fertilizer Production

Bio-digestion also results in fertilized nutrient rich bio-digestion products. Table 2 indicates that a rate of 0.4kg to kg ratios provides approximately 4000kg (4tons) of fertilizer per day. Assuming that the market price is PKR/kg = 5, the by-product will earn PKR/kg = 20, 000/day. This shows the importance of biogas systems as combined energy providers and agriculture.

Table 2: Fertilizer Production Metrics

Parameter	Value
Dung to fertilizer conversion rate	0.40 kg/kg
Daily fertilizer output	4,000 kg/day
Fertilizer price	PKR 5/kg
Daily fertilizer revenue	PKR 20,000

4.3 Financial Performance

The significant financial values are provided in Table 3. The two sell PKR 35,200 worth of methane and fertilizers per day. The net after operating costs and capital amortization annual profit is approximately PKR 11 million. In 10 years and assumed discount rate of 10 percent, NPV is PKR42.2million and IRR is above 25 percent. This demonstrates that the project is a viable financial venture.

Table 3: Economic Performance Indicators

Metric	Value
Daily revenue (methane + fertilizer)	PKR 35,200
Annual net profit	PKR 11 million
Net Present Value (10 years)	PKR 42.2 million
Internal Rate of Return	> 25%

Discount rate	10%

4.4 Environmental Benefits

The table with the description of the environmental impact is given in Table 4. The system prevents the emission of 27.14kg of methane per day by the livestock waste. This would save 28 kgs of CO2 equivalent per day in the global warming potential and would be 760 kg / m^2 of CO$_2$ equivalent per day, or 277 metric tons per year on average. The data outline the advantages of decentralized biogas on climate reduction.

Table 4: Environmental Impact Indicators

Metric	Value
Methane avoided per day	27.14 kg CH_4
Global warming potential	28
Daily CO$_2$e reduction	760 kg
Annual CO$_2$e reduction	277,400 kg

4.5 Sensitivity Analysis

To test robustness with the experiment of key technical and economic parameters. The table 5 tabulates the limits of the parameters. The findings indicate that profitability varies with the changes in price and yield of biogas, but the system remains but profitable in most conditions. This shows that decentralized biogas is robust to the changing markets and technology..

Table 5: Sensitivity Analysis Ranges

Variable	Range
Biogas yield	0.03 – 0.05 m^3/kg
Methane content	60% – 70%
Methane price	PKR 70 – 100/m^3
Fertilizer price	PKR 4 – 8/kg
Discount rate	8% – 12%

4.6 Comparison with Imported LNG

Table 6 compares purified biogas and imported LNG. On the one hand, LNG has a higher energy density, and on the other, biogas is less expensive per kilowatt-hour. It also reduces the dependence of imports, minimizes foreign-exchange pressure and reduces greenhouse-gas emissions. The aforementioned comparison reveals that biomethane that is produced locally is cheaper and greener.

Table 6: Comparison of LNG and Biogas in Pakistan

Aspect	LNG	Biogas (Methane)
Energy content	13.6 kWh/kg	6.0-6.5 kWh/m^3
Market price	PKR 250/kg	PKR 80/m^3
Cost per kWh	PKR 18.38	PKR 12.30
Source	Imported	Local livestock waste
Environmental impact	High emissions	Emission reduction
Strategic value	Import-dependent	Energy self-sufficiency

4.7 Summary of Results

Concisely, it can be noted that the findings affirm that village-scale biogas is technically feasible, profitable and environmentally safe. This is because the production of couplings with organic fertilizer recovery increases viability, which strongly affirms the need to enhance the use of decentralised biogas in rural Punjab.

5. Discussion

It can be observed in the tables 1-6 that the decentralised biogas in rural Punjab is technically feasible, economically justifiable, as well as valuable to the environment. Combined, the results provide important information on the subject of energy security, rural development, climate conservation, and policy alternatives.

To begin with, **Table 1** reveals that the process of purification of biomethane in village units is reliable and yields grid-compliant biomethane. These systems have a potential of 247 m^3 of methane/day, and they can contribute significant portion of domestic energy when spread all over livestock intensive regions. This disputes the perception of renewable gas as marginal and it underscores the fact that a large number of small units can become a significant source of energy in Pakistan.

Second, **Table 2** reveals that organic fertilizer is a co-product offered by biogas. The day-to-day production of four tons of fertilizer is additional income and reduces the use of costly chemicals. In general, this advantage strengthens the resiliency of farming, as fertilizer is expensive, and the health of the soil is a challenge. Its data implicates that biogas contributes to other advantages related to energy, which have contributed to sustainability of broader agriculture. Given that digestate is a recognised fertilizer, its market demand and support among farmers may potentially increase.

Third, the financial indicators presented in **Table 3** prove positive investment performance with an internal rate of return of above 25 percent and the Net Present Value of the project life cycle is large. The findings suggest that under no heavy subsidies, decentralized biogas systems are commercially viable. Nonetheless, the first cost and coordination problems might remain restrictive to the adoption of privately. This does not mean that the policy intervention required is not to emphasize on increasing the prices in the long-run, but the ease of entry should be improved by concessional financing, credit guarantees or models of public-private partnerships. This tailored assistance would be able to speed up the deployment and stay within fiscal discipline.

The issues of the environment indicated in **Table 4** also reinforce the argument in favor of biogas as a tactical mitigation measure in climate change. Evaded methane emissions would lead to significant CO_2-equivalent savings, and this is especially significant since methane has a high global warming potential. These findings are consistent with the climate promises of Pakistan and indicate that decentralized biogas could become a part of the national mitigation policies. Carbon markets or results-based climate funding of these emission reductions would also enhance the economics of these projects and encourage their implementation in the high-livestock regions.

These conclusions are further supported by its sensitivity analysis in **Table 5**, which demonstrates that the system viability can be achieved at a large variety of parameter values. Although profitability is vulnerable to both the price and the conversion efficiency of methane, and the existence of positive returns despite the conservative assumptions minimizes policy risk and investment risk. This strength is essential in the eyes of the policymakers because it indicates that slight changes in the market conditions will not bring down the sustainability of biogas investments in the long term.

Lastly, the results are put in context of the wider energy policy by the comparative analysis with LNG in **Table 6**. Although biogas has a lower energy density, this does not invalidate the fact that it provides energy at significantly cheaper cost per kilowatt-hour than imported LNG and has the strategic benefits of less dependence on imports and creation of rural values. These results indicate that the existing energy pricing schemes could underestimate the value of biomethane compared to its environmental value across the system. Motivation of prices and regulatory support should be adjusted to match these benefits, which can help greatly in the energy transition of biogas in Pakistan.

On the whole, it has been discussed that decentralized biogas systems cannot be considered as rural independent technologies but energy-agriculture-climate solutions. Technical feasible, financially viable, and environmental profitable convergence contributes to the change in policy towards mainstreaming biogas in national development planning.

6. Conclusion

The present research will entail a detailed economic and environmental analysis of decentralized village-level biogas systems, which will be configured to inject purified biomethane to the national gas grid of Pakistan and at the same time generate organic fertilizer out of livestock waste. In the case of rural Punjab, the analysis indicates that biogas systems can be used to cope with several structural issues to the Pakistani energy and agriculture sectors where livestock density is high, and wastes have not been fully used yet.

According to the results, decentralized biogas units can be technically operated under realistic operating conditions. At village level, these systems can generate a predictable supply of grid quality biomethane which is why such systems are likely to contribute to domestic energy production when they are scaled to livestock-intensive areas. Notably, the recovery of organic fertilizers plays a significant role in improving the functionality of the systems since it diversifies the sources of revenues and the connection between the energy production and the sustainable agriculture of the soil. This system with two outputs will be more resilient and less dependent on one market result.

Economically, there is an affirmation of high financial viability. When internal rates of returns are high with a positive net present value this shows that decentralized biogas systems are commercially viable in a medium term horizon even without a high dependency on subsidies. These findings imply that policy interventions should focus on facilitating entry, enhanced access to funds and simplified regulation processes at the expense of price support in the long term. Partnerships between the government and enterprises and collective ownership models can be especially the most fitting to scale up to rural settings.

The strategic significance of the biogas systems is further advanced by the environmental benefits. Decentralized biogas units contribute to a significant amount of greenhouse gases emission rates by capturing the released methane that otherwise evolves when waste is not controlled through biogas. Since methane has a big global warming potential, these avoided emissions mean that the outcomes of high impact climate mitigation would be quite consistent with Pakistan national climate commitments. The further incentive to invest in the biogas projects may be enhanced by including biogas projects into climate finance mechanisms and carbon markets.

All in all, this paper places decentralized biogas not as a sole intervention to energy security in the rural setting but as a comprehensive solution to energy security, agricultural sustainability, and climate action. The results affirm the need to change the current policy into mainstreaming bio-gas in national development, especially in provinces that have high livestock densities. This framework can be further expanded in future research by adding the element of spatial scaling analysis, institutional and behavioral constraints, and dynamic policy situations. However, the current results establish a strong and policy-relevant basis of facilitation of biogas as one of the fundamental elements of the sustainable energy transition and agricultural change in Pakistan.

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