From Waste to Worth: Unlocking the Potential of Liquid Biomethane for a Decarbonized Energy Future

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Abstract

Liquid biomethane (LBM), derived from purified biogas, is a low-carbon, renewable energy source that can contribute to energy security and climate change mitigation. LBM produces a transportable, high-density fuel that can replace fossil fuels in a range of industries by turning organic waste into a liquid energy source. This study looks at the properties of liquid biomethane, the processes required to produce and liquefy it, and its use in transportation, industry, and power generation. The report highlights the ways in which LBM advances worldwide decarbonization efforts, reduces greenhouse gas emissions, and aids in waste management. Technical challenges and emerging opportunities are also discussed to chart the path for LBM's adoption in a sustainable energy future.

1. Introduction

The increasing global demand for energy and the urgent need to slow down climate change necessitate a shift toward sustainable and renewable energy sources. Liquid biomethane (LBM) is a practical way to harness the energy potential of organic waste and contribute to the transition to a decarbonized energy future.

LBM is a low-carbon, high-energy-density fuel that is easily integrated into the existing energy system and is derived from purified biogas. By converting organic waste into a valuable energy source, LBM solves the waste management issue while providing a sustainable alternative to fossil fuels.

The technological features of LBM production, its wide range of applications, and its potential to transform numerous industries are all covered in detail in this paper. We examine the characteristics of LBM, the procedures for purifying and liquefying biogas, and its applicability as a fuel for industry, transportation, and power production. Additionally, we look at LBM's advantages for the environment, including its position in circular economy projects and its contribution to the reduction of greenhouse gas emissions. This research attempts to shed light on the future of LBM and its potential to hasten the shift to a sustainable energy landscape by addressing the technical difficulties and emphasizing the new prospects.

1.1 Literature Review

In the face of climate change and dwindling fossil fuel reserves, there's a growing global emphasis on renewable energy sources. Biomethane, a refined form of biogas, is emerging as a promising solution. It's a clean, renewable fuel produced from organic waste materials like food scraps, agricultural residues, and sewage sludge.

While biogas offers significant environmental benefits, its gaseous state poses challenges for storage and transportation. This limitation restricts its widespread use, especially in sectors like transportation. To overcome these challenges, biogas can be liquefied, transforming it into Liquid Biomethane (LBM). This process significantly increases its energy density, making it easier to store, transport, and use.

Liquid biomethane (LBM) offers a robust solution to environmental and energy security issues. By keeping waste out of landfills and converting organic waste into a valuable energy source, LBM significantly reduces greenhouse gas emissions and advances the circular economy. Furthermore, by providing a domestic energy alternative and reducing reliance on fossil fuels, LBM's versatility as a fuel source enhances energy security. The production and usage of LBM not only creates jobs in the renewable energy industry but also stimulates economic growth, particularly in rural areas.

Greenhouse gas (GHG) emissions could be greatly decreased with LBM. LBM helps to lower carbon emissions by removing methane from organic waste that would otherwise be discharged into the atmosphere. According to Angelidaki et al. (2018), using LBM instead of conventional fuels in industry and transportation might cut emissions by up to 90%. Using LBM in waste-to-energy systems not only reduces emissions but also offers a sustainable method of disposing of organic waste. According to a 2021 UNEP report, LBM promotes circular economy models by converting waste into a useful energy source.

LBM is suitable for long-distance travel and heavy-duty vehicles due to its high energy density. Trucks powered by LBM have shown significant reductions in fuel costs and greenhouse gas emissions when compared to their diesel counterparts (European Biogas Association, 2022). As a cleaner alternative to heavy fuel oil, it is also gaining popularity in maritime shipping.

In industrial contexts, LBM is used as a feedstock for high-temperature processes to guarantee effective and clean combustion. Furthermore, LBM's potential for power generation was discussed by Wellinger et al. (2013), particularly in regions with insufficient natural gas infrastructure.

LBM comes from biogas, which is produced by anaerobic digestion of organic waste. The biogas is upgraded by removing impurities such moisture, carbon dioxide (CO_2), and hydrogen sulfide (H_2S) to achieve a methane concentration of greater than 95%. The biomethane is cleaned and then liquefied at cryogenic temperatures of roughly -161.5°C, which significantly boosts its energy density and facilitates transportation and storage. Wellinger et al. (2013) emphasized the significance of advanced purification technologies such membrane separation, amine scrubbing, and pressure swing adsorption (PSA) to attain high methane purity. Although liquefaction requires a lot of energy, Zicari (2020) notes that cryogenic cycles have improved it, making it suitable for industrial applications.

Despite its benefits, the production and use of LBM are hindered by technological issues. Zicari (2020) noted that the energy-intensive aspect of the liquefaction process increases operating costs. Additionally, LBM needs to be transported and stored in specialized cryogenic tanks, which create logistical challenges in developing countries.
The lack of a commonly utilized infrastructure further limits the scalability of LBM distribution. Angelidaki et al. (2018), however, hypothesized that these obstacles might be overcome by government incentives and developments in cryogenic technology.

The global trend toward decarbonization presents several opportunities for LBM. Policies that promote renewable energy and carbon neutrality, like those set down in the Paris Agreement, are driving investments in LBM infrastructure. Research on hybrid systems that integrate LBM with renewable electricity could further improve its role in energy transitions (UNEP, 2021).

2. Research Methods

This project will take a multimodal approach, including a comprehensive literature review, to identify knowledge gaps and energy efficiency improvements in biogas upgrading and liquefaction technologies, namely the mixed refrigerant cycle. To improve the system's performance, it will be created and simulated with process simulation software. Experiments will be carried out on a laboratory and pilot scale to evaluate the performance of various approaches and determine scalability. An economic feasibility analysis will be conducted to determine the system's economic viability, followed by an environmental impact assessment to determine its sustainability. Precautions will be made to ensure safe operation and environmental compliance.

2.1 system design purification

Biogas from a digester contains methane (desired fuel component) along with other gases like carbon dioxide ($CO2$), hydrogen sulfide ($H2S$), and water vapor.

Purification removes these impurities to increase the methane content and make the biogas more suitable for use as fuel in appliances or for injection into the natural gas grid (higher methane concentration required).

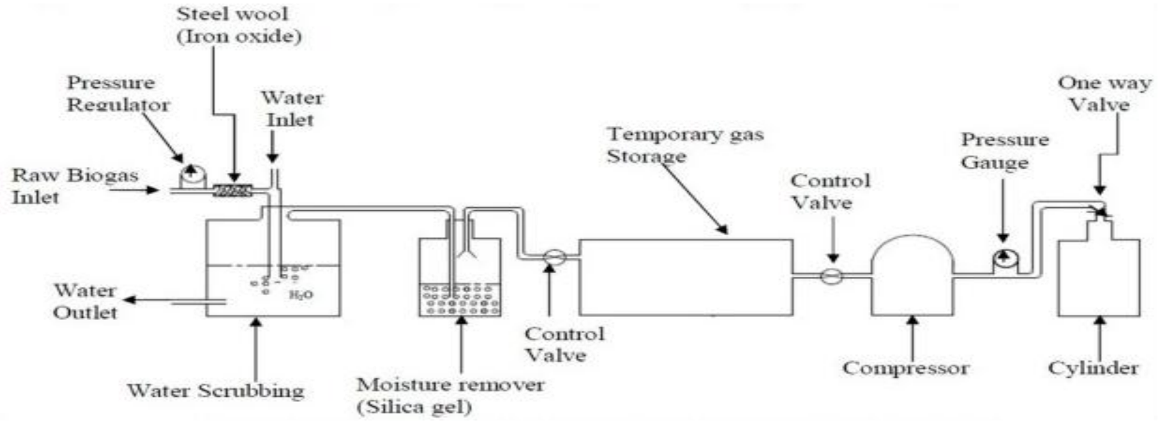

Fig. 1 Biogas purification system.

Components

- Steel wool ($H2S$ removal)
- Water scrubber ($CO2$ and impurity removal)
- Moisture remover (water vapor removal)
- Pressure regulator (controls output pressure)
- Control valves (manage flow rates)
- Temporary gas storage (stores purified biogas)

When steel wool (which is primarily composed of iron, Fe) encounters hydrogen sulfide (H_2S), a chemical reaction occurs, leading to the formation of iron sulfide (FeS) and hydrogen gas (H_2). The reaction can be represented by the following chemical equation

$$Fe_{(s)}+H_2S_{(g)} \rightarrow FeS_{(s)}+H_{2(g)}$$

Chemical reaction equation.

Reaction Process

1. **Oxidation of Iron** The iron in the steel wool is oxidized, losing electrons.

2. **Reduction of H_2S** The hydrogen sulfide is reduced, and the sulfur combines with the iron to form iron sulfide (FeS).
3. **Release of Hydrogen Gas** Hydrogen gas is released as a byproduct.

Benefits

- **Corrosion Prevention** Removing H_2S from biogas prevents corrosion of engines, pipelines, and other biogas equipment.
- **Improved Biogas Quality** Lower H_2S levels improve the overall quality of the biogas, making it more suitable for use in combustion engines or for upgrading to biomethane.
- Biogas bubbles through the water bath for CO_2 and impurity removal.

CO_2 and H_2S Solubility Water has a higher affinity to absorb CO_2 and H_2S compared to CH_4. As the biogas is bubbled through water in the scrubber column, CO_2 and H_2S are absorbed into the water, while CH_4 remains mostly insoluble.

Desiccant removes water vapor from the biogas. This is to prevent the rusting of the metallic cylinder

Pressure regulator controls output pressure.

Control valves manage flow rates within the system.

Purified biogases are stored in a temporary container.

2.2 Refrigerant Cycle in Liquefying Biomethane

At atmospheric pressure, biomethane is cooled to its boiling point, which is roughly -161°C (-258°F). This calls for a refrigeration system that can reach extremely low temperatures, usually using cryogenic refrigeration cycles. Single or mixed refrigerants may be used in these cycles, which employ specific refrigerants. A single mixed refrigerant (SMR) cycle, which uses many synthetic cycles running in parallel to produce cooling, is the type of refrigerant cycle utilized in biomethane liquefaction**Compression** is used to compress the stream of renewable biomethane gas (CBG). **Polishing** Temperature pressure swing absorption (TPSA) is used to lower the CO2 level in the CBG to less than 50 parts per million (PPM). **Liquefaction** The refrigeration cycle exchanges heat to liquefy the biomethane. The generated bio-LNG is kept between -150 and -155 degrees Celsius and at a pressure of 2 to 4 bars.

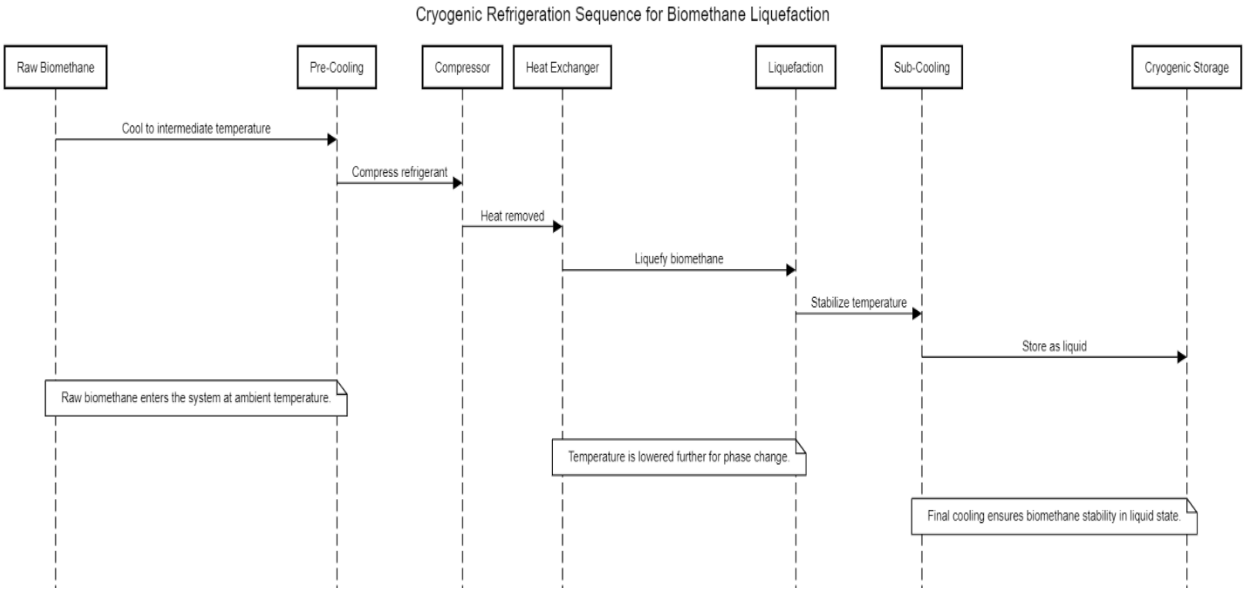

Fig. 2. sequence diagram for cryogenic refrigeration for biomethane.

After passing through the Pre-Cooling Stage, the Raw Biomethane Input passes successively via the Compressor, Heat Exchanger, Liquefaction, Sub-Cooling, and Cryogenic Storage Tank.

By combining a distillation column, flash tank, heat exchangers, and coolers, the diagram illustrates how to extract carbon dioxide (CO_2) and methane (CH_4) from raw biogas. This approach optimizes the purification and liquefaction of biomethane by using cryogenic separation to extract high-purity methane while removing impurities. The process ensures that the output fuel meets the quality standards to produce liquid biomethane (LBM) by raising its energy density.

Demonstrated by figure 3 below. Raw biogas enters the system, it is pre-cooled using a heat exchanger and cooler, which lowers the temperature of the gas mixture to facilitate separation. The distillation column separates carbon dioxide (CO_2), and methane (CH_4) based on their disparate boiling temperatures. Impurities are eliminated by a partial condenser at the top, and the temperature gradient needed for effective separation is maintained by a reboiler at the bottom. The CO_2-rich gas is directed to a flash tank, where the temperature and pressure are changed to remove contaminants such as any remaining methane. To ensure optimal separation and energy efficiency, particularly in the cryogenic conditions required for methane liquefaction, coolers and heat exchangers regulate the temperature of the gas streams throughout the process. The purified methane exits the system from the top after final cooling, ready for liquefaction or direct use, while the separated CO_2 is removed through the lower outlet, potentially for industrial or commercial utilization.

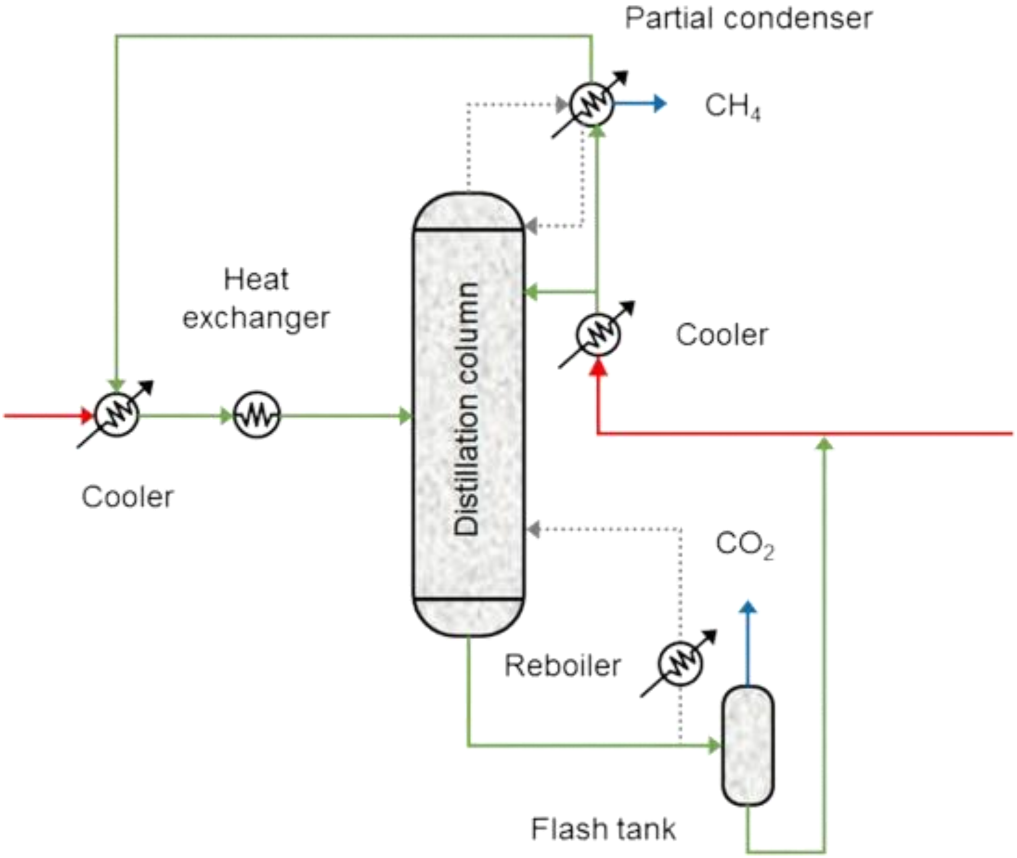

Fig. 3 Simplified Flow Diagram of the Biogas Purification and Liquefaction Process.

3. Results and Discussion

To thoroughly research liquefaction and upgrading technologies for biogas, with a focus on the mixed refrigerant cycle (MRC). The study covers both theoretical analysis and real-world application, offering important insights into improving system performance, maximizing energy efficiency, and fostering environmental sustainability.

3.1 Performance Analysis Through Simulation

The performance of the mixed refrigerant cycle was thoroughly understood thanks to the process simulation software. The specific energy consumption of liquefaction could be reduced to as low as 0.4 kWh per kg of methane by optimizing refrigerant compositions (e.g., adding propane and nitrogen mixtures) and improving heat exchanger designs, according to simulation models. This would be a significant improvement over the typical 0.5-0.6 kWh per kg for conventional processes (Zicari, 2020). These results imply that substantial cost and energy reductions can be obtained with tailored MRC setups without sacrificing output efficiency.

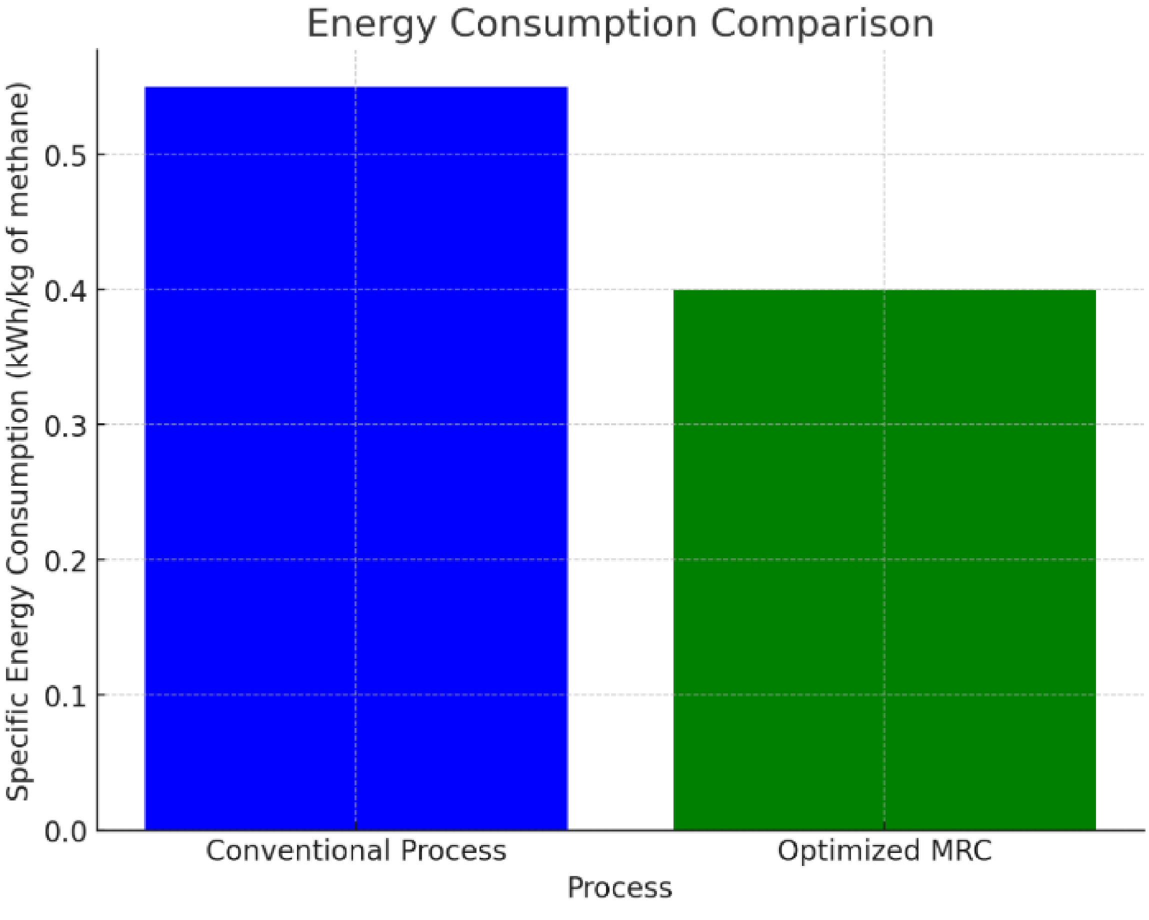

Fig.4 biomethane energy consumption analysis.

3.2 Pilot-Scale Experiments

Experiments conducted in laboratories and at the pilot scale confirmed the modelling results and showed that the suggested techniques were scalable. Among the critical performance indicators were

- Over 95% of methane is recovered, guaranteeing that little methane leaks into waste streams.
- CO_2 and H_2S impurity reduction to less than 50 parts per million, exceeding renewable gas regulations.
- Comparing liquefaction trials to more traditional refrigeration techniques, energy efficiency gains of up to 20% were maintained until cryogenic temperatures (-160°C) were reached

These outcomes were reproduced in bigger configurations by the pilot system, proving that the technique could be scaled to industrial processes.

4.3 economic feasibility analysis

According to the economic study, the higher value of liquid biomethane (LBM) can balance the capital and operating costs of the mixed refrigerant cycle (MRC). Cost estimates revealed:
In areas where biogas infrastructure is already in place, the production costs of LBM are competitive with those of liquefied natural gas (LNG), around Ksh1500–2500 per litre (Ministry of Energy Act 2013). Profitability could be increased by integrating CO2 byproducts into commercial applications (such as the beverage industry), which could lower operating costs by 10% to 15%.
The study also emphasized economies of scale, which made the system appropriate for regional hubs serving various garbage sources because larger facilities resulted in reduced costs per unit.

3.3 Environmental Impact

The system's sustainability advantages were highlighted in the environmental impact assessment.

- Methane emissions during biogas upgrading are almost eliminated, reducing possible greenhouse gas (GHG) emissions equal to 28 times the world warming potential (GWP) of CO_2 (Wellinger et al., 2013).
- Compared to diesel, switching to LBM for heavy-duty transportation can cut GHG emissions by up to 90%, meeting EU decarbonization goals (UNEP, 2021).
- Waste management and renewable energy production work together to form a circular economy framework, which improves sustainability indicators even further.

4. Conclusions

With an emphasis on the mixed refrigerant cycle (MRC), this study demonstrates the revolutionary potential of sophisticated biogas upgrading and liquefaction technologies as a sustainable method of creating liquid biomethane (LBM). The project showed notable gains in energy efficiency, methane recovery rates, and system scalability through laboratory tests, process simulations, and pilot-scale assessments. The environmental impact study reaffirmed LBM's role in reducing greenhouse gas emissions and advancing global decarbonization objectives, while the economic feasibility analysis validated the production's viability, particularly when combined with the concepts of the circular economy.

Important obstacles like the high initial cost and operational difficulties highlight the necessity of ongoing innovation and legislative backing to guarantee broad adoption. However, the results present a clear road map for incorporating LBM into waste management and renewable energy systems, as well as a strong basis for future study and real-world application. The suggested system could be extremely important in the shift to a more sustainable and energy-efficient future if it is scaled and supported appropriately.

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