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Biogas as Alternative to Liquefied Petroleum Gas in Mauritania: An Integrated Future Approach for Energy Sustainability and Socio-Economic Development

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Abstract: The global shift from conventional energy sources to sustainable alternatives has garnered significant attention, driven by the promise of economic benefits and environmental sustainability. The current study rigorously investigated the economic advantages and sustainability achieved from the transition of households in Mauritania from liquefied petroleum gas (LPG) to biogas utilization. The study constitutes a robust case study that centers on assessing the multifaceted impacts of this transition on household finances and overall quality of life in Mauritania. This case focuses on biogas technology adoption and its role as a competitor of LPG in Mauritania. The energy poverty portfolio of the nation has been explored and livestock waste generation and biogas production potential have been estimated at 2451 million cubic meters annually. Biogas production can fulfill 50% of the energy requirement for cooking purposes within the country. The community scale fixed-dome-type biogas digesters have been recommended for Mauritania by considering a community of 100 families. The calculated payback period for the community project is 74 months, and after the payback period, continuous monthly benefits of USD 1750 will be started. Livestock manure is directly utilized for farming practices in Mauritania, which produces 10.7 Gg of methane emissions per year. Biogas production is a clean and economically viable option for Mauritania, which can also be beneficial for reducing the methane emissions footprints of the livestock sector. This case study will prove as a vital project for other African nations if successfully implemented. Multiple recommendations for the policy-makers of Mauritania have also been formulated, like tariffs on biogas production facilities and swift financing schemes, which can further strengthen the biogas production on a national scale. International funders should also take part in coping with the energy demand of Mauritania and its mission to mitigate climate change rather than utilizing LPG on a national scale. Biogas production and utilization are much cheaper compared with the fluctuating prices of LPG and ensure health when cooking.

Keywords: sustainable energy transition; biogas network; household budgets; environmental benefits; economic viability; social acceptance

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1. Introduction

The global energy landscape is undergoing a significant transformation, driven by the imperative of sustainability and the quest for energy security. While Africa stands as a net energy exporter, it paradoxically grapples with a heavy reliance on imported energy sources. Notably, sub-Saharan Africa (SSA) bears a disproportionate burden, with approximately 74% of its energy consumption derived from biomass, predominantly in the form of fuelwood and charcoal, in stark contrast to 37% in Asia and 25% in Latin America [1,2]. This reliance on traditional, often inefficient, and environmentally detrimental fuels underscores the region's energy access and sustainability challenges. About 2.5 billion people still use traditional kitchen methods and depend on wood and available biomass as primary energy resources, and 1.5 billion people on this planet still do not have access to electricity [3]. The share of biogas production is much less, about 1.2% with a 10% renewable energy installed capacity of 1500 MW. There are estimates that the energy production form biogas is expected to grow to 22,040 MW by 2025 [4]. About 900 million people in the sub-Saharan region depend on natural wood and animal waste for kitchen purposes, and due to respiratory infections from these dirty cooking fuels, 490,000 deaths are recorded annually [5].

A staggering half a billion people in SSA depend on solid fuels, including fuelwood, agricultural residues, and animal waste, for their daily energy needs, primarily for cooking, heating, and lighting, due to the lack of access to electricity [6]. Urban centers and distant villages are also largely dependent on liquefied petroleum gas. The prices of LPG are very much fluctuating due to international market pricing and transportation charges. The utilization of LPG is very costly for the Mauritanian people and is not a sustainable option. The LPG distribution in Mauritania is also severely affected by its availability in different seasons. In this context, the transition from LPG systems to anaerobic digester networks has gained much significance. This transition holds promise not only for economic benefits but also for its potential to mitigate environmental challenges. Mauritania's widespread reliance on LPG for domestic energy needs underscores the urgency of exploring accessible and sustainable energy alternatives. Biogas, derived from the anaerobic digestion of organic matter, presents a compelling solution with the potential to enhance energy sustainability and waste management simultaneously [7]. While domestic biogas initiatives have made substantial strides in Asia, their adoption in Africa remains relatively limited. In addition to that, Africa faces pressing energy needs, with traditional biomass accounting for a substantial portion of energy consumption [8]. The collection of traditional fuels often consumes valuable time, especially for women and children, hindering their educational and economic opportunities [9].

The transition from LPG (liquefied petroleum gas) to a biogas network in households offers substantial economic benefits supported by empirical evidence. Notably, households can achieve remarkable cost savings through this transition. According to a study by the International Renewable Energy Agency (IRENA) in 2020, the cost savings associated with switching from LPG to biogas for cooking and heating purposes can be as high as 50% [10]. This significant reduction in energy expenditure can have a profound impact on the financial well-being of households, particularly in resource-constrained regions like Mauritania. Furthermore, the economic advantages extend to reduced import dependency. Mauritania has a heavy reliance on LPG imports, accounting for approximately 20% of the nation's total energy consumption in 2019, as reported by the World Bank in 2021 [11]. The transition to a biogas network not only reduces the financial burden of importing LPG but also contributes to enhanced energy security by decreasing dependency on external energy sources. This reduction in energy import costs can result in more stable household budgets and greater economic resilience, thereby improving the overall economic well-being of transitioning households in Mauritania.

Mauritania, a country located in West Africa, faces a complex energy landscape characterized by a heavy reliance on imported fossil fuels. The nation's energy sector has been dominated using liquefied petroleum gas (LPG) for cooking and heating, which has led to several challenges. The high dependence on LPG imports has made Mauritania susceptible to the fluctuations in global fuel markets, contributing to economic vulnerability and energy insecurity [8]. The demand for energy in Mauritania has been steadily rising due to population growth and urbanization. However, the availability of locally produced energy resources is limited, prompting the country to explore alternative solutions that can address both economic and environmental concerns [8].

Additionally, the reliance on traditional fossil fuels like LPG contributes to greenhouse gas emissions, impacting the environment and the nation's commitment to global sustainability goals. Mauritania's energy mix heavily favors imported fossil fuels, leading to high import bills and trade deficits. The exploration of renewable and locally sourced energy options gains importance in this context, as it can help reduce dependency on foreign energy sources, stabilize energy costs, and contribute to the national economy. Biogas, a renewable energy source produced from organic waste, has emerged as a viable alternative that aligns with Mauritania's goals of energy security and environmental sustainability. Figure 1 represents the growth of the adoption of biogas plants in African countries [8]. Organic waste, which includes agricultural residues, livestock manure, and household waste, is abundant in the country. Biogas production harnesses this waste to generate cleaner energy, reducing the environmental impact of waste disposal while simultaneously offering an alternative to fossil-fuel-based energy sources.

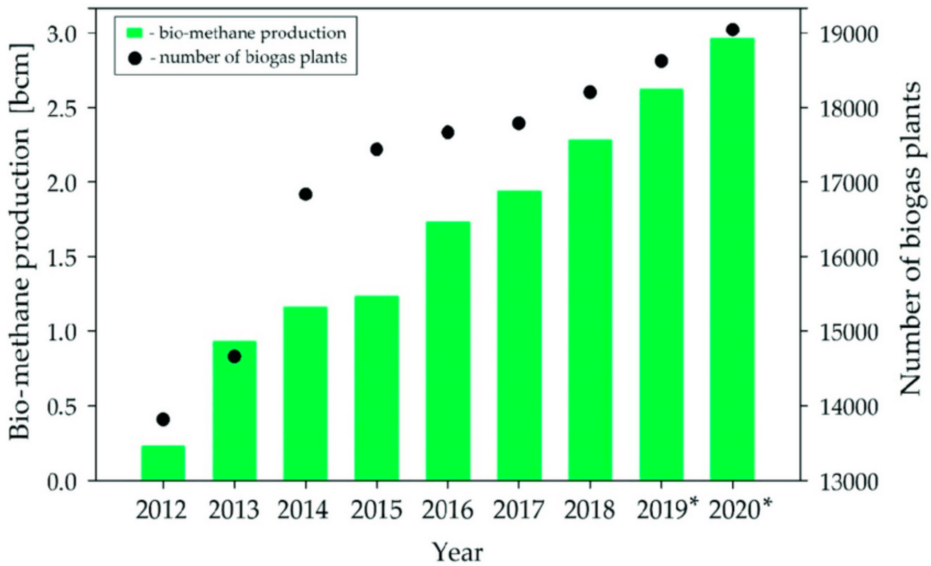

Figure 1. Statistics for biogas plants in African countries, adapted from [8]. [* there was rapid expansion of biogas plants observed in African countries during 2019 and 2020].

This study focuses on Mauritania, a West African nation facing energy sector challenges that necessitate innovative solutions. This study seeks to unravel the economic, environmental, and societal implications of transitioning households from LPG to a biogas network. By elucidating the multifaceted benefits and challenges of this transition, this study focuses on policy decisions and contributions to the sustainable energy transitions in Mauritania and highlights the crucial nexus between energy access, environmental stewardship, and socio-economic well-being in Mauritania. The objectives of this research encompass investigating the short- and long-term economic benefits associated with transitioning households in Mauritania to biogas networks while also evaluating the level of satisfaction among households following this transition. Moreover, this study aligns with the broader recognition of the significance of reliable renewable energy sources for global progress. Domestic biogas holds the potential to significantly impact the health, nutrition, and environmental sustainability of farming households in low-income nations, as demonstrated by its successful implementation in Asian countries. This transition will not only reduce pollution and streamline food preparation, particularly benefiting women and children, but will also contribute to environmental preservations.

2. Energy Poverty in Mauritania

Energy poverty is a very common term utilized by world-famous organizations like the United Nations (UN), the International Energy Agency (IEA), the International Atomic Energy Agency (IAEA), and the World Bank to measure the energy index and prosperity rate of a specific country and region [12]. Energy poverty is referred to as higher unaffordable prices for electrical energy that the common public cannot access for domestic and industrial applications, lower domestic income, and lower energy performance and development rates in the region [13]. Energy utilization is termed as the core model of economic development across nations and reducing the political interventions within the region which are the agenda points in the Sustainable Development Goals by 2023 [14,15]. In Mauritania, about 58.6% of the population lies under the poverty line and cannot afford electrical energy. The basic fuel prices, like those for petroleum products, are also considered vital for the transportation sector, and the energy poverty levels can also be measured for the availability of these resources and their routes. The energy and fuel poverty indicators are measured for the national levels in Mauritania, and higher fluctuations in prices of LPG seriously affect the socio-economic situation of individuals [16]. Considering the primary energy usage in Mauritania, 36% of energy needs are met by wood resources, which are very unhealthy for forestation and result in higher greenhouse emissions trends [8]. This wood burning should be replaced by biogas utilization among the nations with clean and sustainable energy generation resources [8]. The population in Mauritania is composed of small villages and is sparingly distributed over the sub-Saharan continent, which is not very well connected with the paved roads, therefore creating hurdles in distributing LPG for domestic purposes. This factor thus enhanced the risks of energy poverty in Mauritania. Higher energy poverty also indicates a lower economy, lower lifestyle, and poor livelihood, which negatively contributes to the gross domestic product.

The United Nations High Commissioner for Refugees (UNHCR) has successfully launched several renewable-energy-based projects in Mauritania to eradicate energy poverty. They have biogas pilot scale projects in collaboration with the United Nations Development Program (UNDP) and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) to produce environmentally friendly options for renewable energy, like biogas production from local and available sustainable resources. These projects were launched in 2022 with the main objective of providing sustainable cooking solutions for households with reduced health risks [17]. Biogas production from livestock manure and from available crop residues fosters clean energy generation and is an environmentally friendly option and provides cash for gas projects. In the coming years, the UNHCR has plans to install the biogas plants at schools and at the community level to enhance the clean energy portfolio at the institutional level and community level in Mauritania [17]. UNHCR has plans to construct five biogas digesters at the community level in the years 2024, 2025, and 2026, with annual funding of USD 276,780, USD 86,280, and USD 276,780, respectively [17]. The UNHCR is also working in close relationship with the Mauritanian government to develop the plans for electrification of the Mbera camp and its vicinity with a hybrid solar and diesel-operated power plant by the year 2026. The Mbera camp is a refugee camp that lies in southeast Mauritania, just 50 km from the border with Mali. The Mbera camp in Mauritania consists of a population of 80,000, mostly refugees, and is prone to severe climate risks, droughts, and flooding. The population is extremely poor in terms of energy utilization, and therefore the UNHCR is setting examples for building renewable energy production focusing on this community. Energy poverty in Mauritania will be majorly alleviated by harvesting biogas from available sustainable resources. The community-based renewable energy project will provide sustainable energy resources, along with reduced risks of greenhouse emissions and providing green jobs within the camp community and at the community level.

3. Rural and Urban Household Biogas Potential in Mauritania

Utilizing biomass energy at the household level has emerged as an important option for meeting energy demands, improving sustainability, and fostering rural development. Biomass, which includes a wide variety of organic materials, has been used for centuries as a flexible and readily available source of energy [18]. This article explores the relevance and dynamics of the residential usage of biomass energy, highlighting its positive and negative effects on individuals, communities, and the environment. Biomass is still relied upon as a key energy source in many parts of the world, especially for rural and remote locations. Mauritania is very rich in sustainable energy resources like biomass and biowaste, which can be utilized for biogas production and provide a sustainable energy supply for the nation. In Mauritania, there is huge potential for biomass and crop residues, like rice husk and rice straw, which can produce up to 3.7 GWh of electrical energy annually [19], which needs to be tapped through community-scale biogas plants. Mauritania is very rich in livestock resources and has a potential of 2125 million cubic meters of biogas production per year, which needs to be tapped and can be a possible replacement for LPG [8]; by considering all the possible waste categories, Mauritania has a total biogas production potential of 2451 million cubic meters of biogas annually [8]. The utilization of livestock manure for biogas production is very much a sustainable option and environmentally friendly as the livestock sector is the major methane emission source worldwide. Limited accessibility to modern energy resources, economic restraints, and cultural practices strongly established in local communities typically encourage the reliance on biomass energy. The availability and low cost of biomass energy provides a crucial resource for millions of homes without other options. Figure 2 depicts the general setup of a floating-dome-type biogas plant, indicating the area utilization and the component setup. Biogas production is a biochemical conversion process in which the volatile contents of the waste are microbially consumed by the micro-organisms and further converted into biogas, which contains mainly CO_2 and methane. Methane is a highly flammable and combustible gas and can be utilized for combustion purposes and acts as an excellent fuel. Anaerobic digestion is further categorized into four stages, consequently called hydrolysis, acidogenesis, acetogenesis, and methanogenesis, and these stages are well presented in Figure 3. During the hydrolysis of the waste, the organic matter is mixed with water and then enters the acidogenesis and acetogenesis steps. During these steps, intra-molecular species like ethanol, amino acids, and fatty acids are produced, which are finally converted into methane and carbon dioxide during the methanogenesis stage.

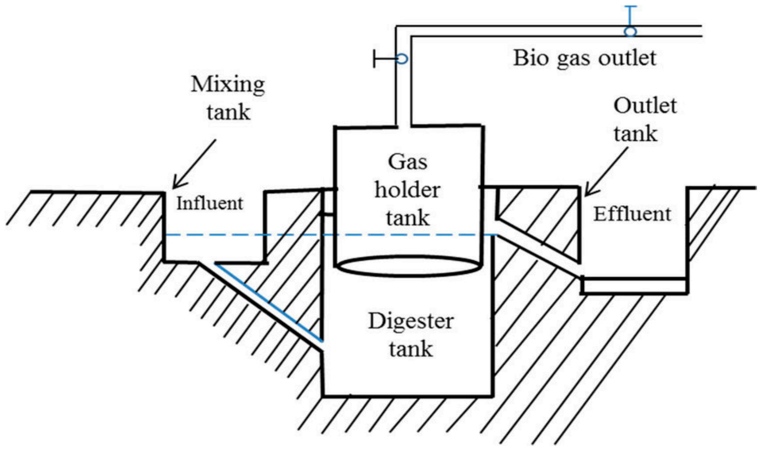

Figure 2. Schematics of a biogas plant.

The usage of biomass energy has many advantages, especially for low-income households in Mauritania. Biomass is a reliable energy source that lessens reliance on external fuel supply networks since, first and foremost, it is often readily available. As a result of this regional accessibility, consumers are less vulnerable to the flow of global markets regarding energy and supply interruptions. Further, many communities in Mauritania already possess a collection of agricultural residues, forests, and animal byproducts that may be transformed into usable energy, making biomass a cheap or even free option. While there are benefits to using biomass for energy, there are also some drawbacks to consider. Traditional biomass cooking methods, such as open flames and inefficient stoves, are a major contributor to indoor air pollution. Household members, especially women and children who spend a disproportionate amount of time indoors, are at serious risk from the harmful pollutants released as a result of these practices, such as particulates and carbon monoxide [20]. Figure 4 presents the biogas production facilities that have been installed globally, and the African continent is far behind the rest of the countries in terms of biogas plant installation and biogas production facilities; in addition to that, the

African continent is very rich in biogas production feedstock resources. Table 1 presents the biogas generation potential and possible methane generation capability of all the provinces in Mauritania, while Table 2 presents the biogas production potential and capability of different livestock manures.

Recent years have seen an increase in efforts to improve the efficiency of biomass power plants. The development of more efficient cook stoves and gasification technology has helped to lessen the amount of pollution created when cooking. Households may now use organic waste to generate reliable power for cooking and lighting thanks to the introduction of small-scale biogas digesters, which also helps with trash management [24]. Furthermore, the integration of biogas systems at the local level can stimulate job creation and local entrepreneurship. As communities invest in biogas infrastructure, opportunities arise for skills development, maintenance services, and organic waste collection systems. This decentralized approach to energy production can empower local communities while contributing to the broader national energy agenda [25].

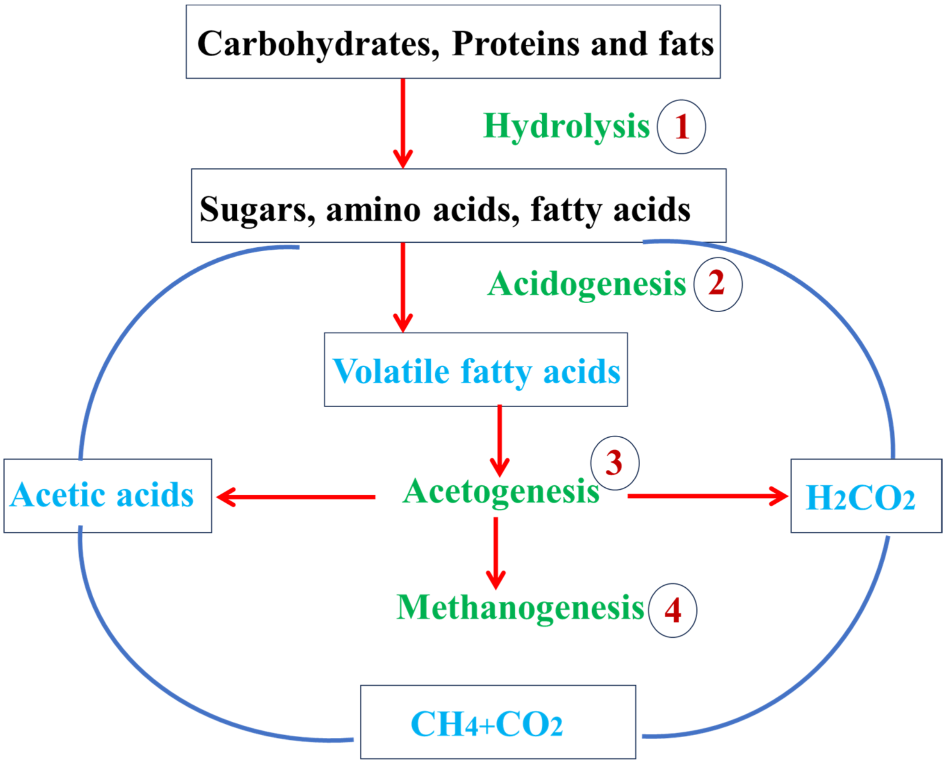

Figure 3. Schematics of different stages during anaerobic digestion and waste degradation.

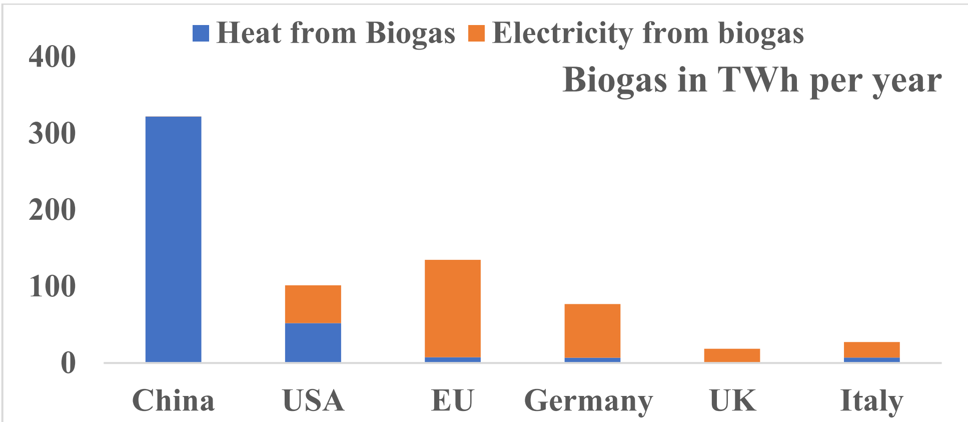

Figure 4. Global heat and electricity production scenario from biogas, adapted from [21].

Table 1. Energy generation potential by livestock manure in different provinces in Mauritania; data obtained from [8].

Provinces	Methane (Million m^3/year)	Heat Energy (10^6 MJ/year)
Adrar	78	2814
Assaba	168	6144
Brakna	98	3635
Guidimakha	77	2823
Gorgol	78	2899
Hodh Ech Chargui	284	10,306
Hodh El Gharbi	205	7483
Inchiri	39	1418
Nouadhibou	12	421
Nouakchott	10	370
Tagant	75	2744
Trarza	103	3746
Tiris Zemmour	24	880

Table 2. Biogas production potential of different livestock manures; data obtained from [22,23].

Livestock Waste	TS (%)	Biogas Production (m^3/kgTS)
Poultry manure	10–28	0.3–0.8
Camel manure	30–45	0.3–0.4
Goat manure	18–25	0.3–0.5
Cow manure	25–28	0.6–0.8

The anaerobic decomposition of organic materials yields biogas, primarily composed of methane and carbon dioxide [26]. Notably, biogas may contain contaminants such as nitrogen, hydrogen sulfide, ammonia, and siloxanes [27]. In 2016, global biogas production reached a significant milestone of 360 terawatt-hours (TWh), with Europe contributing 180 TWh. Remarkably, approximately half of Europe's biogas output originates from Germany, responsible for over 25% of global biogas production [26]. While Europe maintains a substantial share, Asia has rapidly emerged as a prominent biogas producer, driven by extensive production initiatives in several of its countries [26]. In contrast, Africa has lagged in biogas production [26] compared with other Asian and European countries, and the global biogas production scenario is provided in Table 3. Mauritania is poised to harness the potential of biogas production to address its energy challenges, including limited energy access and dependence on scarce resources. By leveraging its abundant organic waste resources, the nation can significantly enhance both energy security and waste management. Although Mauritania is yet to realize its full biogas production potential, a sustainable biogas sector could serve as a regionally suitable solution, aligning with the country's specific energy needs [26]. Figure 5 depicts the maximum utilization by households, followed by transport, indicating the requirement of higher adoption of biogas by the agriculture sector.

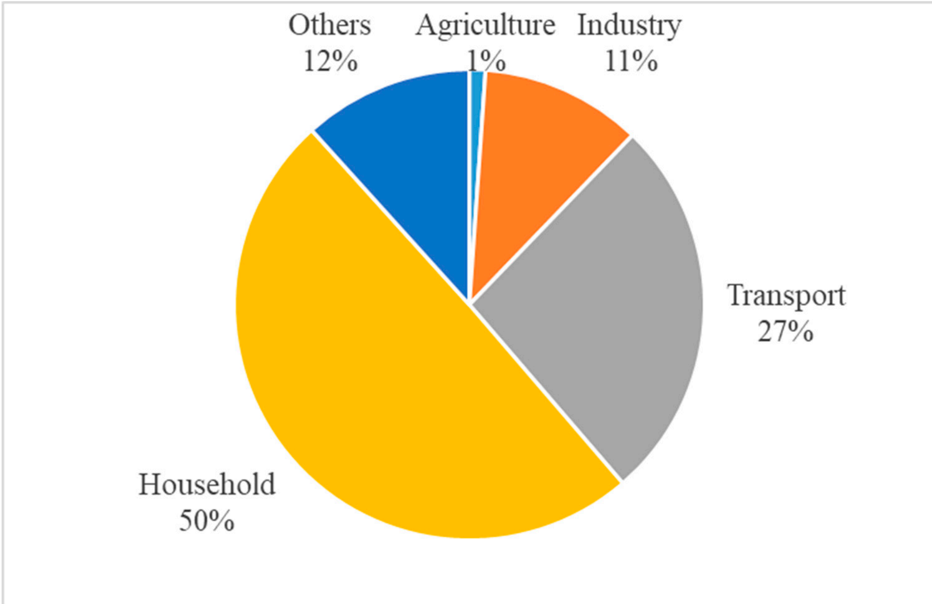

Figure 5. Adoption of biogas sector-wise in Mauritania.

4. LPG Replacement by Biogas in Mauritania: A Sustainable Approach in Societal Uplift

Through comparative analyses of pre- and post-transition conditions, this study unveils the significant transformations in terms of cost savings, reduced reliance on imported LPG, and potential environmental amelioration. To comprehensively assess the economic advantages of transitioning from LPG to a biogas network in Mauritania, a systematic analysis was conducted. This analysis involved a detailed comparison of various cost factors associated with both energy sources, along with considerations for their long-term viability and sustainability [28]. The methodology employed herein aims to provide a holistic understanding of the economic implications of adopting biogas systems. The study's scope encompassed several key factors crucial to the assessment of economic benefits. These factors included initial setup costs, monthly fuel expenses, ongoing maintenance requirements, and the overarching long-term sustainability of biogas systems. Initial setup costs for both LPG and biogas systems were determined based on industry standards, local market prices, and expert consultations. Monthly fuel expenses for LPG were estimated considering consumption rates and variable prices [29]. In contrast, biogas production costs were evaluated based on the availability of organic waste and its potential conversion to biogas [30]. To gain insights into maintenance costs, information was gathered from industry reports, expert opinions, and case studies. These sources helped establish a comparative framework for understanding the financial commitments associated with maintaining LPG and biogas systems. The study extended its analysis beyond immediate costs by considering the long-term economic viability of biogas adoption. This aspect involved assessing the stability of fuel costs over time. For LPG, the study acknowledged the volatility of global fuel prices and their potential impact on consumer expenses. On the other hand, biogas costs were expected to remain relatively stable due to the localized nature of organic waste availability. While primarily focused on economic factors, the analysis also took into account the environmental advantages of biogas systems. The reduction in greenhouse gas emissions associated with biogas production and usage played a role in highlighting the broader societal benefits of transitioning to renewable energy sources. A structured comparison framework was developed to juxtapose the economic aspects of LPG and biogas adoption. This framework enabled a clear assessment of costs, benefits, and trade-offs [29]. The goal was to provide stakeholders, policymakers, and individuals with a robust understanding of the financial implications associated with biogas adoption.

The biogas production systems are also very complex and there are chances of little methane production, methane leakage, and sometimes lower supply of the livestock manure fed to biogas digesters. Recognizing the inherent variability in factors such as fuel prices and organic waste availability, a community-scale biogas plant feasibility analysis was prepared considering 100 families. This community-scale biogas plant will accommodate the requirement of 100 families. The design of the biogas plant also ensured the least methane production throughout the year that can fulfill the communal needs. In this case, the community scale biogas plant is proposed near denser livestock populations which surround villages or are in the suburbs of large cities in Mauritania. Thousands of livestock herds are present in all suburbs of large cities, which fulfills the demands for milk in the city centers. The basic assumptions in this case study of manure transportation considers that the livestock manure will be collected within a 5 km radius of the biogas production facility, which will minimize the transportation cost. This approach involved assessing how changes in these factors would impact the overall economic assessment. By acknowledging the potential variations, the study aimed to offer a more nuanced perspective on the potential outcomes of biogas adoption. While efforts were made to gather accurate and representative data, certain limitations were acknowledged. Data availability and accuracy varied across sources, potentially introducing bias into the analysis. Additionally, the study's scope focused primarily on the community-based economic considerations of biogas plants that could acceptably adopt commercial-scale biogas production [5]. The Energy Biomass Fraction Index (BFI) serves as a valuable indicator for identifying regions with high energy demand and limited access to traditional energy sources. Central African countries, as exemplified by the severe domestic energy problem they face, stand out as areas where biogas adoption could play a significant role in addressing energy poverty and environmental concerns [29]. In summary, Mauritania has a large potential to benefit significantly from the adoption of biogas systems in its residential sector. The economic advantages, coupled with the environmental benefits and the potential to address energy poverty, make biogas a promising solution [5,31]. However, it is crucial to conduct a comprehensive analysis that considers local factors and circumstances to ensure the successful implementation and long-term sustainability of biogas adoption in the region. African nations are also striving to install biogas plants under a clean development mechanism under the project termed the African Biogas Carbon Program, determined in 2016 [32]. According to the Petroleum and Natural Gas Act, 2001, the National Electricity Regulatory of South Africa has recognized 38 biogas-producing activities, most of which are of the fixed-dome type. Moreover, this study emphasized policy recommendations for private entities and governmental stakeholders for the possible commercializing of biogas plants and replacement of LPG in Mauritania. Biogas production is widely adopted technology across the globe, and the number of installed biogas plants are presented in Table 3.

Table 3. Biogas plants installed across developing nations, including Asia and Africa; data obtained from [31–33].

Country	Year of Program Initiation	Cumulative Biogas Plants Installed
China	1974	35,000,000
India	1970s	4,500,000
Nepal	1992	268,464
Vietnam	2003	152,349
Bangladesh	2006	26,311
Cambodia	2006	19,173
Lao PDR	2006	2888
Indonesia	2009	7835
Pakistan	2009	2324

Table 3. *Cont.*

Country	Year of Program Initiation	Cumulative Biogas Plants Installed
Bhutan	2011	265
Rwanda	2007	2619
Ethiopia	2008	5011
Tanzania	2008	4980
Kenya	2009	6749
Uganda	2009	3083
Burkina Faso	2009	2013
Cameroon	2009	159
Benin	2010	42
Senegal	2010	334
Rawanda	2018	2400

Biogas technology offers a multitude of benefits that extend beyond its role in generating clean and renewable energy, which can power entire homes for free in underdeveloped nations. These advantages have far-reaching implications for economic development, environmental sustainability, public health, and societal progress in Mauritania. The residue material leftover in biogas plants is termed as digestate, a byproduct of biogas production, and can be used as a potent organic fertilizer. When applied to agricultural land, it enhances soil quality by improving its biological, chemical, and physical characteristics, translating into increased crop yields and contributing to food security, particularly in regions with struggling agricultural practices [34,35]. The biogas industry offers economic opportunities on multiple fronts. Job creation within the biogas sector, from system installation and maintenance to the management of biogas plants, can bolster local economies. Moreover, the generation of carbon credits through reduced methane emissions and the savings on imported chemical fertilizers and fossil fuels provide a substantial economic prosperity [29]. Biogas technology contributes to societal progress, particularly in areas where it replaces traditional, time-consuming energy-gathering activities, such as collecting fuelwood or cow dung. With readily available, clean home energy, women and children gain more time and opportunities for education, skill development, and other productive activities. Bond and Templeton (2011) estimate that biogas technology has the potential to cut worldwide anthropogenic methane emissions by 4%, making a notable contribution to global emissions reduction targets [36].

Another indirect but significant advantage of biogas technology is its potential to slow down deforestation. In many rural areas, the primary source of energy comes from burning wood, which contributes to deforestation and increased vulnerability to floods and droughts due to soil erosion. Global deforestation accounts for 17–25% of all anthropogenic greenhouse gas emissions. Biogas technology not only reduces environmental pollution but also addresses waste management issues by converting organic waste into a valuable energy resource while simultaneously mitigating the adverse effects of waste disposal, including groundwater contamination and foul odors. In remote and off-grid regions, biogas technology provides a reliable energy source, enabling communities to access clean energy for lighting, cooking, and small-scale electrical appliances, contributing to an improved quality of life. In summary, biogas technology offers a range of benefits encompassing public health improvements, enhanced agriculture and food security, economic opportunities, societal progress, greenhouse gas emissions reduction, forest conservation, waste management, and improved energy access. These advantages make biogas technology a valuable tool for sustainable development, environmental protection, and addressing pressing global challenges, including climate change and energy access in Mauritania.

5. Possible Types of Bio-Digesters That Can Be Deployed in Mauritania

The regions of Mauritania often present unique challenges, from resource constraints to varied local conditions. Customizable biogas systems offer a tailored approach to address these challenges. We explore the key design considerations, components, and strategies for creating biogas plants and digesters that are both effective and adaptable. Biogas technology holds great promise as a sustainable energy solution, particularly in economically weaker countries. These regions frequently face energy poverty, limited access to clean fuels, and environmental degradation due to the use of traditional energy sources. Customizable biogas plants and digesters can play a pivotal role in addressing these issues by providing a clean, sustainable, and locally sourced energy alternative. The design and size selection of the biogas plants depends on local resource availability, namely the availability of feedstock material like animal dung or crop residues that can be digested to produce biogas. It also depends on the climatic conditions and geological conditions of the vicinity and community needs, such as how much biogas they require and can consume during different seasons. Customizable biogas plant and digester design is essential to provide economically weaker countries with a sustainable and locally sourced energy solution. The design considerations, key components, and customization strategies discussed here are fundamental to creating effective biogas systems that can adapt to varying regional conditions. By investing in these customized solutions, we can pave the way for cleaner, more sustainable, and accessible energy sources in these regions.

Customizable biogas plants and digesters consist of several essential components that work together to convert organic waste into biogas. The inlet chamber receives organic feedstock, which can include animal manure, crop residues, kitchen waste, and other types of substrate. The design should ensure efficient loading and minimal heat loss. The heart of the biogas system is the anaerobic bacteria that break down the organic matter, producing biogas as a byproduct. The digester's size and shape can be customized based on available space and waste volumes. Biogas storage facilities are crucial to store the produced biogas. Depending on the design, this can include gas balloons, storage tanks, or other solutions. The produced biogas is stored right above the feedstock materials where it is produced. When the biogas pressure increases, then it flows into the pipes, steel vessels, and anywhere a path is provided. The distribution system is customized based on the end-use of the biogas, whether it is for cooking, lighting, or electricity generation. The digester produces nutrient-rich slurry or digestate that can be used as fertilizer. Customization should address the removal of this output efficiently. Creating a customizable biogas plant and digester involves several strategies. A modular approach is implemented, allowing the addition or removal of digester units to match changing waste volumes. Materials readily available in the region are used to lower costs and increase the feasibility of constructing biogas systems. The system is designed to handle a variety of organic waste types and qualities, enabling adaptation to seasonal variations. Customized biogas systems should be user-friendly, allowing local communities to operate and maintain them with minimal training. Basic monitoring and control mechanisms are incorporated to optimize biogas production, ensuring the system operates efficiently. Figure 6 indicates the general schematic sketch of the community-scale fixed-dome biogas plants, while the floating-type biogas plants are depicted in Figure 2.

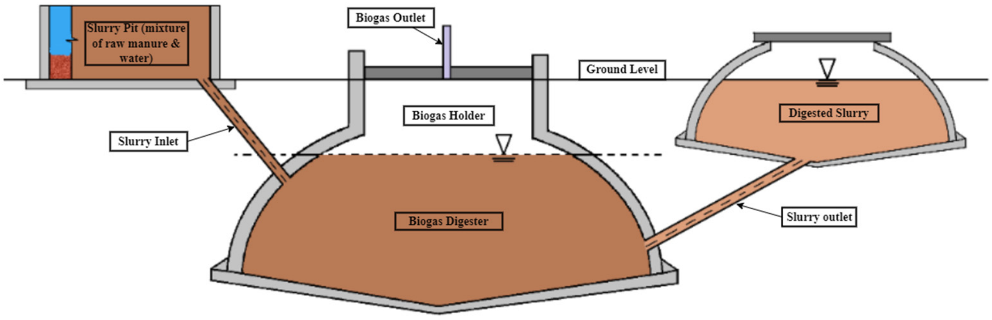

Figure 6. General schematic sketch of the community-type fixed-dome biogas digester adapted from [9].

6. Advantages of Community-Scale Bio-Digesters

Energy consumption patterns in Mauritania, as in many African countries, primarily rely on traditional energy sources, such as fuelwood, agricultural residues, and dung. These sources are associated with high emissions of toxic gases and low efficiency, leading to negative environmental and health consequences [29]. Additionally, the commercialization of these traditional energy sources, coupled with deforestation, exacerbates the energy crisis in the region. Biogas presents a viable alternative that can alleviate these environmental stresses and address the energy crisis [37]. While biogas lighting may not be as aesthetically pleasing as conventional electric lighting, it offers a practical solution in off-grid areas. Moreover, the use of biogas for lighting and minor electrical appliances can be linked to the ease of access to marketing and other forms of information, suggesting a relationship between biogas penetration and increased access to development opportunities in rural areas [38,39].

Biogas technology offers a promising alternative to LPG in Mauritania, and its utility varies based on several key factors. In the context of this diverse and dynamic nation, where geographical location, energy access, cultural practices, and socio-economic conditions play pivotal roles, understanding when and why biogas proves more advantageous than LPG becomes crucial. In the vast, remote, and often off-grid regions of Mauritania, the benefits of biogas become particularly pronounced. Access to modern energy sources, such as LPG, is often limited or unreliable, primarily due to distribution challenges. Here, biogas's decentralized nature, derived from locally available organic waste, provides a practical solution. It helps bridge the energy access gap, reducing dependence on sporadic LPG distribution networks and promoting energy equity [29]. Agriculture is a cornerstone of Mauritania's economy, and households engaged in farming activities generate substantial organic waste, including crop residues and animal dung. In these settings, biogas systems shine. They efficiently convert agricultural waste into valuable energy, supporting cooking and lighting needs. Beyond these immediate benefits, this sustainable practice aligns with Mauritania's agricultural and environmental goals, minimizing resource waste and enhancing crop productivity [35]. Agricultural farms in Mauritania often house significant livestock populations, which translates to ample organic waste. Biogas systems offer an innovative solution, turning waste into a resource. The energy generated can cater to household energy needs, while the resulting digestate, a nutrient-rich byproduct, serves as an excellent crop fertilizer. In essence, livestock waste transforms into a sustainable energy source and a boon for agriculture, closing the loop on resource utilization [40]. Waste management is a persistent challenge for communities across the world, including Mauritania. Biogas systems serve a dual purpose by addressing both waste disposal and energy provision. Organic waste, if left unattended, could contribute to environmental pollution. However, biogas transforms this waste into a useful energy source, effectively tackling waste management issues while simultaneously providing energy [41]. Cost-effectiveness often plays a pivotal role in energy decisions. Biogas relies on locally available organic waste, which is frequently more affordable or even free compared to imported LPG. This economic advantage positions biogas as a financially appealing choice, particularly over the long term. Households seeking to reduce energy expenses while accessing a cleaner energy source may find biogas a highly attractive option [41].

Mauritanian households with a strong emphasis on environmental conservation and global climate goals may prefer biogas. These systems significantly reduce methane emissions, a potent greenhouse gas, by capturing methane from organic waste. This dual benefit serves both global climate objectives and local environmental preservation, making biogas an environmentally responsible choice [40]. Communal engagement can amplify the impact of biogas systems. Households in communities willing to collaborate on waste collection and management can enhance the efficiency and viability of biogas production. Collective efforts can make biogas more useful than individual LPG usage by optimizing resource utilization and fostering a sense of shared responsibility [29]. In summary, biogas's utility over LPG in Mauritania hinges on diverse factors. It thrives in rural and remote areas, where access to modern energy sources is limited, and it finds its strength in agriculture, livestock farming, waste management, cost-consciousness, and environmental consciousness. Harnessing these benefits involves a strategic consideration of local factors and a strong community spirit, keeping in mind its suitability to Mauritanian geo-climate and economic conditions.

Wood is mostly being utilized in households for kitchen purposes due to the higher cost of the LPG and its shortage, especially in distant areas of the country. Wood burning or livestock dung burning cause severe respiratory syndromes in the communities' women, who are prone to serious health consequences in the country. The tapping of the biogas from livestock resources not only provides LPG replacement but also guarantees forestation and reduces soil erosion and greenhouse gas emissions as surplus benefits [42]. The livestock manures are directly utilized for farming practices in Mauritania, which produces 10.7 Gg of methane emissions per year [8]. Biogas production is a clean and economically viable option for Mauritania and can also be beneficial for reducing the methane emissions footprints of the livestock sector. These reduced emissions of methane can also be traded in the international market under the defined international carbon trading market prescribed by the United Nations Framework Convention on Climate Change (UNFCCC). It has been calculated in the current study that almost 50% of the energy demand for cooking purposes in Mauritania can be met by producing biogas within the country [8]. The current case study ensures forest conservation, reducing energy poverty within the country and creating new entrepreneurship and employment horizons for the community. The current research work provides guarantees for women's health, reducing poverty and producing organic fertilizer for local crops as additional benefits if the proposal is implemented. The current research work increases the renewable energy mix of the country, which ensures reduced carbon emissions and provides higher effectiveness in climate change perspectives globally.

7. Biogas Utilization's Economic Benefits over LPG Usage in Mauritania

Access to clean, affordable energy is a critical concern for economically weaker communities. This study investigates the practicality and economic feasibility of transitioning from LPG to a biogas network in residential buildings within communities. This study examines monthly operational costs, required digester volume, and cost comparisons between LPG and biogas systems. In economically weaker communities, ensuring access to clean and affordable energy is a fundamental challenge. This study explores the potential of biogas as a sustainable energy source for residential buildings by comparing it with LPG. The biogas plant proposed is a very logical and easier technology option, which is a sustainable onsite energy solution and is socially beneficial. We consider a medium-sized residential community with 100 families, with each family comprising four members, in a suburban area dedicated to sustainable practices. A family of four consumes a considerable 3.6 cubic meters of biogas per day [43] for cooking and heating requirements. Therefore, we need a biogas plant with about 400 cubic meters of biogas production per day for the proposed community. The analysis includes an exploration of the monthly operational costs of LPG and biogas systems. The calculation of LPG consumption considers daily usage for cooking, heating, and hot water. Total daily LPG usage is determined by multiplying the number of families by the daily LPG usage per apartment for cooking. A community of 100 households consumes 15 kg of LPG per month for kitchen purposes and heating purposes. The cost of LPG in Mauritania is about USD 3/kg [44]. The total LPG requirements for the 100 families will be around USD 4500, which is very high. LPG transportation also makes hurdles multiple times a year due to unavailability in the national market and reduced supply in the local markets. Local vendors of LPG also affect the LPG prices multiple times a year, which makes its utility very problematic. The detailed economic constraints of the biogas plants on community scales are provided below in Table 4, while the monthly benefits of utilizing biogas over LPG for a community of 100 families have also been presented in Figure 7.

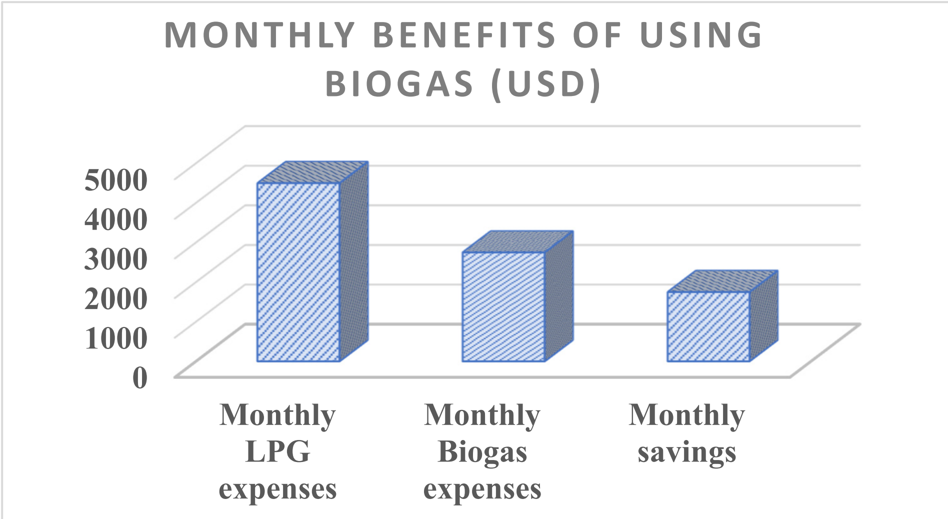

Figure 7. Economic benefits of replacing LPG with biogas on community scale.

Table 4. Economic benefits and operation cost of LPG and biogas plant system.

Attributes	Cost in USD
Total monthly LPG expenses	
Total monthly cost of LPG per family	15 × 3 = USD 45
Total monthly cost of LPG per 100 family community	45 × 100 = USD 4500
Total monthly expenses of the biogas plant	
Capital/fixed costs	
Construction of biogas plant and facilities, 400 m^3	USD 100,000
Site acquiring and feasibility cost	USD 30,000
Total capital cost	USD 130,000
Distributing the capital cost over 6 years to achieve the monthly net positive benefits	130,000/72 = USD 1805.6
Operating/running costs	
5 laborers required to operate biogas plant @ USD 250/month	USD 1250/month.
Tractor/trolley cost for manure transportation and crop residue collection	USD 1000/month
Maintenance of biogas plant	USD 500/month
Total biogas plant operational/running cost	USD 2750/month
Net monthly benefit of utilization biogas over LPG	USD 4500 − 2750 = USD 1750/month
Payback period	130,000/1750= 74 months

The biogas site acquisition cost is based on the actual land prices in the vicinities of the Mauritanian suburbs [45]. The biogas plant and facilities costs also consider the available plant design sizing and cost parameters measured in international markets. Different Chinese vendors and websites like Alibaba have also been consulted for these costs and have provided a comprehensive solution [46]. The transportation cost is basically the cost of bringing livestock manure to the biogas plant. In this case, the community scale biogas plant is proposed near the denser livestock populations which surround villages or are in the suburbs of large cities in Mauritania. The daily manure transportation required for the community project is 12,000 kg. One tractor and one trolley can perform this transportation once a day at a cost of around USD 1000/month. Thousands of livestock herds are present in all the suburbs of the large cities, which fulfills the demands for milk in the city centers. The total capital cost for this community-size biogas plant will be around USD 130,000. This cost also includes all the biogas production systems like scrubbers and biogas refining systems. If we distribute this capital cost over the span of 6 years, then the minimum monthly revenue should be around USD 1800 to meet the break-even point. To operate the biogas plant, a minimum of five laborers will be required, which also includes technical personnel. The monthly operational cost of the biogas plant will be USD 2750, which also includes the transportation and tractor costs. In addition to the economic benefits of the community-scale biogas projects in Mauritania, these projects will have multiple beneficial aspects like entrepreneurship options for young talent, environmental benefits by reducing the greenhouse gas footprints of the livestock industry within the nation, saving the ground water from manure contamination, and the empowerment of women. The capital cost for the project is USD 130,000, which is very high. The government of Mauritania, national banks, and international donor agencies, like the United Nations Agency Framework Convention on Climate Change (UNFCCC) under Clean Development Mechanism (CDM) projects, can support such community projects, which have a wider scope of applications, like energy security and environmental benefits. The national banks in Mauritania can provide tariffs and swift loan schemes for such community projects for national needs. The women of the community can take the lead in terms of transportation of the feedstock to the site and operational duties of the biogas plants, thus enabling the empowerment of women within the nation. The economic return benefits indicated that after the 74th month, the biogas plant will be running on a monthly profit of USD 1750, which is a very significant achievement, and there will be energy sustainability within the communities, which are rich in agricultural and animal dung resources. The LPG process is also very much fluctuating in the international market and has strong influences on the national income and household expenses of the family. If the primary feedstock material is available, then biogas utilization is much better compared with LPG resources. A cost comparison between LPG and biogas systems sheds light on the financial aspects of these energy sources. It is important to note that while the calculated biogas cost in this model appears high, practical applications typically yield significantly lower costs. Explaining the key components and considerations driving the cost and feasibility of LPG and biogas systems helps us understand the differences and factors involved in choosing between these energy sources. LPG setup costs cover the purchase of LPG cylinders and regulators, while biogas network setup encompasses expenses for the biogas digester, piping, and gas collection and conversion systems. LPG costs vary with market rates, while biogas costs depend on the availability of organic waste. Regular maintenance for LPG includes checks on regulators and cylinders, whereas biogas network maintenance focuses on the digester and associated components. LPG is derived from finite fossil fuel reserves, while biogas relies on locally available organic waste as a renewable energy source. LPG combustion releases emissions and pollutants, while biogas production results in less greenhouse gas emissions (GHGs) due to the utilization of organic waste. LPG depends on finite global reserves, while biogas contributes to sustainable energy generation by utilizing locally available organic waste. This research provides a comprehensive analysis of LPG and biogas systems for residential buildings in economically weaker communities. It evaluates monthly operational costs, calculates the required biogas digester volume, and compares the costs of both energy sources. While the calculated biogas cost may appear high in this simplified model, practical applications typically yield more economic results. The research underscores the potential of biogas as a sustainable and locally sourced energy alternative for economically weaker communities, facilitating cleaner and more accessible energy sources in these regions.

The economic advantages of biogas adoption extend beyond energy security. By transitioning from LPG to a locally produced biogas network, Mauritania can potentially reduce its dependence on costly fossil fuel imports. This shift could have a positive cascading effect on the national economy by freeing up resources that could be allocated to other developmental initiatives. Moreover, the integration of biogas systems at the local level can stimulate job creation and local entrepreneurship. As communities invest in biogas infrastructure, opportunities arise for skills development, maintenance services, and organic waste collection systems. This decentralized approach to energy production can empower local communities while contributing to the broader national energy agenda. The initial cost of the biogas plant is high, but there are larger economic benefits over the passage of time, providing energy sustainability within the nation.

8. Conclusions and Policy Recommendations for the National Stakeholders in Mauritania

The case study on transitioning households from LPG to a biogas network in Mauritania presents a promising outlook, revealing notable economic and environmental benefits on a communal scale.

8.1. Concluding Remarks

- The community-scale fixed-dome-type reactors are recommended for at least a community of 100 families. The community-scale biogas plants will have a payback period of about 74 months, and afterward the project will run with a monthly benefit of USD 1750.
- Mauritania has total biogas production potential of 2451 million cubic meters annually.
- In addition to economic gains, the transition to biogas aligns with Mauritania's commitment to addressing environmental concerns and mitigating greenhouse gas emissions. The utilization of organic waste for biogas production effectively reduces methane emissions, a potent greenhouse gas, contributing to both global climate goals and local environmental preservation. Installation of communal-scale biogas plants in Mauritania will result in reducing the 10.7 Gg of methane emissions per year.
- Biogas production in Mauritania is a sustainable approach which provides energy security and energy sustainability within the nation and an excellent approach in replacing LPG across the nation.
- Biogas production in Mauritania is a practical approach and depends on the local waste feedstock available and is less dependent on the fluctuations in the price of LPG globally.
- The proposed methodology of biogas production ensures waste management, mitigates climate change, and provides a cleaner environment on a community-scale.
- Women's health will be more protected because the cleaner fuel as biogas is available in the kitchen for cooking purposes.

8.2. Policy Recommendations for the National Authorities of Muritania

- The communal scale biogas digesters are very much sustainable for the suburbs of Mauritania, which have large populations of livestock.
- There should be swift and interest-free loans for the development and installation of the biogas plants across the nation.
- There should be no import tax on the equipment and manufacturing facilities related to biogas technology within the country.
- The Ministry of Energy in Mauritania should take concrete steps in organizing international training, certification, knowledge, and awareness seminars regarding biogas technology development.

- The Government of Mauritania should take steps to approach international funders like the United Nations Framework Convention on Climate Change (UNFCCC), the United Nations Development Program (UNDP), the World Bank, and all other possible funders to mine commercial projects to promote biogas technology within Mauritania.

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