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TECHNO-ECONOMIC ANALYSIS OF BIOGAS UPGRADING

A Thesis in
Agricultural and Biological Engineering and International Agriculture and Development

by
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ABSTRACT

Water scrubbing is a physical absorption method which uses absorption to remove impurities from biogas. The feasibility of water scrubbing to upgrade biogas was analyzed for two fluids (tap water and digestate liquid), and in two settings (U.S and Nigeria). Experiments were carried out to test the absorption capacity of carbon dioxide using these fluids. A techno-economic model was created to simulate the performance of a biogas upgrading system, and the model was used to estimate the viability of the system.

Results indicate that biogas upgrading for a small-scale farm in Pennsylvania yields a negative net present value (NPV) of -\$795,246, with all but the optimistic scenario producing negative values. Sensitivity analysis indicates that pipeline cost, number of cows, and biogas production costs have the greatest impact on NPV, while utility costs have the least influence.

Digestate liquid can be used to absorb carbon dioxide; however, its performance is lower than that of water. It was found to be most effective at 4°C and 1440 minutes. The techno-economic analysis of using digestate liquid for upgrading also results in a slightly improved but still negative NPV (-\$65,240), compared to using water, despite no associated cost for the liquid. This outcome can be attributed to the required height of the column, which is approximately twice the height needed when using water to achieve the same carbon dioxide removal efficiency.

Techno-economic analysis of biogas upgrading in Nigeria using biomethane as a substitute for liquefied petroleum gas (LPG), with a base case of 60 cows, also yields a negative NPV of -~~₦~~10,253,874, only the optimistic variation of this scenario result in a positive NPV. While the NPV of these systems tends to be negative, their use may be justifiable in favorable settings and conditions. Sensitivity analysis shows that the biogas production cost has the greatest impact on NPV, followed by compressed biomethane cost and the number of cows. However, biogas production costs could be reduced through funding incentives, grants, and financing

mechanisms. The farming system in Nigeria also affects the availability of manure, as cows are not typically confined to a single location.

Overall, this thesis provides an assessment of the economic and technical feasibility of biogas upgrading using water and digestate liquid in two different continents, showing the significant variables assessing the adoption of the use of biomethane as electricity, renewable natural gas or liquified petroleum.

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Chapter 1

INTRODUCTION

Global energy consumption has risen markedly, which is attributed to the increasing global population and economic development. To satisfy this growing demand, the global energy supply has remained heavily reliant on fossil fuels, namely coal, oil, and natural gas, which collectively contribute to 80% of the world's energy consumption (Aghel et al., 2022; Chakravorty et al., 2005; Rapier, 2021).

These conventional energy sources are major emitters of pollutants, prompting increasing international concern due to their detrimental effects on air quality, human health, the ecosystem and global climate. This has led to a transition toward alternative, cleaner energy sources. Concurrently, waste management, particularly the disposal of municipal, agricultural, domestic, and industrial waste, has emerged as a pressing environmental issue, often leading to the contamination of water bodies, posing significant risks to both aquatic and terrestrial ecosystems (i.e. Zahmatkesh et al., 2022). This highlights the necessity for more sustainable and environmentally friendly waste management solutions.

Renewable energy sources such as wind and solar have great promise for reducing negative impacts of the energy sector, and they have grown drastically in use in the twenty-first century. Biogas is another less common sustainable renewable energy alternative source derived from the anaerobic digestion of organic biomass, serving as a viable alternative to natural gas (Budzianowski et al., 2017). It offers a dual advantage by addressing energy needs as well as environmental degradation (Abu Seman & Harun, 2019). Biogas contributes to environmental sustainability and

economic development by valorizing waste streams, promoting renewable energy technologies, and supporting rural economies and ecosystems.

It is produced in anaerobic digesters, where microbes consume organic matter in an oxygen-limited environment. The first documented use of digesters and biogas is from the 1800s in India and New Zealand (Bond and Templeton, 2011).

Biogas is primarily comprised of methane (CH_4), the combustible component, and impurities such as carbon dioxide (CO_2) and hydrogen sulfide (H_2S). It is used in combined heat and power (CHP) systems for heating and electricity (i.e. Wilken et al., 2017).

In this context, animal manure produced on farms presents an opportunity for biogas production. By converting manure into biogas, farmers can recycle farm waste, reduce odors, generate energy in the form of heat and electricity, and even inject the biogas into natural gas pipelines, as shown in Figure 1-1. As such, biogas holds considerable promise for smallholder farmers. Therefore, evaluating the techno-economic performance of on-farm biogas systems, which offers insights into their technical feasibility and economic viability, is a critical and worthwhile pursuit.

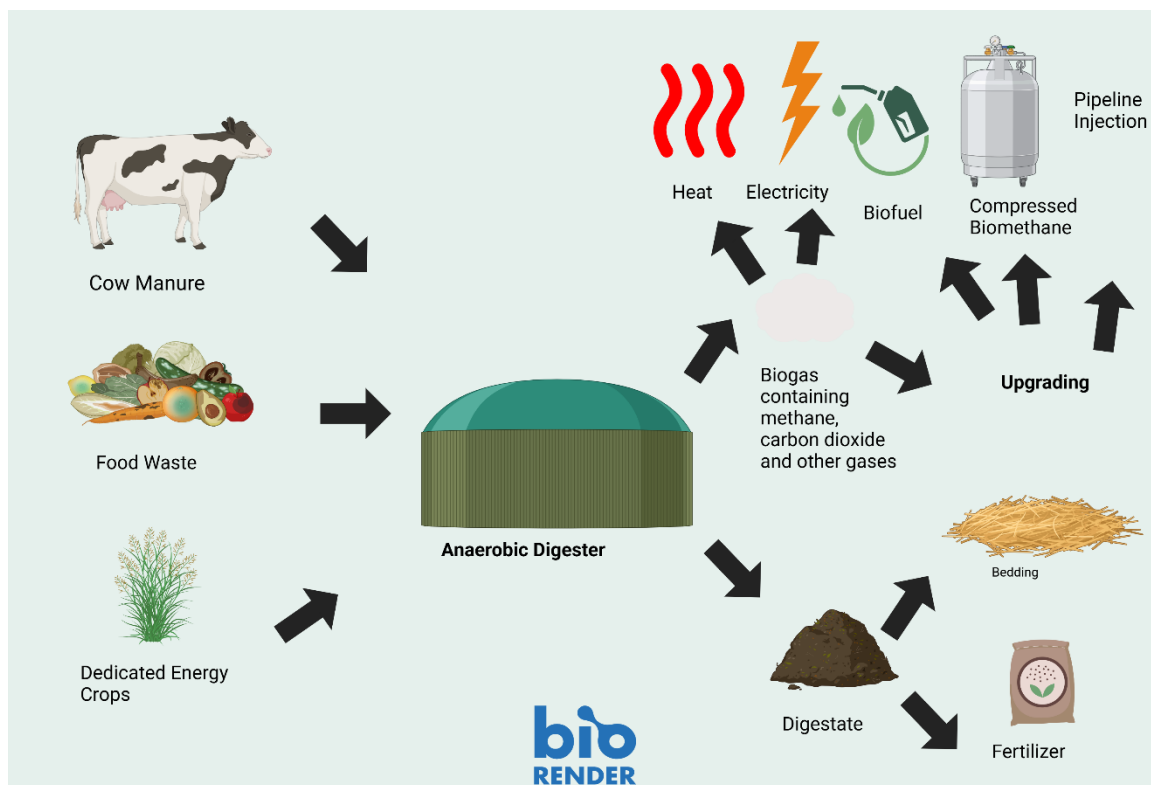


Figure 1-1: Biogas System (Image: Mary Akingbasote).

Substituting fossil fuels with biogas is widely recognized to reduce greenhouse gas emissions by advancing renewable energy sources (Deng & Hägg, 2010). Among the various feedstock options, agricultural waste is often available on farms, and as such it provides opportunities for energy generation, income diversification, and the production of organic fertilizer. This not only enhances farm resource utilization but also addresses challenges related to waste treatment and disposal.

The direct combustion of biogas for heating is often characterized by low energy efficiency (Deng & Hägg, 2010). Although natural gas and biogas share similar uses, they differ primarily in methane concentration and application (Figure 1-2), the CO_2 in biogas diminishes its energy content, flame velocity, and flammability limits (Noorain et al., 2019). Natural gas with a methane content ranging from 75% to 98%, delivers a higher calorific value (Noorain et al., 2019). Biogas

has potential applications for use in vehicle fuel and pipeline injection; however, its utility in these areas is currently limited due to impurities. It must be upgraded to enhance its methane concentration to maximize energy recovery for high-value uses. Upgrading involves removing CO₂, thereby increasing the fuel's calorific value (Cozma et al., 2014).

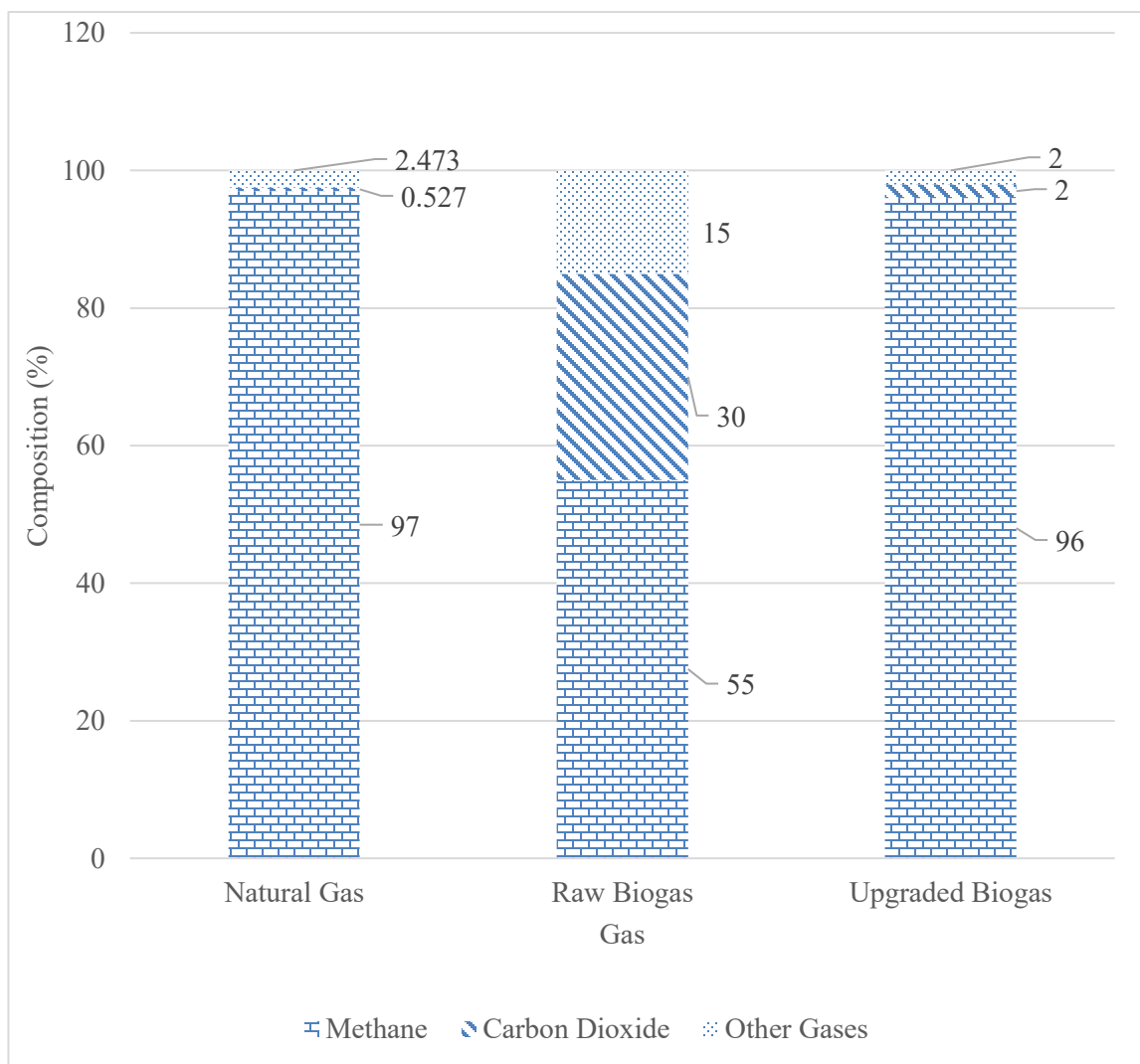


Figure 1-2: Gas Composition of Natural Gas, Raw and Upgraded Biogas (MET Group, 2023; Awe et al., 2017; Xie et al., 2020).

Given the need to upgrade biogas for high-value applications, feedstock availability becomes critical. In Pennsylvania, there are about 4,940 dairy farms, which make up about 17.4% of the dairy farms in the USA (Center for Dairy Excellence, 2024). These farms produce a

significant amount of manure daily, which is an ideal feedstock for biogas production. This can help reduce the odor produced on the farm while generating a renewable energy source

Similarly, Nigeria, a country in the western region of Africa, derives about 22.35% of its Gross Domestic Product from agriculture, with over 70% of the country's residents being farmers (Food and Agriculture Organization, n.d.). Most of them are subsistence or rural farmers who generate organic waste, the full potential of which remains largely untapped. Despite the abundance of available feedstock, biogas production in Nigeria remains underutilized. Tapping into this resource could help address the country's energy poverty, as biogas could serve as a viable alternative for electricity generation and clean cooking fuel.

The potential of biogas upgrading in both developed and developing economies is immense, as it decreases dependence on fossil fuels, curbs deforestation in African countries, promotes environmental cleanliness, and serves as a source of income.

The objective of this research is to provide insights into the feasibility of using digestate liquid as a cost-effective and sustainable scrubbing medium and assess the economic viability of water-based and digestate liquid-based scrubbing technologies. These findings are expected to inform decision-making among farmers and stakeholders. This study examines the potential for biogas upgrading both in a developed (USA) and developing economy (Nigeria) context.

1.1- Thesis Overview

This research project is presented in “paper” format, where each chapter is a semi-autonomous paper reporting an individual component of the overall project.

Chapter Two presents Techno-Economic Analysis of Biogas Upgrading in Pennsylvania. This study evaluates the technical and economic feasibility of employing water scrubbing technology for biogas upgrading on a dairy farm in Pennsylvania.

Chapter Three presents Techno-Economic Analysis of Biogas Upgrading Using Digestate Liquid. This research investigates the CO₂ absorption capacities of water and digestate liquid and uses these results to compare digestate liquid to water as a scrubbing medium.

Chapter Four presents Techno-Economic Analysis of Biogas Upgrading in Nigeria, which explores the upgrading and compression of biogas into liquefied petroleum gas (LPG) cylinders for practical application in the Nigerian context.

The overall result and implication of these results are then presented in Chapter Five: Discussions and Conclusions. All measured data are placed in the appendix and electronic files for the Techno-Economic model are stored in The Penn State University Data Commons.

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Chapter 2

TECHNO-ECONOMIC ANALYSIS OF BIOGAS UPGRADING FOR A SMALL FARM IN PENNSYLVANIA (WATER SCRUBBING)

2.1- Abstract

Biogas, a renewable energy source, can be upgraded to biomethane for injection into natural gas pipelines or for direct onsite utilization. This study evaluates the techno-economic feasibility of a small-scale on-farm (Pennsylvania) biogas upgrading system that uses water scrubbing. The technical and economic process was modeled using BioSTEAM software, with a baseline scenario corresponding to a farm digester on a 100-cow dairy farm. The analysis evaluates five scenarios: (i) biomethane production for pipeline injection with a flash column, (ii) biomethane production without a flash column for pipeline injection, (iii) electricity generation using biomethane with a flash column, (iv) electricity generation using only the water scrubbing column, and (v) electricity generation using raw biogas. The model included mass transfer calculations, equipment sizing, and economic evaluation using the discounted cash flow method with net present value (NPV) as the primary financial metric. Sensitivity analysis was conducted to assess the impact of key cost variables such as biogas production, pipeline installation, and electricity pricing. The results show a carbon dioxide removal efficiency of 93.03% with a methane loss of 3.78%. However, economic analysis revealed that all scenarios have negative NPVs ranging from -\$795,246 to -\$157,671, indicating unprofitability, with pipeline installation, number of cows and biogas production costs as the major factors influencing profitability. While electricity generation exhibits a less negative NPV than pipeline injection, profitability remains challenging without incentives. This study highlights the economic constraints of small-scale

biogas upgrading and suggests alternative strategies like community digesters or financial subsidies to improve viability.

2.2- Introduction

Pennsylvania is ranked eighth in the United States in total milk production, with an average herd size of 94 cows (Center for Dairy Excellence, 2024). Most dairy farm operations in Pennsylvania are classified as small-scale operations; however, they still generate waste that has the potential for biogas production.

Biogas is produced through the process of Anaerobic Digestion (AD), utilizing residual biomass derived from various sources, including municipal solid waste, livestock manure, agricultural residues, and wastewater (Soto et al., 2022). The production of biogas involves a series of intricate biochemical processes, including hydrolysis, acidogenesis, acetogenesis, and methanogenesis, which depend on a range of physical, chemical, and biological factors, such as the type of feedstock, pre-treatment methods, pH levels, anaerobic digestion temperature, and microbial diversity in the anaerobic environment (Mishra et al., 2021).

Biogas is composed of a mixture of methane (CH_4), carbon dioxide (CO_2), hydrogen sulfide (H_2S) and some other gases. CH_4 has value as a low-cost and renewable energy source (Khan et al., 2021). The other gases are of limited usefulness since they do not contribute to energy generation. Biogas with a high methane concentration (i.e. $> 90\%$) is more desirable, as it is comparable in quality to commercial natural gas and may be suitable for injection into the natural gas pipeline network as “renewable natural gas” (RNG). As a result, high concentrations of CO_2 and trace contaminants such as H_2S , N_2 , O_2 , water, and NH_3 restrict the potential applications of biogas (Zhao et al., 2021). Therefore, biogas upgrading can be used to increase the

CH₄ content, increase its usefulness in equipment, and make it suitable for new markets such as pipeline injection (Gkotsis et al., 2023). However, any biogas upgrade must be practically feasible and economically viable.

Biogas upgrading techniques include water scrubbing, chemical scrubbing, physical scrubbing, membrane separation, pressure swing adsorption, and cryogenic distillation (Cucchiella et al., 2018). Investing in biomethane can benefit the farmer and his community economically and environmentally. However, such an investment must be evaluated by a thorough economic and energetic analysis (Pochwatka et al., 2023). The comprehensive cost of producing biomethane incorporates capital and operating expenses of the equipment, power supply costs, gas network injection costs, methanation and electrolysis costs for renewable hydrogen production, and the electricity required by various machinery components (Ghafoori et al., 2022).

This study aims to answer the question: Is biogas upgrading via water scrubbing financially viable for a 100-cow dairy farm that is representative of dairy farm in Pennsylvania? The discounted cash flow (DCF) method was used, with net present value (NPV) as a financial indicator. Five specific scenarios were analyzed: (i) biomethane production for pipeline injection with a flash column, (ii) biomethane production without a flash column for pipeline injection, (iii) electricity generation using biomethane with a flash column, (iv) electricity generation using only the water scrubbing column, and (v) electricity generation using raw biogas.

The next section provides a review of existing biogas upgrading techniques, biomethane uses and economic considerations.

2.3- Literature Review

This review examines the state of the art of biogas scrubbing methods, with a focus on water scrubbing. It also explores the utilization of biomethane, such as injection into pipeline and production of electricity. Additionally, it delves into the economic aspects of upgrading biogas.

2.3.1- Biogas Upgrading Techniques

Biogas upgrading techniques remove impurities (all other gases except methane) from biogas. Figure 2-1 depicts the prevalence of different biogas scrubbing techniques, with membrane separation as the most used method. Membrane separation, as its name implies, involves the separation of gas mixtures using membranes, which are selective barriers that allow a certain component to permeate through them (Soto et al., 2022). It requires minimal maintenance, operates with a smaller plant, less skilled labor, does not rely on water or chemicals, and can scale down with minimal loss of efficacy. However, the main drawback of this technique is the necessity for multiple stages to achieve a high purity level (Chen et al., 2015).

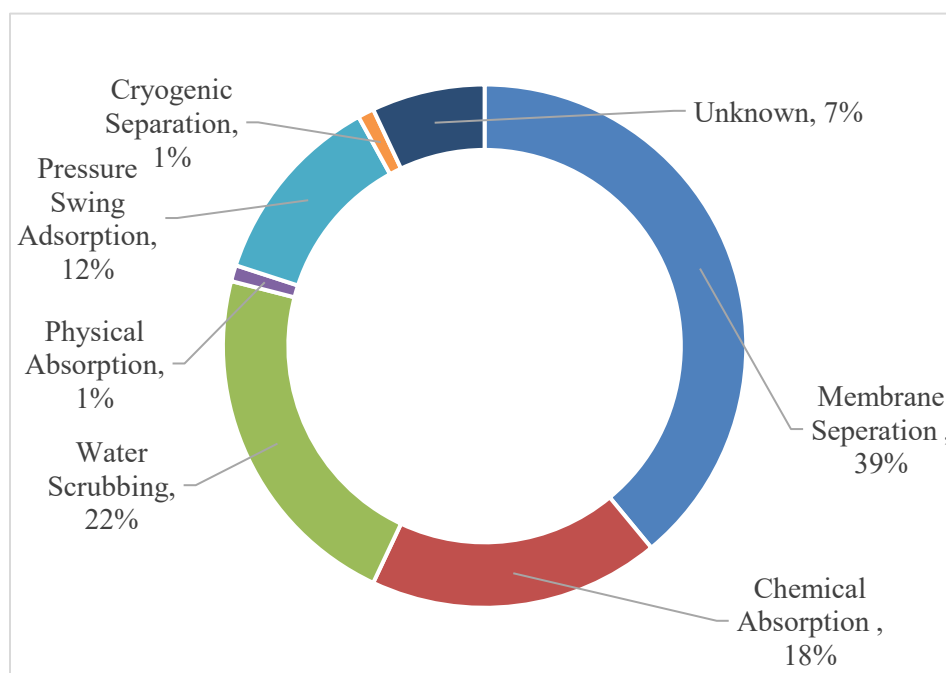


Figure 2-1: Types of Scrubbing Techniques. Adapted from Soto et al. (2022).

Cryogenic scrubbing uses temperature differences to separate the gases (Awe et al., 2017). It produces bio-methane with high purities and minimal methane losses (less than 1%). A distinctive feature is the generation of a valuable byproduct, liquid CO₂, typically reaching up to 98% purity. However, removing CO₂ under cryogenic conditions can introduce critical challenges, limiting its practical applications like CO₂ freezing out, which can occur on distillation column's tray (Yousef et al., 2019).

Pressure swing adsorption (PSA) utilizes a packed column containing adsorptive materials like zeolite, active carbon, or silica gel, to preferentially adsorb contaminant gases (such as CO₂) and enable CH₄ to pass through. The gases extracted by this process primarily consist of CO₂, H₂S, and other impurities (Yang & Li, 2014). PSA consists of the following steps: adsorption, depressurization, desorption, and pressurization (Bhattacharjee, 2022). This technique offers benefits, such as CH₄ enrichment exceeding 97%, low power consumption and minimal emissions. However, the PSA process requires dry gas, necessitating the drying of crude biogas before it enters

the system. PSA usually has a high capital cost, and methane can be lost due to the malfunctioning of the valves (Andriani et al., 2014).

Chemical scrubbing is a chemical absorption technique that eliminates pollutants from biogas through chemical processes, typically involving a solvent (Upadhyay et al., 2022). It depends on CO₂ reactive absorbents, such as alkanol amines, monoethanolamine (MEA) or dimethyl ethanolamine (DMEA), and alkali aqueous solutions like KOH, K₂CO₃, NaOH, Fe(OH)₃, and FeCl₂. The unit includes a packed bed (either random or structured) coupled with a desorption unit equipped with a reboiler to streamline the process configuration. There is no risk of biomass growth due to the high pH of the amine solutions (Awe et al., 2017). The drawbacks of this technique include challenges in handling the solvent, issues related to corrosion, and the need for waste chemical treatment facilities.

Water scrubbing (WS) is a physical absorption technique that involves the solubility of CO₂ and H₂S in water. Water is an affordable and environmentally safe solvent for removing CO₂ through gas-liquid absorption. CO₂ and H₂S exhibit higher solubility in water than CH₄, rendering water scrubbing an effective method for CO₂ removal (Budzianowski et al., 2017). The core principle of this process is the physical absorption of gases, such as CO₂ and H₂S, in water. Figure 2-2 shows the solubility of CO₂ and CH₄ in water at different temperatures.

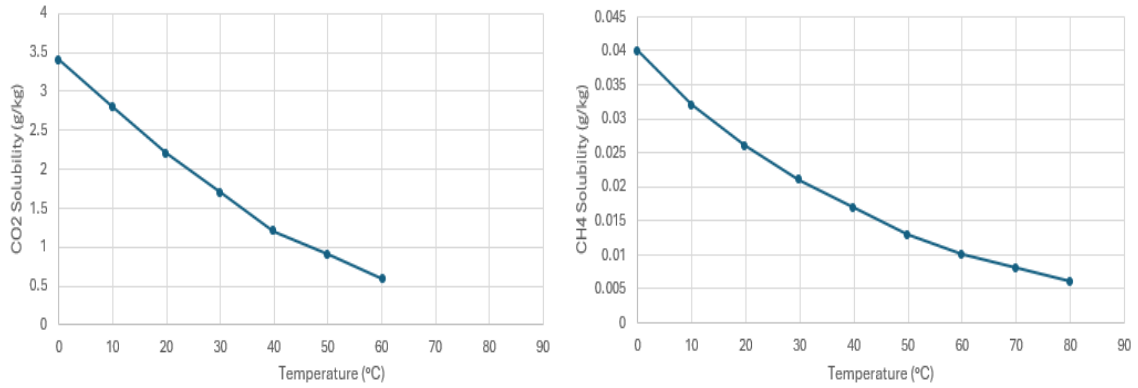


Figure 2-2: Solubility Curve of CO₂ and CH₄. Adapted from The Engineering Toolbox and Geological Digressions (2016).

High-pressure water scrubbing (HPWS) is an attractive form of WS for biogas purification due to its low cost, elevated methane purity, high yield, and considerable potential for industrialization (Qian et al., 2023). Water is generally available as feedstock for AD applications in locations with abundant biomass, such as farms or other agricultural areas. Agricultural sites are often located in remote areas, increasing operational costs for delivering chemicals or unique consumables like membranes or replacement parts. Water as a CO₂ absorber helps lower these costs (Saldarriaga, 2018). Equations 2-1 to 2-3 describe the reactions between H₂O and CO₂, while Equation 2-4 describes that of H₂S (Budzianowski et al., 2017).



Due to impurities and other compounds in water, the actual sorption of CO₂ tends to be more complex. Thus, direct measurement of CO₂ solubility is often necessary to obtain reliable estimates of scrubbing performance.

2.3.2- Working Principles of a Water Scrubber

In WS systems, biogas is injected into the bottom of a column, and water is introduced at the top, creating a counterflow. The scrubber's operating pressure is typically set between 0.8 and 1.2 MPa to increase CO₂ partial pressure and its solubility in water (Abu Seman & Harun, 2019). Packing material in the column increases the surface area available for gas and water interaction, facilitating the water's absorption of CO₂ (Budzianowski & Budzianowska, 2015; Warren, 2012). The CO₂-laden water that exits the column can be stripped of its dissolved gases and reused or replaced with fresh water.

The pH, hydraulic retention time (HRT), temperature, pressure, and flow rates all affect a water scrubber's performance. Noorain et al. (2019) presents the effect of these parameters on scrubbing and notes that the liquid-to-gas flow ratio is a crucial factor that affects the purification process, with temperature also having a strong effect. Biogas can be scrubbed at a pressure of 1 MPa and temperature of 20°C to achieve a methane content of 96.6% using a counter-current HPWS process at a liquid to gas flow rate by volume of 0.169 (Cozma et al., 2014).

De Hullu et al. (2008) explains that HPWS's superior performance is evident due to its low cost, high purity, and impressive yield, indicating that it is a promising upgrading technique. Despite the necessity of treating a single waste stream, it operates as a nearly self-sustaining continuous process.

2.3.3- Pipeline Injection

One potential market for scrubbed biogas (biomethane) is to compress and inject it into pipelines transporting natural gas. Each injection terminal has devices that regulate the gas conditions to ensure smooth integration into the grid (Schröer et al., 2024). The requirement for pipeline injection of biomethane is CH₄ content greater than 90%, with the preferred level between 96-98% (U.S. Environmental Protection Agency, 2024).

Pipeline transmission grids transport gas from the source site or the transfer point (terminal) to various regions, metropolitan areas, or even borders. Direct connections to gas transmission grids are typically established for only a selected number of industrial large-scale consumers, underground storage facilities, and gas filling stations (Wilken et al., 2017).

Leveraging the gas grid for biomethane distribution and sale presents several advantages. A notable benefit is the expanded market for gas, reaching more consumers as the grid connects production sites to densely inhabited areas. This allows for increased production at distant locations while utilizing all the gas effectively. Furthermore, adding biomethane to the gas system enhances the local security of supply (Persson et al., 2006). However, biogas digesters are often not located at a natural gas pipeline injection point. Thus, the upgraded biogas must be transported to the nearest injection point.

Pipeline layouts, such as star and fishbone layouts, were modeled to study a regional biogas grid for transporting biogas from digesters to a single centralized hub. Compared to a fishbone layout, the overall length of the pipes in a star layout is greater. In a fishbone layout, the capacity of the backbone and, to a lesser extent, the branches will be larger than that of a pipeline in a star layout. The capacity (m³h⁻¹), length (km), and additional diameter (m) of the pipeline segments all affect the pressure drop (MPa) in the pipes, and the cost of the fishbone layout is less than the star

layout (Hengeveld et al., 2016). Truck transport of RNG to an injection point (a “virtual pipeline”) may also be an option, which is cost-effective for small-scale biogas production (Hoffman et al., 2024).

Indeed, due to the costs linked with biogas upgrading and injection, aggregating biogas from several digesters into a central site offers distinct benefits. The system can be larger and often produce RNG at a cheaper cost per unit due to the economics of scale (Hengeveld et al., 2016).

2.3.4- Economics of Biogas Upgrading and Pipeline Injection

The integration of upgraded biogas, or biomethane, into natural gas pipelines requires careful consideration of its economic performance. This mainly depends on biogas upgrade, compression, transportation, and pipeline costs (Sheets & Shah, 2018). These economic factors are critical in determining the feasibility and scalability of biogas project. This is important because it underlines the cost dynamics and profitability metrics to optimize biogas applications. The system's profitability can be scrutinized by evaluating NPV. NPV represents the sum of expected net cash flows measured in today's currency (i.e. Akbulut, 2012; Gebrezgabher et al., 2010).

Equipment cost alone is not the only factor affecting the cost of producing biomethane; other factors include contingencies, financing fees, electricity rates, subsidies and taxes, and installation and owner costs. Precisely estimating these site-specific characteristics can be difficult (Magli et al., 2018). However, the selection of biogas upgrading technology is not solely based on cost considerations; it also depends on the intended application of the biomethane and the CH₄ concentration in the final upgraded gas mixture (Ghafoori et al., 2022).

In terms of economics, the investment cost for water scrubbing upgrading units has mainly remained stable in recent years (Bauer et al. 2013). As the capacity of water scrubbing units rises from 100 to 750 m³/h of raw biogas, the documented investment cost decreases from 5500 to 2000 €/m³/h of raw biogas. Furthermore, with an increase in the plant's raw biogas capacity to 2000 m³/h, this cost further decreases to 1500 €/m³/h (Magli et al., 2018).

The specific factors and assumptions used in an economic analysis can impact the result of the analysis. In a landfill gas to RNG scenario, a biogas flow rate of 500 m³/h that uses water scrubbing results in a payback period of six years (Ghafoori et al., 2022). For the same scenario, due to higher startup costs, higher annual expenses, and lower income, a 200 m³/h biogas flow rate can never recoup its initial investment.

In contrast to that, a generic study of small-scale farm and water upgrading, (Cucchiella et al., 2018) used a mathematical and economic model to evaluate the profitability of small-scale biomethane injection into the gas grid on the scales of 50 m³/h, 100 m³/h, and 150 m³/h. The study concludes a scale of 150 m³/h is profitable with NPV €615,694, Discounted Payback Time (DPBT) of 3 years, and Internal Rate of Return (IRR) of 33%, and Profitability Index (PI) of 0.18%.

While existing literature provides insights into biogas upgrading technologies designed for large-scale operations, these systems are often associated with significant capital and operational expenses, making them unsuitable for small farms with constrained budgets and limited technical capacity. Consequently, it is essential to investigate cost-effective, scalable, and efficient biogas scrubbing technologies specifically adapted for on-farm applications.

2.4- Materials and Methods

2.4.1- Scenarios

A simulation modeling approach was used to analyze the technical and economic performance of five biogas scenarios: (i) biomethane production for pipeline injection with a flash column, (ii) biomethane production without a flash column for pipeline injection, (iii) electricity generation using biomethane with a flash column, (iv) electricity generation using only the water scrubbing column, and (v) electricity generation using raw biogas.

In the first and second scenarios, biomethane was utilized for pipeline injections, while the third, fourth and fifth scenario's end use was electricity generation. The base case (first scenario) includes a water pump, biogas compressor, scrubbing column, stripping column, flash column, and RNG compressor. The second scenario includes all units from the base case except the flash column. The third scenario incorporates all units from the base case, but the RNG compressor is replaced with a generator for electricity production. In contrast, the fourth scenario consists of only the scrubbing column and the generator, and the last scenario includes just the generator utilizing the raw biogas (CO_2 and CH_4) onsite, which results in low calorific value of the biogas. The upgrading system is assumed to operate on a 100-cow dairy farm with an existing biogas digester.

2.4.2- Overall Process Description

The amount of biogas processed was calculated based on the manure obtained per the number of cows used in the scenario. The scrubber inlet water flow rate was calculated using the

mass balance equation, assuming the targeted CO₂ removal was 95%. The scrubbing and stripping column size and performance, which is a packed bed column, was also calculated. The biogas is introduced into the scrubbing column from the bottom at a pressure of 1 MPa (10 bar) and a temperature of 20 °C (the columns were operated at 20 °C). The packed bed in the column is sized to create enough contact surface area for the water and biogas (Krich et al., 2005). The water is pumped into the column from the top, thus creating a counter-flow in the column. The water leaving the scrubbing column, having absorbed CO₂ and some CH₄, cannot be immediately reused, hence the need for a flash column (which removes some CH₄) and a stripper column (to remove the CO₂ absorbed in the water). The flash column operates at a pressure of 0.3MPa (3 bar) (Rotunno et al., 2017); due to the reduced pressure, an amount of CH₄ absorbed by the water is recovered (Ma et al., 2018; Magli et al., 2018; Qian et al., 2023) and returned to the biogas inlet. The water containing CO₂ is sent to a stripper column at a pressure of 0.1MPa (1 bar), where air displaces the CO₂. The air flowrate was calculated using the mass-balance equation (the air acts as a sweeping gas). The water is then recycled back to the water inlet for reuse in the scrubbing column. The biomethane produced is compressed and injected into the pipeline stream at a pressure of 1.6MPa (16 bar). (Scholz et al., 2013). The process flow diagram of the scenarios is shown below (Figure 2-3).

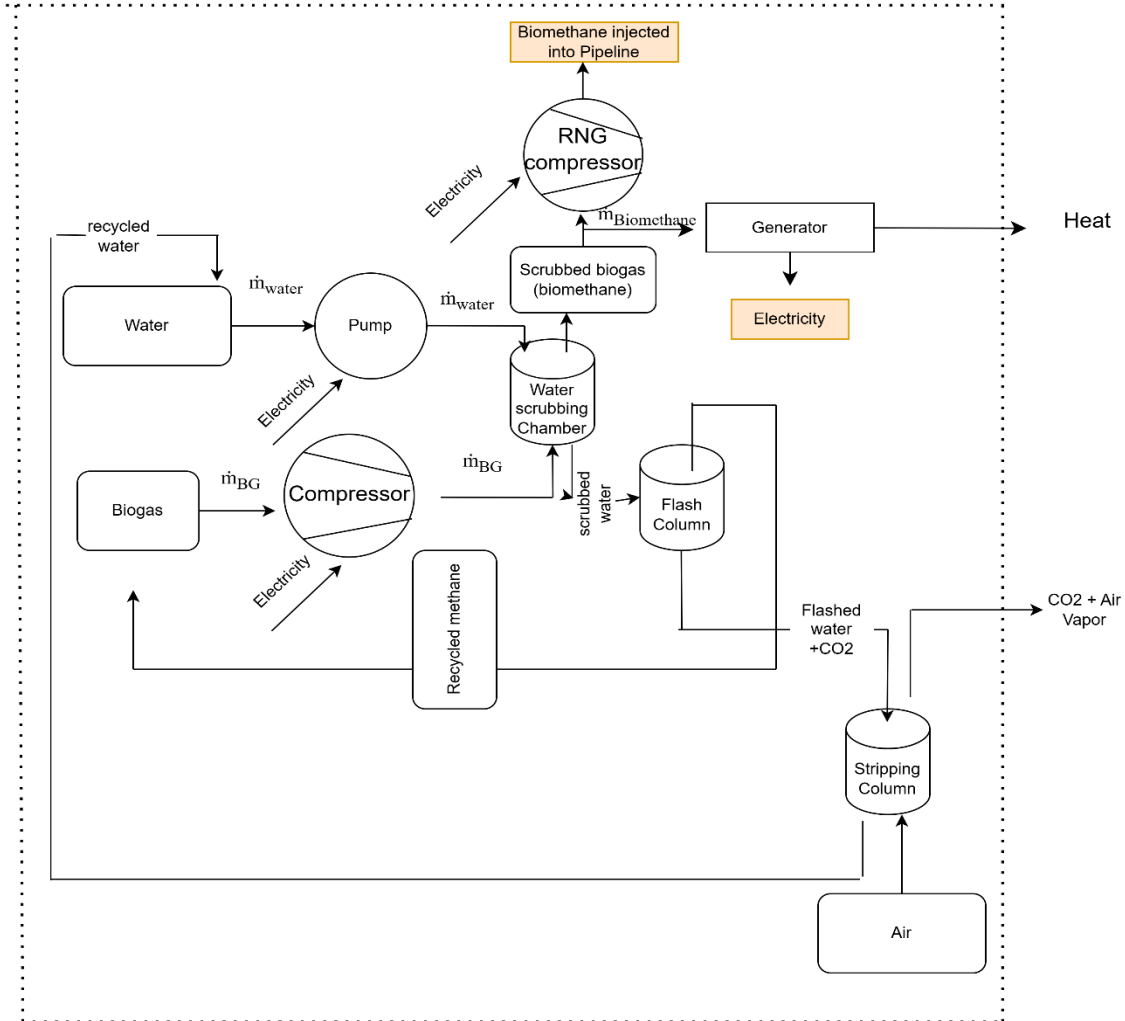


Figure 2-3: Scenario Process Flow Diagram.

2.4.3- Data

The data used for this model were obtained from published literature. Modeling was performed using BioSTEAM software (version 2.38.6) in Python 3.11.5 (Sanchis-Sebastiá et al., 2020), using created, modified and available units (Wild et al., 2024).

2.4.4- BioSTEAM Software

BioSTEAM is an open-source steady-state process simulation software, developed as a Python 3.6-compatible package, that enables users to design and simulate biorefineries using an object-oriented programming approach (Cortes-Peña et al., 2020). It is a robust and versatile platform designed for biorefinery design, simulation, and techno-economic analysis (TEA). It allows for the development of new unit operation types and the comprehensive evaluation of biofuel and bioproduct production processes (Cortes-Peña et al., 2020). It was chosen due to its open-source nature and flexibility in modeling.

In BioSTEAM, stream objects are used to specify material flow rates and their corresponding thermodynamic states, necessitating the definition of a thermodynamic property package. The software connects units via pipe-notation, where the output of one-unit feeds into the input of another, collectively forming the system. The Peng-Robinson equation is the default model for all pure components. BioSTEAM estimates the properties of mixtures by assuming a molar-weighted average of the pure chemical properties. The phase equilibria are calculated using modified Raoult's law. This software employs a sequential-modular approach to computing unit operations. Consequently, the mass and energy balance of each unit in the system can be iteratively evaluated. This structure enables the execution of TEA within the software, using discounted cash flow analysis.

2.4.5- Assumptions

This biogas upgrading model assumes the system operates on a dairy farm that already has an anaerobic digester in operation. The biogas composition is assumed to be 60% CH₄ and 40% CO₂ by volume, and the scrubber achieves 95% CO₂ removal and 95% CH₄ recovery

efficiency. The scenarios assume a farm size of 100 cows. The number of transfer units for the scrubbing column was assumed to be 6. The farm is also assumed to be located less than a mile from an injection point to the natural gas grid.

2.4.6- Modeling Biogas Production

The first step after the setup of the BioSTEAM environment was to calculate the amount of biogas produced, which was obtained from literature data. It was assumed that this scenario, which is a Pennsylvania scenario, used manure obtained from dairy cattle to produce biogas. A 2010 study of manure in Pennsylvania reports 69 kg/day as the average mass of manure produced by a cow (Holly et al., 2019). Values for total solids (TS) (12%) and volatile solids (VS) (84%) were obtained from Hamilton (2012), and the biogas-specific production was assumed to be 0.320 m³/kg VS (Varol & Ugurlu, 2017). The total biogas produced was calculated using Equation 2-5, based on the number of cows and system parameters (Table 2-1) used in this study (Jarrar et al., 2020).

$$\text{Total biogas produced} = N * M * TS * VS * BS \quad (2-5)$$

Where:

N = Number of cows

M = Manure yield for cow (kg/day/cow)

TS = Total solid (decimal)

VS = Volatile solid (decimal)

BS = Biogas specific production (m³/kg VS)

Table 2-1: Data for Biogas Production.

Parameter	Unit	Data	Reference
M	kg/day/cow	69	(Holly et al., 2019)
TS	%	12	(Hamilton, 2012)
VS	% of TS	84	(Hamilton, 2012)
Biogas production	m ³ /kg	0.320	(Varol & Ugurlu, 2017)

2.4.7- Modeling of Scrubbing and Stripping Packed Bed Column

Both the scrubbing and stripping columns were modeled using a rate-based mass transfer model (Magli et al., 2018; Nock et al., 2014), which calculates the mass transfer of CO₂ and CH₄ from biogas to liquid and the effective surface area of the packed bed (Nock et al., 2014). The overall mass transfer coefficient (K) was determined by combining the gas and liquid mass transfer coefficients using Onda's method (Nock et al., 2014; Pérez Sánchez et al., 2016; Sindhuja et al., 2018) along with Henry's law (Equation 2-6). The parameters used in the model are listed in Table 2-2.

$$C = P / K \quad (2-6)$$

Where:

C = Concentration (kmol·m⁻³)

P = Partial pressure of biogas (bar)

K = Henry's constant (kmol·m⁻³ bar)

Table 2-2: Data for Scrubbing and Stripping Column.

Parameter	Unit	Data	Reference
CH ₄ / CO ₂	%	60/40	Assumption
Flooding Factor	%	60	(Magli et al., 2018)
Ceramic packed bed element size	m	25 * 10 ⁻³	(Budzianowski et al., 2017)
Packing factor of ceramic packing	m ² /m ³	320	(Budzianowski et al., 2017)

The surface area of packing (a)	m^2/m^3	250	(Budzianowski et al., 2017)
Surface tension of packing	N/m	$61 * 10^{-3}$	(Budzianowski et al., 2017)
Surface tension of water	N/m	$72 * 10^{-3}$	(Sindhuja et al., 2018)
Raw biogas pressure	MPa	0.1	(Scholz et al., 2013)
Temperature of scrubber	$^{\circ}\text{C}$	20	(Abu Seman & Harun, 2019; Cozma et al., 2013)
Temperature of stripper	$^{\circ}\text{C}$	20	(Abu Seman & Harun, 2019)
Pressure of stripper	MPa	0.1	(Abu Seman & Harun, 2019)
Pressure of scrubber	MPa	1	(Abu Seman & Harun, 2019)
RNG compressor pressure	MPa	1.6	(Scholz et al., 2013)
R	$\text{bar m}^3/\text{kmol K}$	0.08314	(Sinnott, 2005)
Density of water	kg/m^3	@ 20 $^{\circ}\text{C}$ / 998	(Gerber & Schneider, 2015)
Density of biogas	kg/m^3	1.158	(Kim et al., 2023)
Density of air	kg/m^3	1.205	(Legg, 2017)
Density of biomethane	kg/m^3	0.8	Calculated
Density of methane	kg/m^3	0.657	Engineering ToolBox
Viscosity of water (20 $^{\circ}\text{C}$)	Pa.s	$1 * 10^{-3}$	(Sindhuja et al., 2018)
Viscosity of carbon dioxide (20 $^{\circ}\text{C}$)	Pa.s	$1.47 * 10^{-5}$	(Pérez Sánchez et al., 2016)
Viscosity of methane (20 $^{\circ}\text{C}$)	Pa.s	$1.1 * 10^{-5}$	
Viscosity of air (20 $^{\circ}\text{C}$)	Pa.s	$1.8 * 10^{-5}$	Engineering toolbox
Lennard-Jones parameter (e/K) CO_2	K	195.2	(Pérez Sánchez et al., 2016)
Lennard-Jones parameter (e/K) CH_4	K	148	(Pérez Sánchez et al., 2016)
Collision diameter of CO_2	Å	3.941	(Pérez Sánchez et al., 2016)
Collision diameter of CH_4	Å	3.758	(Yu, 2023)
Henry's constant CO_2	Bar	1650	(Graf et al., 2011)
Henry's constant CH_4	Bar	40100	(Graf et al., 2011)
Diffusivity of water	m^2/s	$1.64 * 10^{-9}$	(Sindhuja et al., 2018)

Diffusivity of air	m ² /s	22.07 * 10 ⁻⁶	(Sindhuja et al., 2018)
Number of transfer units		6	Assumed
CEPCI 2013		567.3	(Chemical Engineering, 2023)
CEPCI 2023		802.9	(Chemical Engineering, 2023)

2.4.8- Model Design

The design process used for sizing the scrubbing and stripping columns utilized the following three-step process:

1. Assume a scrubbing efficiency value (95%) to calculate the water flow rate required for scrubbing.
2. Calculate the column diameter needed to achieve suitable liquid and gas velocities through the column.
3. Calculate the height needed to achieve the required mass transfer rate of CO₂ to the water (for the scrubbing column) or CO₂ to the air (for the stripping column).

2.4.9- Amount of Water Required for Scrubbing

The amount of liquid required for scrubbing biogas must be determined before calculating the column height (Rotunno et al., 2017). In this study, the desired CO₂ removal and CH₄ recovery efficiency for biogas scrubbing is 95%, resulting in the expected composition of gas to be 95% CH₄ (assuming 5% loss to the water) and 5% CO₂. The mass balance Equations (2-7 & 2-8) were used (Rotunno et al., 2017; Wantz et al., 2022).

$$\dot{m}_{G1} + \dot{m}_{L1} = \dot{m}_{G0} + \dot{m}_{L0} \quad (2-7)$$

Where:

$$\dot{m}_{G1}(\text{kg/s}) = 0.60 \text{ CH}_4 + 0.40 \text{ CO}_2$$

$$\dot{m}_{G0}(\text{kg/s}) = 0.95 * .60 \text{ CH}_4 + 0.05 * .40 \text{ CO}_2$$

Solving for liquid out

$$\dot{m}_{L0} = (\dot{m}_{G1} + \dot{m}_{L1}) - \dot{m}_{L1} \quad (2-8)$$

2.4.10- Estimation of Column's Diameter

The column's diameter was determined based on the biogas flow rate into the column.

The gas mass flow rate per unit cross-sectional area required for the scrubber's height was calculated using Equation 2-9, along with the column area and diameter (Equations 2-10 to 2-11) (Sindhuja et al., 2018).

$$R_{GM} = \left[\frac{Ff * \rho_{biogas} * (\rho_{water} - \rho_{biogas})}{13.1 * Pf * \left(\frac{\mu_{water}}{\rho_{water}} \right)^{0.1}} \right]^{0.5} \quad (2-9)$$

Where:

R_{GM} = Gas mass flow rate per unit cross-sectional area ($\text{kg/m}^2\text{s}$)

Ff = Flooding factor (%)

ρ = Density (kg/m^3)

μ = Viscosity (Pa.s)

Pf = Packing factor (m^2/m^3)

$$\text{Column Area} = \frac{\text{Raw biogas flowrate} \left(\frac{\text{kg}}{\text{s}} \right)}{R_{gm}} \quad (2-10)$$

$$\text{Column Diameter} = 4 * \left(\frac{\text{Column Area}}{\pi} \right)^{0.5} \quad (2-11)$$

2.4.11- Determination of the Height of the Scrubbing Column

The height of the column plays a crucial role in removing the targeted CO₂ in the water and CO₂ fraction in the air by controlling the amount of time available for the gas and liquid to be in contact (Wylock & Budzianowski, 2017). The height of the scrubber and stripper was calculated using Onda's method, which makes use of the effective area of the packed bed and mass transfer coefficient for both the liquid and gas (Nock et al., 2014; Sindhuja et al., 2018), using the gas-phase and liquid-phase transfer unit (Sindhuja et al., 2018). Onda's correlation was developed from literature data covering experimental conditions for liquids (Nock et al., 2014). Equations 2-12 to 2-28 were used for this process.

The effective area of the packed bed (A_p) was calculated as follows:

$$\frac{A_p}{a} = 1 - \exp \left[-1.45 \left(\frac{\sigma_p}{\sigma_w} \right)^{0.75} * \left(\frac{Wl}{a * \mu_w} \right)^{0.2} * \left(\frac{wl^2 * a}{\rho_w^2 * g} \right)^{-0.05} * \left(\frac{wl^2}{\sigma_w * \rho_w * a} \right)^{0.2} \right] \quad (2-12)$$

Where:

A_p = Packed bed effective area (m²/m³)

σ_p = Surface tension of the packing bed (N/m)

σ_w = Surface tension of water (N/m)

W_l = Water mass flow rate per unit cross-section area (water flow rate(kg/s)/ column area (m²))

a = Surface area of packed bed (m²/m³)

μ_w = Viscosity of water (Pa.s)

ρ_w = Density of water (kg/m³)

g = 9.81m/s²

The diffusion coefficient of biogas (CH₄ and CO₂) was calculated using the Wilke and Lee correlation; the theory studied the diffusion process in binary gas mixtures at low to moderate temperatures (Pérez Sánchez et al., 2016). The theory was used since biogas is assumed to contain just CH₄ and CO₂ for simplicity's sake. The diffusion coefficient of biogas was calculated using Equation 2-13 (Sindhuja et al., 2018).

$$D_b = \frac{\left[3.03 - \left(\frac{0.98}{M_{mb}^{0.5}} \right) \right] * (10^{-3}) * T^{\frac{3}{2}}}{P * M_{mb}^{0.5} * \sigma_{mb}^{0.5} * \Omega_B} \quad (2-13)$$

Where:

D_b = Diffusion coefficient of biogas (m²/s)

T = Temperature (K)

P = Pressure (bar)

$$M_{mb} = 2 \cdot \left[\frac{1}{M_{CO_2}} + \frac{1}{M_{CH_4}} \right]^{-1} \quad (2-14)$$

$$\Omega_B = \frac{1.06036}{(T^*)^{0.15610}} + \frac{0.19300}{\exp(0.47635 * T^*)} + \frac{1.03587}{\exp(1.52996 * T^*)} + \frac{1.76474}{\exp(3.89411 * T^*)} \quad (2-15)$$

Ω_B = Diffusion collision integral

$$T^* = \frac{T}{\sqrt{\frac{e}{K} CO_2 * \frac{e}{K} CH_4}} \quad (2-16)$$

T^* = Factor

T = Temperature (K)

$$(\sigma_{mb}) = \frac{\sigma_{CO_2} + \sigma_{CH_4}}{2} \quad (2-17)$$

σ_{mb} = Average collision diameter (Å)

The mass transfer coefficient of the liquid is calculated as follows:

$$K_L \left(\frac{\rho_W}{\mu_W g} \right)^{\frac{1}{3}} = 0.0051 \left(\frac{Wl}{Ap * \mu_W} \right)^{2/3} \left(\frac{\mu_W}{\rho_W * D_L} \right)^{-\frac{1}{2}} (a * dp)^{0.4} \quad (2-18)$$

Where:

K_L = Mass transfer coefficient of the liquid (m/s)

D_L = Diffusion coefficient of liquid (m²/s)

dp = packing size (m)

The mass transfer coefficient for biogas is calculated as follows:

$$\frac{K_G RT}{a D_b} = K_5 \left(\frac{V_b}{a * \mu_b} \right)^{0.7} \left(\frac{\mu_b}{\rho_b D_b} \right)^{1/3} (a * dp)^{-2} \quad (2-19)$$

Where:

K_G = Mass transfer coefficient of biogas (kmol/sm² bar)

μ_b = Viscosity of biogas

D_b = Diffusion coefficient of biogas (m²/s)

The viscosity of biogas (μ_b) was calculated using this correlation (Pérez Sánchez et al., 2016)

$$\mu_b = \left[\frac{M_b}{\left(\frac{\text{Mole fraction} * M_{CO_2}}{\mu_{CO_2}} \right) + \left(\frac{\text{Mole fraction} * M_{CH_4}}{\mu_{CH_4}} \right)} \right] \quad (2-20)$$

$$M_b = (\text{Mole fraction}_{CO_2} * M_{CO_2}) + (\text{Mole fraction}_{CH_4} * M_{CH_4}) \quad (2-21)$$

M_b = Molecular weight of biogas (g/mol)

M = Molecular weight (g/mol)

$$V_b = \frac{\text{Raw biogas flow rate}}{\text{Cross-sectional Area}} \quad (2-22)$$

V_b = Biogas flow rate per area (kg/m²s)

K_5 = 5.23 for packed bed size above 15mm (Sinnott, 2005)

The overall mass transfer coefficient can be calculated using the mass transfer coefficient and Henry's law (Ma et al., 2018; Rotunno et al., 2017).

$$\frac{1}{K_{L*}} = \frac{1}{H_{CO_2} * K_G} + \frac{1}{K_L} \quad (2-23)$$

$$\frac{1}{K_{G*}} = \frac{1}{K_G} + \frac{H_{CO_2}}{K_L} \quad (2-24)$$

Where:

K_{L*} = Overall liquid mass transfer coefficient (m/s)

K_{G*} = Overall gas mass transfer coefficient (kmol/sm² bar)

The scrubber and stripper's height were calculated using equations from Rotunno et al. (2017), and Sindhuja et al (2018).

$$H_G = \left(\frac{\text{Molar gas flow rate}}{K_G * P * A_p} \right) \quad (2-25)$$

$$H_L = \left(\frac{\text{Molar liquid flow rate}}{K_L * A_p * C_l} \right) \quad (2-26)$$

H_G = Height of the overall gas-transfer unit (m)

H_L = Height of the overall liquid transfer unit (m)

C_l = Total concentration (kmol/m³) = density of liquid/ molecular weight of liquid

$$Z = NTU * HOG \quad (2-27)$$

NTU= Number of the transfer unit

$$HOG = H_G + m_{Lm}^{Gm} * H_L \quad (2-28)$$

2.4.12- Determination of the Height of the Stripping Column

The height of the stripping column was determined following a similar approach to that used for the scrubbing column. The column diameter was assumed to be 0.78 m, consistent with the value utilized by Ma et al. (2018). The required airflow was calculated based on a mass transfer balance, targeting a CO₂ removal efficiency of 90%. The mass transfer coefficient for air was determined using Equation 2-19, incorporating parameters such as airflow rate, viscosity, density, and diffusivity.

2.4.13- Flash Column, Pump and Compressor

This model's flash column, pump, and compressor utilized BioSTEAM's built-in unit operations. The flash drum column was developed using an equilibrium-based model, with its design procedure guided by heuristics in the program documentation (BioSTEAM, n.d.).

2.4.14- Generator

Generating electricity from biogas entails burning biogas in a controlled combustion system to produce mechanical energy, which is then harnessed using a heat engine (Kabeyi & Olanrewaju, 2020). Using biogas as fuel can be achieved by adapting the fuel system of a conventional diesel-powered generator set to enable it to function as a biogas generator (Wresta et al., 2015). In Scenarios Three, Four, and Five, the biomethane and biogas produced are used to generate electricity. Equations 2-29 to 2-31 were used to calculate the energy produced, generator capacity, and expected electric production to estimate the electricity generated from the gas. Table 2-3 lists the assumptions used to model the generator.

In BioSTEAM, electricity is not regarded as a physical property. Consequently, the generator does not produce a tangible output. However, the electricity generated is deducted from the electricity consumed within the system, and the corresponding utility cost is computed. Therefore, BioSTEAM accounts for electricity as a single net value, assuming that the cost of electricity purchased from the grid is equivalent to the price sold back to the grid.

$$E_D = B_D * LHV \quad (2-29)$$

Where:

E_D = Daily energy content of biomethane (MJ)

B_D = Biogas production (m^3/day)

LHV= Low heating Value (MJ/m^3)

$$\text{Generator capacity (kW)} = \frac{ED * \eta}{3.6 * 24} \quad (2-30)$$

η = Engine Efficiency (%)

$$\text{Expected electric production (kWh/year)} = \text{Generator capacity} * t \text{ (hour/year)} \quad (2-31)$$

Table 2-3: Assumptions for the Generator.

Parameter	Unit	Value	Reference
LHV of biomethane*/raw biogas	MJ/m^3	36/21.6	Assumed
LHV of methane	MJ/m^3	38	(Barragán-Escandón et al., 2020)
Engine efficiency η	%	40	(Ahmed & Busadee, 2023; Barragán-Escandón et al., 2020)

*Biomethane is the scrubbed biogas going into the generator

Note that the engine efficiency value is based on the LHV.

2.4.15- Economic Cost

Project costs are classified as capital cost and operating costs. Capital costs or “fixed capital investments” consists of equipment costs and installation costs.

2.4.15.1- Cost Assumptions

The total capital investment is the sum of the fixed capital investment (FCI) and working capital investment. The FCI includes the expenditure for plant construction, equipment cost, installation of pipe and other costs (Lawson et al., 2021).

BioSTEAM software was used for the techno-economic analysis of the system, with some modifications to the capital cost of some units (flash column, pump, compressor). The calculation of the cost of the absorption and stripper columns was based on equations obtained

from published literature. The Chemical Engineering Plant Cost Index (CEPCI) used was for 2023. The land cost was not included, as the system was assumed to be built on an existing farm. The pipeline cost for Scenarios One and Two was assumed to be \$600,000 (U.S. Environmental Protection Agency [EPA], 2024), assuming the farm is less than one mile from the injection point.

In published literature, the installation cost (IC) is reported to be 40% of the equipment cost in some studies (Aguilera & Gutiérrez Ortiz, 2016; Xie et al., 2018), while other studies have used 47% of the equipment cost (Ji et al., 2016; Ma et al., 2018), which was also implemented in this model. For this model, maintenance and administrative costs are assumed to be 2.0% and 0.5% of the FCI.

2.4.15.2- Equipment Cost

The equipment purchase cost for each component was calculated in the sections below.

Scrubbing and Stripping Column Cost

These columns were estimated using Guthrie's method (Equations 2-32 and 2-33), which uses the height and diameter to calculate the bare cost of the columns (Ji et al., 2016; Ma et al., 2018; Scholz et al., 2013; Xie et al., 2018). The reference parameters were obtained from Scholz et al. (2013), while the height and diameter were obtained from BioSTEAM.

$$EC = BC (f_{mp} + f_m - 1) \quad (2-32)$$

Where:

EC = Equipment cost (\$)

BC = Bare cost of the purchase equipment cost (\$)

f_{mp} = Material and pressure factor (3.67)

f_m = Module factor (6.23)

$$BC = C_o \left(\frac{h}{h_o}\right)^\alpha \left(\frac{d}{d_o}\right)^\beta \quad (2-33)$$

Where:

C_o , h_o , and d_o = Reference cost, height and diameter

$C_o = 1000$ (\$)

$h_o = 1.22$ (m)

$d_o = 0.91$ (m)

$\alpha = 0.81$

$\beta = 1.05$

h and d = Height and diameter of the column

Flash Column Cost

The cost of the flash column was calculated using the sixth-tenth equation (Aguilera & Gutiérrez Ortiz, 2016), and the reference cost (\$15,100, diameter = 3 ft, Length = 12ft) was obtained from Seider et al. (2016).

$$\text{Cost of flash column} = R_c * \left(\frac{V_F}{V_R}\right)^{0.6} * \frac{CEPCI\ 2023}{CEPCI\ 2013} \quad (2-34)$$

Where:

V_F = Volume of flash

V_R = Volume of reference flash

R_c = Reference cost

CEPCI 2023 = 802.9

CEPCI 2013 = 567.3

Generator, Compressor and Pump Cost

The cost of the pump and compressor equipment was obtained from a commercial vendor using the technical requirement provided by BioSTEAM, while the reference cost of the generator was from Sganzerla et al. (2023).

Operating Cost

The operating costs for running this system include utilities (water and electricity) and the production cost of biogas. The labor cost was assumed to be zero (since it is a small farm, it is assumed that the worker in charge of the digester would be in charge). The cost of water was assumed to equal the published cost of city water in State College, PA, \$0.00174 /kg; biogas, as earlier stated, is the cost of biogas production and is calculated to equal \$0.350/m³ based on the International Renewable Energy Agency (IRENA), which stated that as at 2017, the cost of biogas production was between 0.22 to 0.39 \$/m³ and considering an inflation rate of 2%. The electricity was assumed to be \$0.1705/kWh (for the Scenario One and Two) based on published rates from Central Electric Coop, Inc (PA), a utility provider in Pennsylvania. The cost breakdown can be found in Table 2-4.

Table 2-4: Operating Cost Breakdown.

Parameter	Unit	Cost
Water	\$/kg	0.00174
Biogas	\$/m ³	0.35
Electricity	\$/kWh	0.1705

2.4.15.3- Revenue

The end uses of biomethane include renewable natural gas (RNG) and/or electricity sale. The selling price of biomethane as RNG was assumed to be \$1.7/kg plus the D3 RIN value, which typically ranges from \$0.05 to \$3.50 per credit. For this study, a value of \$3.01 per credit

was used. The selling price of electricity exported back to the grid was assumed to be 4 cents/kWh (the cost of electricity in this system will be 4 cents/kWh).

2.4.15.4- Economic Evaluation

The economic feasibility of the upgrading system was evaluated using DCF. The main economic performance index used in this research is the NPV, which is the sum of the present value of cash flows (Ferella et al., 2019) that occur over the project's lifetime. Cash inflows include revenues and additional benefits such as incentives, tax exemptions, subsidies, and similar advantages. On the other hand, cash outflows encompass expenses such as investment costs, operational and maintenance expenses, and income taxes (Ayodele et al., 2018). A positive NPV indicates profit and vice versa when determining the plant's profitability (Cheng et al., 2024). The parameters in Table 2-5 were used for the economic evaluation of the system.

$$NPV = \sum_{t=0}^n \frac{(I_t - O_t)}{(1+r)^t} \quad (2-35)$$

Where:

NPV = Net present value (\$)

I_t = Discounted cash inflows (\$)

O_t = Discounted cash outflows (\$)

r = Discount rate (%)

t = Time of the cash flow (years)

n = Lifetime of investment (years)

Project construction is assumed to take 2 years, and NPV is calculated for the point at which the project begins operating.

Table 2-5: Assumptions for EA. Some Parameters are Percentages of FCI and Total Capital Cost (TCC).

Parameter	Value
Discount rate	10 %
Project lifespan	10 years
Depreciation	MACRS7
Income Tax	0.35
Operating days	342
Construction schedule	40% (first year) 60% (second year)
Working Capital	5%

2.4.16- Model Testing

The model was tested in two ways to evaluate its economic reliability and carbon dioxide removal efficiency. First, parameters were tested by examining the model's response to changes in input parameters (Table 2-6) thereby building confidence in its output. Second, it was tested by comparing its performance to the results of similar studies in published literature. In the case of this study, the carbon dioxide removal efficiency and methane loss were compared to Díaz-Herrera et al., (2023), Ma et al., (2018) and Gupta et al., (2022).

Table 2-6: Parameters for Validation of the Model.

Parameter	Expected Impact on NPV
Increase in water cost	Negative
Decrease in water cost	Positive
Increase in RNG sales	Positive
Decrease in RNG sales	Negative
Increase in electricity cost	Negative
Decrease in electricity cost	Positive
Increase in number of cows	Positive
Decrease in number of cows	Negative

2.4.17- Sensitivity Analysis

Sensitivity analysis is a technique employed to examine how variations in key input parameters influence the overall performance of a model (Lombardi & Francini, 2020). In this study, a sensitivity analysis was conducted to evaluate the effects of electricity costs, water prices, pipeline installation expenses, number of cows and biogas production cost on NPV. This was achieved by comparing the base case scenario with the NPV results obtained from different input variations. Electricity cost data were sourced from the U.S. Energy Information Administration (Appendix A), utilizing the highest and lowest recorded values for the analysis. Additionally, the impact of biogas production costs, as outlined by IRENA, was assessed within its reported range. Water prices were varied using the highest and lowest rates offered by water providers in Pennsylvania. Furthermore, pipeline costs were analyzed by comparing the expense of installing a pipeline extending beyond one mile with a scenario assuming no installation cost, under the assumption that the farm was located directly at the injection point, in addition the impact of the number of cows was tested using 1000 and 50 cows respectively (Table 2-7).

Table 2-7: Data for Sensitivity Analysis.

Parameter	Model Input	Decrease \$(NPV)	Model Input	Increase (NPV)
Biogas	\$0.44/m ³	-836,075	\$0.25/m ³	-749,880
Pipeline	\$1,000,000	-1,283,094	\$0	-63,473
Electricity	22.07 cents/kWh	-795,621	10.49 cents/kWh	-794,755
Water	0.0029 \$/kg	-814,791	0.00135 \$/kg	-798,686
Number of cows	50 cows	-851,922	1000 cows	111,232

2.4.18- Scenario Analysis

An optimistic scenario was evaluated based on a biogas production cost of \$0.25/m³, with no pipeline expenses, an electricity rate of 10.49 cents/kWh, a water cost of \$0.00135/kg, and a

RNG selling price of \$2.50/kg. In contrast, the pessimistic scenario assumes a biogas production cost of \$0.44/m³, a pipeline cost of \$1,000,000, an electricity rate of 22.07 cents/kWh, a water cost of \$0.0029/kg, and an RNG selling price of \$1.50/kg, all using the same quantity of manure.

In addition, the impact of renewable energy production tax credit (PTC), a federal tax incentive under Section 45 of the U.S. Tax Code which provides a corporate tax credit of approximately 1.5 cents per kilowatt-hour (kWh) for electricity generated from qualified renewable energy resources such as landfill gas, open-loop biomass, municipal solid waste, and small irrigation power facilities for up to 10 years after the equipment is placed in service (U.S. Environmental Protection Agency, 2024) together with electricity cost was assessed in Scenarios Three to Five, alongside the biogas production cost.

2.5- Results

2.5.1- Model Testing

The model validation is tested by varying input parameters, assessing if it performs in the expected way, also the model was compared with published literatures. Table 2-8 shows the validation of the model. The CO₂ removal efficiency and CH₄ loss are compared to existing literature as seen in Table 2-9.

Table 2-8: Validation of Model.

Parameter	Expected Impact on NPV	Result of Test
Increase in water cost	Negative	✓
Decrease in water cost	Positive	✓
Increase in RNG sales	Positive	✓
Decrease in RNG sales	Negative	✓
Increase in electricity cost	Negative	✓

Decrease in electricity cost	Positive	✓
Increase in number of cows	Positive	✓
Decrease in number of cows	Negative	✓

Table 2-9: Comparison of Variable to Literature.

Parameter	Literature value	Our result
CO ₂ removal efficiency	82-96.2%	93.07%
CH ₄ loss	0.5-2.7%	3.78%

Mass Balances

The mass balance for the first four scenarios as listed in Table 2-10 below, assuming no water is lost to the system.

Table 2-10: Mass Balance for the Scenarios (kmol/hr).

Equipment	Stream Scenario One	Stream Scenario Two	Stream Scenario Three	Stream Scenario Four
Pump	Water: 3.31	Water: 3.31	Water: 3.31	Water: 3.31
Compressor	CO ₂ -0.155 CH ₄ - 0.232	CO ₂ -0.155 CH ₄ - 0.232	CO ₂ -0.155 CH ₄ - 0.232	CO ₂ -0.155 CH ₄ - 0.232
Scrubber -in	CO ₂ -0.155 CH ₄ - 0.232 H ₂ O- 3.31	CO ₂ -0.155 CH ₄ - 0.232 H ₂ O- 3.31	CO ₂ -0.155 CH ₄ - 0.232 H ₂ O- 3.31	CO ₂ -0.155 CH ₄ - 0.232 H ₂ O- 3.31
Scrubber-out	CO ₂ -0.155 CH ₄ 0.00891 H ₂ O- 3.31	CO ₂ -0.155 CH ₄ 0.00891 H ₂ O- 3.31	CO ₂ -0.155 CH ₄ 0.00891 H ₂ O- 3.31	CO ₂ -0.155 CH ₄ 0.00891 H ₂ O- 3.31
RNG compressor	CO ₂ -0.0108 CH ₄ - 0.223	CO ₂ -0.0108 CH ₄ - 0.223	-	-
Flash-in	CO ₂ -0.155 CH ₄ 0.00891 H ₂ O- 3.31	-	CO ₂ -0.155 CH ₄ 0.00891 H ₂ O- 3.31	-
Flash-out (Gas)	CO ₂ -0.00388 CH ₄ 0.00445 H ₂ O- 1.59e-05	-	CO ₂ -0.00388 CH ₄ 0.00445 H ₂ O- 1.59e-05	-
Flash-out (Liquid)	CO ₂ -0.14 CH ₄ 0.00446 H ₂ O- 3.31	-	CO ₂ -0.14 CH ₄ 0.00446 H ₂ O- 3.31	-
Stripper-in	CO ₂ -0.14 CH ₄ 0.00446 H ₂ O- 3.31	CO ₂ -0.155 CH ₄ 0.00891 H ₂ O- 3.31	CO ₂ -0.14 CH ₄ 0.00446 H ₂ O- 3.31	-
Stripper- Out (Gas)	CO ₂ -0.126 +Air	CO ₂ -0.13 +Air	CO ₂ -0.126 +Air	

Stripper- Out (Liquid)	CO ₂ -0.0014 CH ₄ 0.00446 H ₂ O- 3.31	CO ₂ -0.00144 CH ₄ 0.00891 H ₂ O- 3.31	CO ₂ -0.0014 CH ₄ 0.00446 H ₂ O- 3.31	-
Mixer- one	Stripper- Out (Liquid)	Stripper- Out (Liquid)	Stripper- Out (Liquid)	-
Mixer-two	Stripper Out Gas	-	Stripper Out Gas	-

2.5.2- Base Case Model Result

Table 2-11 lists the system sizes, flowrates, and related performance measures for the base case biogas upgrading scenario (Scenario One). The CO₂ scrubbing efficiency for the scrubbing column was calculated (Gupta et al., 2022), while that of stripping efficiency was assumed to have 90% CO₂ scrubbing efficiency.

$$\text{CO}_2 \text{ removal efficiency (\%)} = \frac{C_{in} - C_{out}}{C_{in}} * 100 \quad 2-36$$

Table 2-11: Result and Parameters Used for Calculating the Height of the Columns.

Parameter	Equation	Value	Unit
Biogas flowrate	2-5	222.57	m ³ /day
Water flowrate for scrubbing	2-7&2-8	0.0166	kg/s
R _{gm}	2-9	0.811	kg/m ² s
Column area	2-10	0.088	m ²
Column diameter	2-11	0.35	m
A _p	2-12	118.41	m ² /m ³
D _b	2-13	1.739e-06	m ² /s
M _{mb}	2-14	23.51	Dimensionless
Ω _B	2-15	1.135	Dimensionless
T*	2-16	1.723	Dimensionless
σ _{mb}	2-17	3.850	Å
K _L	2-18	1.039e-04	m/s
k _G	2-19	2.1e-04	kmol/sm ² bar
μ _b	2-20	1.314e-05	Pa.s
M _b	2-21	27.23	g/mol
V _b	2-22	0.811	kg /m ² s
K _L [*]	2-23	1.039e-04	m/s
K _G [*]	2-24	6.297 e-08	kmol/sm ² bar
H _G	2-25	0.119	m
H _L	2-26	0.366	m

Z (height of scrubber)	2-27	1.96	m
Height of flash column		6.49	m
CH ₄ in		0.232	kmol/hr
CH ₄ out		0.223	kmol/hr
CO ₂ in		0.155	m ³ /hr
CO ₂ out		0.0108	kmol/hr
CO ₂ scrubbing efficiency	2-36	93.03	%
CH ₄ recovered from the flash column		50.00	%

2.5.3- Generator Performance

The biomethane energy produced through the generator (for scenarios Three and Four), which had 40% electricity efficiency, was calculated using Equations 2-29 to 2-31. Table 2-12 contains the results obtained.

Table 2-12: Generator Performance for Scenarios Three and Four.

Parameter	Equations	Values	Unit
Biomethane	2-29	349,115.61 1256816.20	kWh/year MJ
Generator Capacity	2-30	17.01	kW
Electricity production	2-31	139,646.25 502726.5	kWh/year MJ

2.5.4- Base Case Economic Analysis Results

2.5.4.1- Capital Expenses (CAPEX)

The equipment costs can be found in Table 2-13. The total installed equipment cost (TIEC) for the base case scenario in the table does not include the pipeline cost. Figure 2-4 illustrates the distribution of the equipment costs used in the model in percentage.

Table 2-13: Installed Equipment Cost.

Equipment	Cost (\$)
Pump	731
Biogas compressor	4,080
Scrubbing column	1,840
RNG compressor	42,300
Stripping column	2,180
Flash column	29,600
Generator	21,800
Pipeline cost	600,000
TIEC (Scenario One) without pipeline cost	148,401

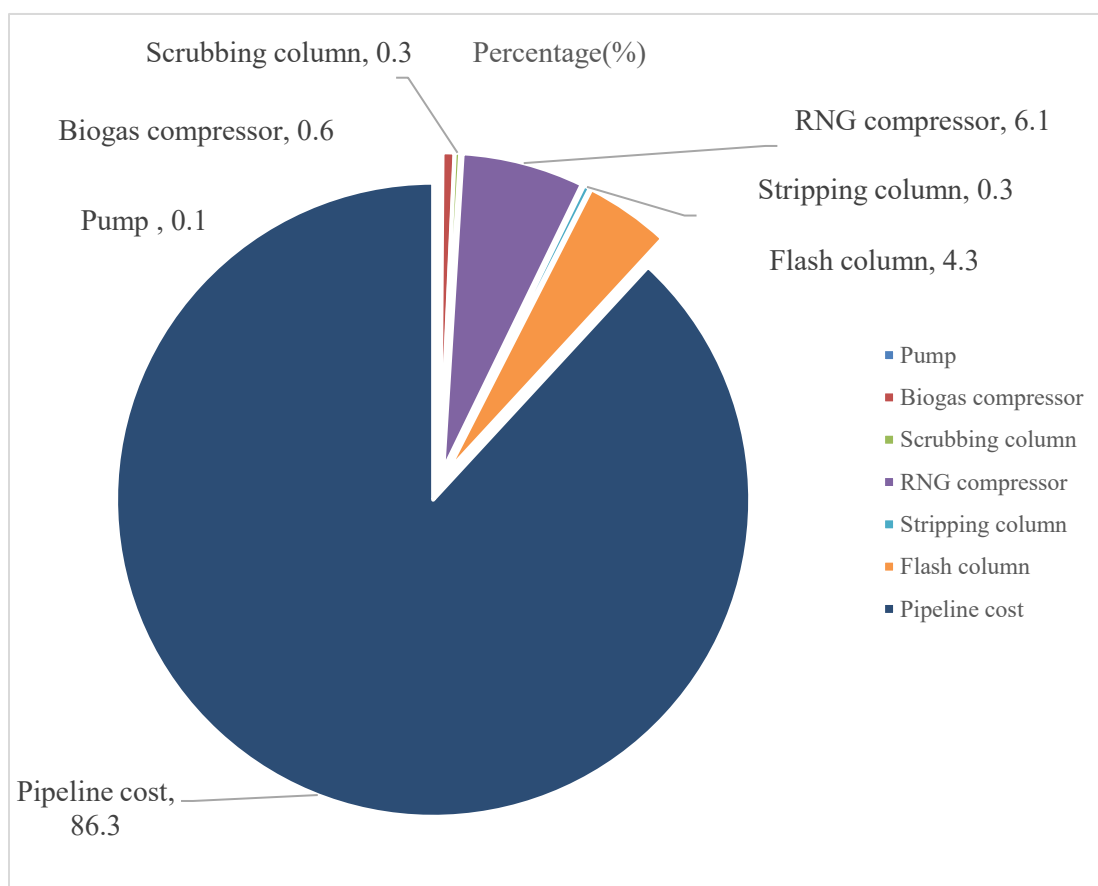


Figure 2-4: Breakdown of Equipment Cost.

Equipment cost is dominated by the cost of the pipeline which accounts for 86.3% of the cost.

2.5.4.2- Total Capital Investment

The Total Capital Investment cost (TCI) for the five scenarios was obtained from BioSTEAM based on the input, as shown in Figure 2-5. Scenario One has the highest TCI, which is due to having the highest amount of equipment. Scenario Five has the lowest TCI of \$17,154.06.

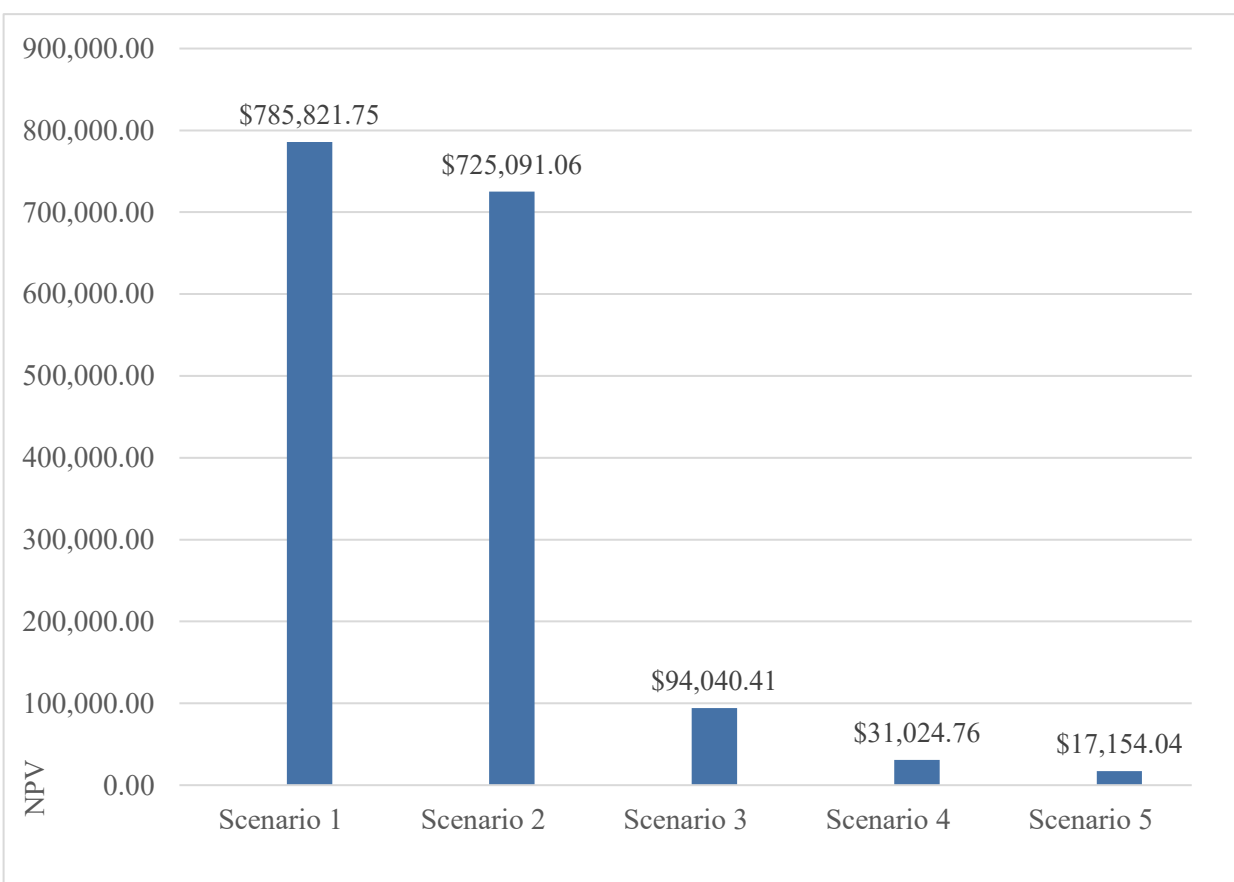


Figure 2-5: Total Capital Investment (TCI) for Scenarios.

2.5.4.3- Cash Flow

The cash flow analysis presents the project's investment, earnings, cashflow and NPV over the project's lifetime. As depicted in Table 2-14, the cash flow for Scenario One reveals that

losses are sustained consistently throughout the project's lifecycle (cash flow for the other scenarios are in Appendix B). The annual operating cost excluding depreciation for this scenario is \$60,639.

Table 2-14: Base Case Cash Flow.

	Depreciable capital [MMS]	Fixed capital investment [MMS]	Working capital [MMS]	Depreciation [MMS]	Net earnings [MMS]	Cash flow [MMS]	Net present value (NPV) [MMS]	Cumulative NPV [MMS]
2022	0.0128	0.0128	0	0	0	-0.00686	-0.00754	-0.00754
2023	0.0192	0.0192	0.0016	0	0	-0.0119	-0.0119	-0.0194
2024	0	0	0	0.00458	-0.012	-0.00746	-0.00678	-0.0262
2025	0	0	0	0.00785	-0.0158	-0.00799	-0.0066	-0.0328
2026	0	0	0	0.0056	-0.0136	-0.00799	-0.006	-0.0388
2027	0	0	0	0.004	-0.012	-0.00799	-0.00546	-0.0443
2028	0	0	0	0.00286	-0.0108	-0.00799	-0.00496	-0.0492
2029	0	0	0	0.00286	-0.0108	-0.00799	-0.00451	-0.0537
2030	0	0	0	0.00286	-0.0108	-0.00799	-0.0041	-0.0578
2031	0	0	0	0.00143	-0.00942	-0.00799	-0.00373	-0.0616
2032	0	0	0	0	-0.0053	-0.0053	-0.00225	-0.0638
2033	0	0	-0.0016	0	-0.0053	-0.0037	-0.00143	-0.0652

2.5.4.4- Economic Evaluation

The NPV for the five scenarios ranges from -\$795,246 to -\$157,671, as shown in Figure 2-6. All scenarios yield a negative NPV. The most negative NPV is Scenario One, which involves biomethane production for pipeline injections.

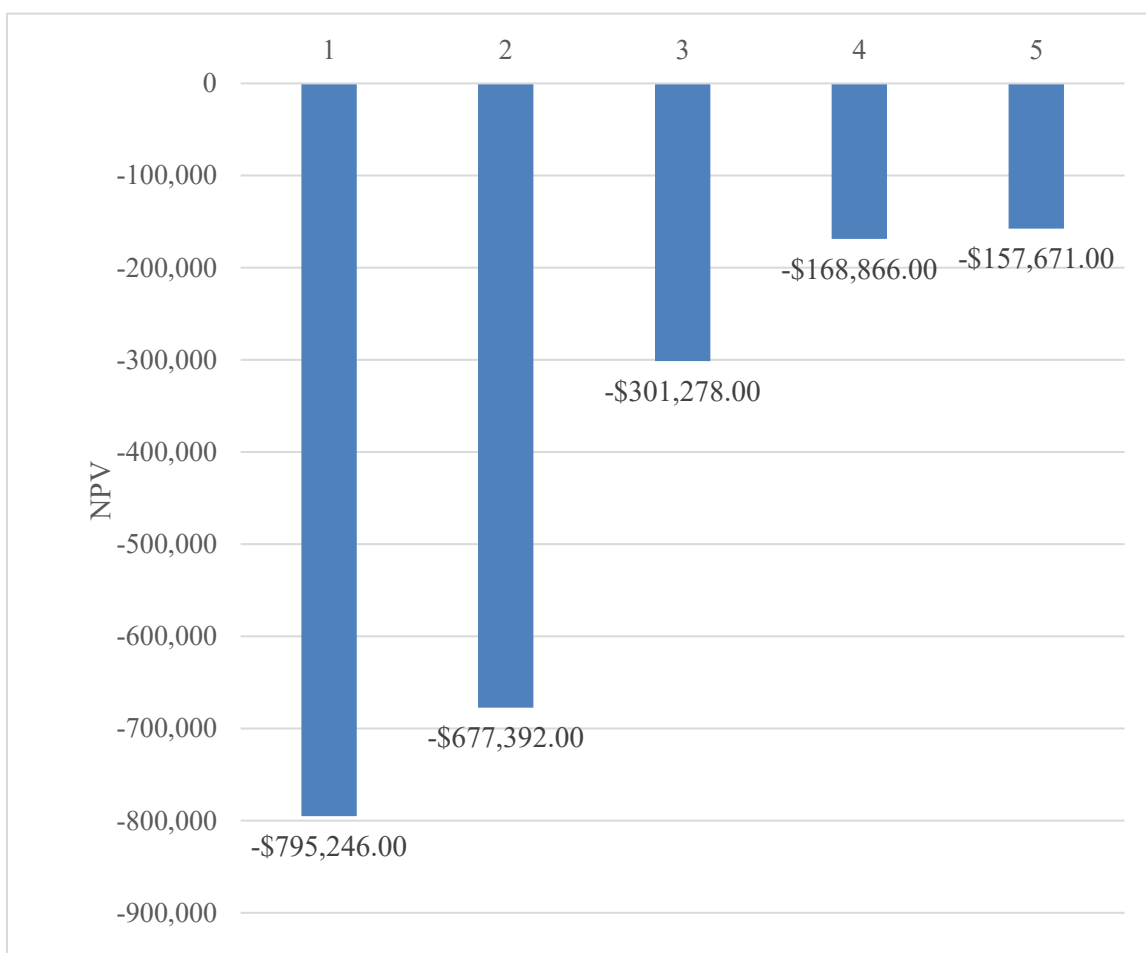


Figure 2-6: Net Present Value (NPV) of the Scenarios.

2.5.5- Sensitivity Analysis

The sensitivity analysis assessed the impact of varying costs on the NPV. The parameters used were water, biogas production cost, pipeline, number of cows, and electricity cost. Variation in the pipeline cost was observed to have the highest impact on the NPV; the higher the pipeline cost, the more negative the NPV becomes (Figure 2-7). The number of cows and cost of biogas also has an impact, while the cost of water and electricity has the least impact on the NPV.

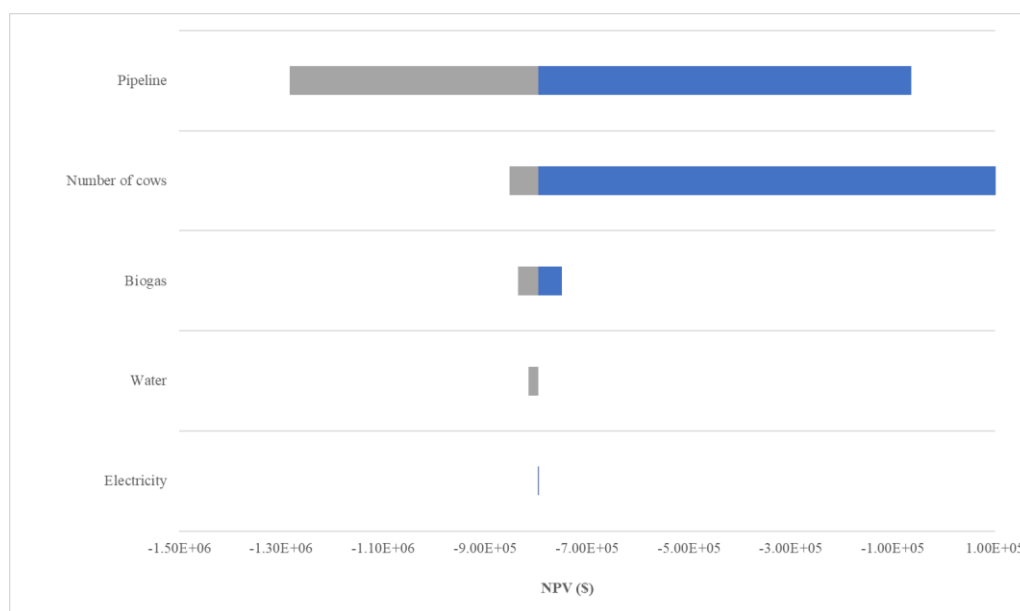


Figure 2-7: Sensitivity Analysis of the Model.

In Pennsylvania, most farms are located many miles from a pipeline injection point, meaning more negative NPV, also the cost of injection point (which was not included in this analysis), is likely to make RNG injection scenarios non-profitable for many farms. In the base case scenario, the pipeline cost was excluded and the NPV remained negative at -\$63,479, indicating that proximity alone does not guarantee profitability. For small farms, virtual pipelines may offer a more practical alternative to installing dedicated pipelines. A virtual pipeline is a delivery system used to transport biomethane via road or rail, commonly adopted in regions with limited access to pipeline infrastructure (Ó Céileachair et al., 2023).

2.5.6- Scenario Analysis

The optimistic scenario using a biogas production cost of \$0.25/m³, no pipeline expenses, electricity rate of 10.49 cents/kWh, water cost of \$0.00135/kg, and RNG selling price of \$2.50/kg, results in an NPV of \$101,720, showing that with lower cost and a higher RNG selling

price, this scenario can be profitable. In contrast, the pessimistic scenario using a biogas production cost of \$0.44/m³, a pipeline cost of \$1,000,000, electricity rate of 22.07 cents/kWh, water cost of \$0.0029/kg, and RNG selling price of \$1.50/kg, resulting in a negative NPV - \$1,368,301, laying emphasis of the effect of cost on the scenario. Only the most favorable combination of the costs and incomes results in a positive NPV.

2.5.7- Effect of Biogas Cost of Production, Electricity Cost and Incentives on the NPV of Scenarios Three to Five

The impact electricity sale price and incentives on the NPV for the electricity production scenarios can be seen in Figure 2-8 below; Scenario Three had the lowest NPV, which improved with the addition of incentive (PTC) and an increase in the electricity sales price. Scenario Four had a slightly lower NPV than Scenario Five but had a higher NPV surpassing that of Scenario Five as the revenue increased, indicating that with an increase in incentive and sales price of the electricity, there is better potential for small scale electricity generation from biomethane than for the usage of the raw biogas due to the calorific value of both gases.

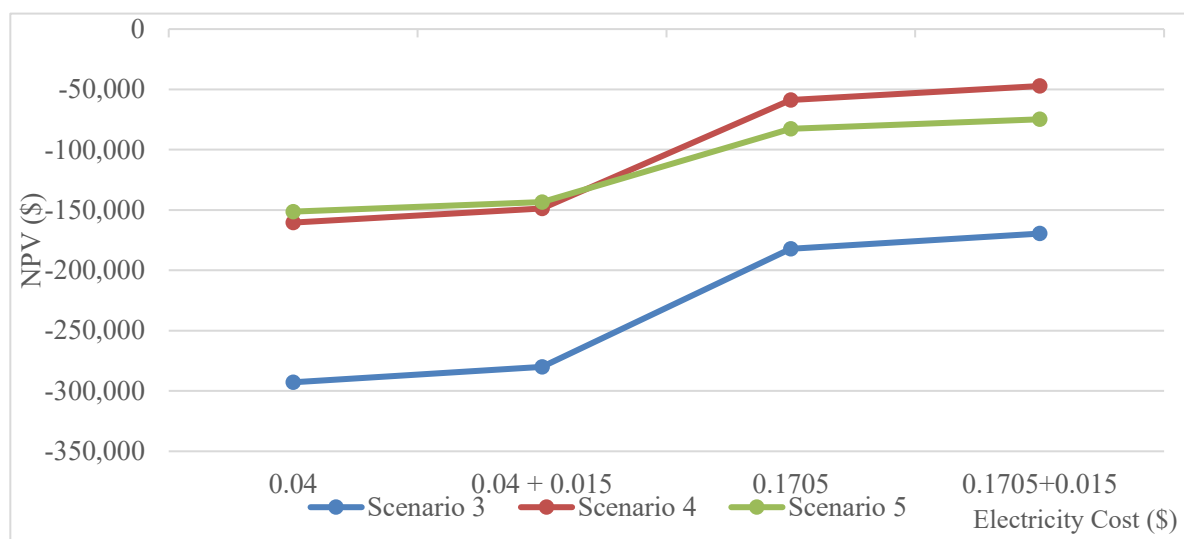


Figure 2-8: Effect of PTC and Electricity Sales Price on NPV.

The reduction in the production cost of biogas impacts on the scenarios (Figure 2-9). As the production cost decreases, the NPV increases.

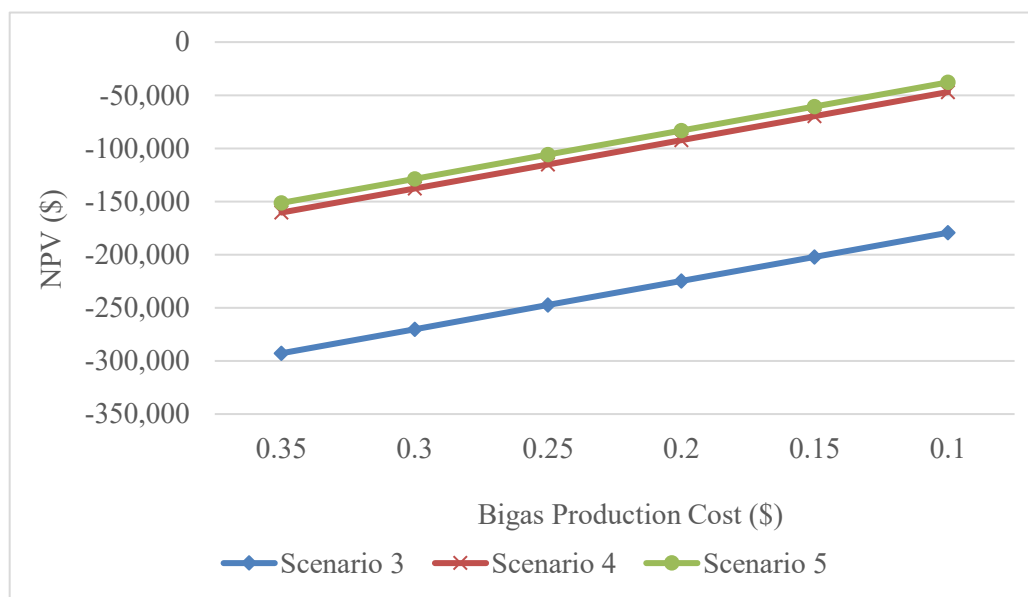


Figure 2-9: Effect of Biogas Production Cost on NPV.

2.6- Discussion

The results of this study highlight the techno-economic feasibility potential of biogas upgrading for small-scale farms (100 cows) in Pennsylvania using water scrubbing. Five scenarios were analyzed to assess both technical and economic performance: (i) pipeline injection with a flash column, (ii) pipeline injection without a flash column, (iii) electricity generation using biomethane with a flash column, (iv) electricity generation using only the water scrubbing column, and (v) electricity generation using raw biogas, with the first scenario as the baseline case.

The biogas produced and the water required for scrubbing were calculated using the mass transfer equation to meet the targeted CO₂ removal efficiency. The calculated CO₂ removal efficiency of the water scrubbing column was 93.07%, with a CH₄ loss of 3.78%. These values align closely with efficiencies reported in the literature for high-pressure water scrubbing systems (Abu Seman & Harun, 2019; Qian et al., 2023; Wantz et al., 2022). The scrubber's calculated height was 1.96m, which was obtained using Onda's coefficient and overall mass transfer coefficient for a biogas flow rate of 222.56 m³/day.

In Scenarios One and Two, the biomethane produced was assumed to be injected into the RNG pipeline, while in Scenarios Three and Four, the biomethane was used in the generator for electricity generation at 40% efficiency. Scenario Five used the raw biogas produced for electricity generation. The estimated electricity production in Scenarios Three and Four, is 349,115.61 kWh/year while that of Scenario Five is 218,848 kWh/year which is due to the lower calorific value in the raw biogas. It should be noted, however, that raw biogas cannot be used directly in generators without prior cleaning or scrubbing, as it can cause significant equipment damage.

The economic assessment shows significant (NPV) variation across scenarios, with all scenarios yielding a negative NPV, indicating that both electricity generation and pipeline injection to the grid are not profitable for a farm with a 100-herd size corresponding to the research by Cucchiella et al. (2018) which analyzed three different small-scale sizes: 50 m³/h, 100 m³/h, and 150 m³/h. For the scenarios with electricity generation, which yield a lower negative NPV, incentives, less biogas cost, and an increase in the price of electricity can help improve the NPV.

Sensitivity analysis identified the pipeline cost as a major impact on NPV, followed by number of cows, biogas production and utility cost. The use of community digesters can be an alternative to installation of digesters on small farms, thereby reducing the cost of biogas production. The pipeline cost used in the baseline (Scenario One) is for 1 mile, which gives a negative NPV. A more expensive pipeline cost will result in a more negative NPV. It may be worthwhile to consider using a virtual pipeline of the scrubbed biogas to the point of injection.

2.7- Conclusions

Pennsylvania, with its many small-scale dairy farms averaging 94 cows per herd, presents a significant opportunity for smaller-scale sustainable energy solutions. This study evaluated the techno-economic feasibility of biogas upgrading using water scrubbing for a farm with 100 cows. Five scenarios were analyzed: pipeline injection with and without a flash column and electricity generation with and without a flash column using biomethane, and raw biogas for electricity generation.

The water scrubbing process was modeled and achieved a CO₂ removal efficiency of 93.07% and a CH₄ loss of 3.78%, aligning with established benchmarks. Most scenarios yields a negative NPV indicating that biogas for a small farm with a 100-cow herd is not profitable, apart from the optimistic scenario. Sensitivity analysis further highlights the impact of electricity costs, water, biogas production expenses, number of cows, and pipeline costs on economic outcomes, with the pipeline, number of cows, and cost of biogas having the highest impact on the model.

In conclusion, this work demonstrates that water scrubbing is not profitable for a 100-cow herd, and pipeline injection is not an option. Electricity generation can be used, but requires grants, funding, incentives, and a high sales price of electricity to be viable. Future studies should explore cooperative models where multiple small farms share a centralized upgrading facility to reduce capital costs. This study underscores the economic constraints of small-scale biogas upgrading and highlights the need for policy interventions and innovative financing models to make the process viable.

2.8- References

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Chapter 3

TECHNO-ECONOMIC ANALYSIS OF BIOGAS UPGRADING USING DIGESTATE LIQUID

3.1- Abstract

Digestate and biogas are renewable by-products of anaerobic digestion, with digestate often separated into solid and liquid fractions. The solid fraction is commonly repurposed as bedding for livestock, while the liquid fraction (digestate liquid), a major part of the digestate, is widely used as organic fertilizers. However, can it be used for another purpose? This study investigates the potential of using digestate liquid as an absorbent for biogas scrubbing. The solubility of carbon dioxide (CO_2) in digestate liquid was compared to that of water, using pH and volume-based measurement methods at 4°C, 22°C, and 34°C. The performance of digestate liquid was then modeled for biogas scrubbing using overall mass transfer coefficients and Henry's law. The experimental results indicate that the highest CO_2 absorption by digestate liquid (116 g) occurs at 4°C, with lower or no absorption occurring at higher temperatures. Results from the pH method and volume method did not match, and it appears that the pH method may not be suitable for use with aqueous solutions, due to buffering and other effects. The design value for digestate liquid sorption is 167% that of tap water. The height of the packed bed required to achieve the targeted efficiency using digestate liquid is almost twice that of the water column, increasing the cost of the system. A techno-economic analysis of the use of digestate liquid for biogas upgrading was analyzed using a once-through process. The system's net present value (NPV) is negative \$65,240; however, it is more favorable than when using water for upgrading as a once-through process. Further studies are recommended to optimize the absorption capacity of digestate liquid for biogas upgrading applications.

3.2- Introduction

Anaerobic digestion is a biochemical process that facilitates the breakdown and stabilization of organic material in an oxygen-deprived environment, yielding biogas (Neri et al., 2023) and digestate as byproducts. Biogas is predominantly comprised of methane (CH_4 , 55%–70%) and carbon dioxide (CO_2 , 30%–45%), with additional trace gases, including nitrogen (0%–15%), oxygen (0%–3%), water vapor (1%–3%), hydrocarbons (0–200 mg m^{-3}), ammonia (0–100 ppmv), hydrogen sulfide (0–10,000 ppmv), and siloxanes (0–41 mg Si m^{-3}) (Awe et al., 2017). The high amount of CO_2 in biogas, diminishes its calorific value while also decreasing flame velocity and flammability limits (Yousef et al., 2019; Noorain et al., 2019).

Digestate, another byproduct of anaerobic digestion, can be divided into a solid fraction (10%–20% of total mass) and a liquid fraction (80%–90%) through mechanical separation methods such as screw press or decanter centrifuge (Xia & Murphy, 2016). The chemical composition and properties of digestate vary considerably depending on factors such as feedstock type, process temperature, retention time, and other operational parameters of the biogas plant (Nielsen et al., 2020). The solid fraction is often repurposed as bedding material for livestock, while the liquid fraction is commonly applied to agricultural fields as fertilizer (Xia & Murphy, 2016), enhancing soil physical properties, reducing bulk density, and improving hydraulic conductivity (Tambone et al., 2019). Compared to raw animal manure, the liquid fraction of digestate contains higher concentrations of nitrogen and potassium (Chuda & Ziemiński, 2023), exhibits an increased total ammonia-nitrogen (TAN) ratio, lower organic matter content, reduced total and organic carbon levels, decreased biological oxygen demand, higher pH, a lower carbon-to-nitrogen (C/N) ratio, and reduced viscosity (Camilleri-Rumbau et al., 2021).

As previously mentioned, biogas contains impurities that reduce its calorific value and flammability, necessitating their removal. Various biogas upgrading techniques include

adsorption, absorption (both water-based and chemical), gas permeation, and cryogenic distillation (Hoyer et al., 2016; Rastegar & Ghaemi, 2022). Among these methods, absorption is particularly advantageous as it requires less energy and does not involve the use of hazardous chemicals (Lawson et al., 2021).

Water scrubbing, an absorption-based biogas upgrading, operates on the fundamental principle of gas dissolution in a liquid, with water serving as the absorbent medium. In this process, CO₂ and H₂S are selectively absorbed by water due to their significantly higher solubility compared to CH₄ (Gantina et al., 2020), but can digestate liquid perform in the same manner as water?

Herbstritt et al. (2023) reports that the liquid fraction of digestate contains approximately 4.6% solids, reinforcing the assumption that it can exhibit water-like behavior and effectively absorb impurities from biogas, thereby reducing water consumption costs in biogas upgrading. Additionally, the ammonia present in the digestate liquid can facilitate CO₂ capture, enabling the concurrent production of ammonium bicarbonate (NH₄HCO₃) fertilizer (Yan et al., 2013). The objectives of this study are to evaluate the CO₂ absorption capacity of digestate liquid and to conduct a techno-economic analysis of biogas upgrading using digestate liquid as the absorbent.

3.3- A Substitute for Scrubbing Biogas

Due to its weakly alkaline nature, digestate liquid has shown promise as a solvent for CO₂ absorption (He et al., 2017). Yan et al. (2013) examines the feasibility of utilizing digestate for CO₂ capture and reports a maximum CO₂ loading capacity of 0.13 mol CO₂/L, highlighting its potential as an absorbent. However, the study also identified phytotoxicity (negative effects on

plant growth resulting from its chemical composition) as a limiting factor for its broader application.

Enhancing the absorption performance of digestate is possible by leveraging its total TAN content. The biogas slurry could serve as a once-through absorbent for biogas upgrading, meaning that after it is used for biogas upgrading, it is not recycled Equation 3-1 illustrates the reaction that produces a more suitable fertilizer as a co-product.



3.4- Materials and Methods

The digestate liquid (DL) used in this study was sourced from a farm-based anaerobic digester in Central Pennsylvania, which co-digests cow manure and food waste for biogas production. The digestate underwent separation using a screw press, and the resulting DL was stored in a cold chamber at 4°C before laboratory analysis.

The water used in the experiment was sourced from the Department of Agricultural and Biological Engineering at Penn State and has a pH of about 7.49. pH measurements were carried out using a Mettler Toledo pH meter (model) equipped with an LE488 model probe. Other equipment used in the experiment included a measuring cylinder, calibrated containers, a hot plate, and pure CO₂.

3.4.1- Experimental Procedure

A sample of the digestate liquid was sent to the Ag Analytical Services Lab at Penn State for characterization, including the determination of total solids, total nitrogen, ammonium, organic nitrogen, phosphate, and potash.

The experiment was conducted using an experimental setup depicted in the schematic diagram below (Figure 3-1). Two approaches were used: the volume method, in which the volume of the sample container (containing both liquid and gas) reduces as CO₂ is absorbed into the liquid and the pH method, in which the pH of the liquid drops as CO₂ is absorbed. To ensure precise measurement of both the sample and CO₂ quantities, 500 mL bottles were carefully calibrated into five equal sections. Sample preparation was conducted by using a hand sieve to remove debris from the digestate liquid (DL) (Figure 3-2). The samples were then heated to 70°C while continuously stirred using a magnetic stirrer to ensure homogeneity. This heating process facilitated the release of absorbed gases from DL by disrupting the bonds with thermal energy. Once CO₂ is desorbed, the absorbents transition into a free state, meaning it regains the capacity to reabsorb CO₂ (Park et al., 2017). The DL was stored at the three temperatures utilized in this experiment and was used for CO₂ absorption tests in the subsequent trials. The experimental results were recorded and computed, after which they were converted into grams of CO₂ absorbed.

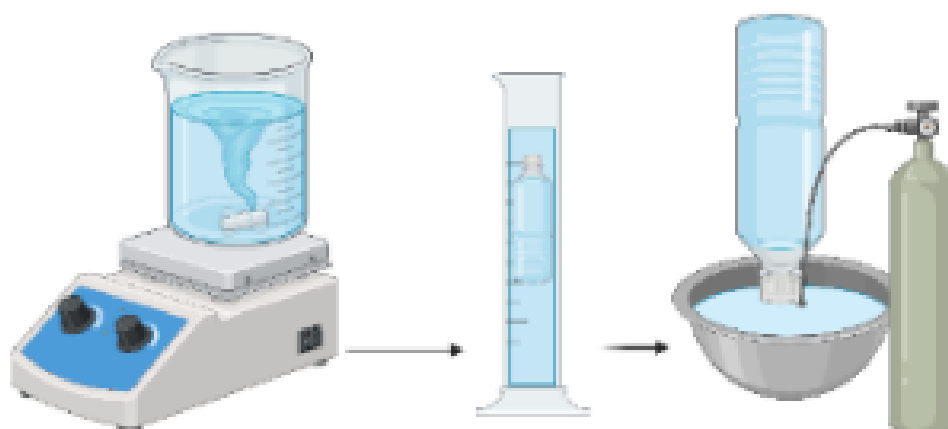


Figure 3-1: Illustration of the Experiment. Digestate liquid is heated to 70°C (left), a sample bottle is filled with liquid digestate (center), and CO₂ gas is added to the bottle (Right). (Source: Biorender).



Figure 3-2: Sample Preparation (Sieving Debris from the Digestate Liquid). (Photo Credit: Francis Akyirem).

The absorption of CO₂ was measured using both the pH and volume methods at temperatures of 4°C, 22°C, and 34°C. The pH meter was calibrated using buffer solutions of about 20 ml with pH values of 4 and 7 to ensure accurate pH measurements. Digestate liquid was then poured into the calibrated 500 mL bottles, filling them to the designated mark. For each sample, the initial pH and volume were recorded. A total of 18 samples were analyzed, with three replicates tested at each temperature under two different time intervals (30 and 1440 minutes).

After recording the initial pH and volume, CO₂ was bubbled into each sample while the calibrated containers filled with digestate liquid were inverted in water to prevent gas escape. The containers were then sealed and placed in controlled environment chambers at 4°C, 22°C, and 34°C.

The volume of each bottle was measured using its volume displacement in a graduated cylinder in the controlled environment chamber. The bottles were then opened and their pH measured using a pH Mettler Toledo meter. The CO₂ absorption capacity of the digestate liquid was subsequently calculated to quantify the amount of gas absorbed under each experimental condition.

The samples underwent only thermal treatment and were not supplemented with additives such as Monoethanolamine (MEA), potassium glycinate, potassium hydroxide (KOH), or aqueous ammonia (AA) to enhance CO₂ absorption efficiency (Yan et al., 2013).

3.4.1.1- Volume Method

The amount of CO₂ absorbed during the experiment was calculated from the change in sample volume using the ideal gas law equation, following the approach described by Rastegar & Ghaemi, (2022).

$$P\Delta V = nRT \quad 3-2$$

Where:

P = Pressure (atm)

T = Temperature in Kelvin (4°C, 22°C and 34°C).

R = Universal gas constant (L.atm/mol).

n = Number of moles of gas (mol).

ΔV = Change in volume (obtained from the experiment) units (L).

P is assumed to be constant for each sample.

3.4.1.2- pH Method

The change in the sample's pH was utilized to determine the quantity of CO₂ absorbed. pH measurements were taken before introducing CO₂ into the sample and subsequently recorded after 30 and 1440 minutes. The amount of CO₂ absorbed was then calculated using Equations 3-3 and 3-4.

$$\Delta\text{CO}_2 = [H^+]_{\text{final}} - [H^+]_{\text{initial}} \text{ (mol/L)} \quad (3-3)$$

$$[H^+]_{\text{initial}} = 10^{-pH_{\text{initial}}}; [H^+]_{\text{final}} = 10^{-pH_{\text{final}}} \quad (3-4)$$

3.4.2- Data Analysis

Data analysis for this experiment (pH and volume methods) was conducted using R software version 2024.09.0+375. The data were visualized using box plots to assess the impact of time duration on CO₂ absorption. Normality was evaluated using the Shapiro-Wilk with the null hypothesis stating that the data follows a normal distribution and the alternative hypothesis indicating non-normality. A p-value less than 0.05 was used as the threshold for rejecting the null hypothesis. Based on the normality results, either a parametric test (t-test) or a non-parametric test (Wilcoxon test) was employed to compare the methods. This was done for four data sets (water sample at 30 mins using volume and pH method, water sample at 1440 mins using volume and pH method, digestate liquid at 30 mins using volume and pH method, and digestate liquid at 1440 mins using volume and pH method).

3.4.3- Modeling of Sorption System

The modeled sorption system consists of a pump, a biogas compressor, a packed column for digestate scrubbing, and a generator. This setup consists of compressed biogas introduced at the bottom of the packed column while digestate liquid is pumped in from the top (Figure 3-3). The base case scenario for the model consists of the following design characteristics and performance data. The biomethane is utilized in a generator for electricity production, with an assumed efficiency of 40%, consistent with the efficiencies reported in literature (i.e. Sillero et al. 2023). Section 2.4.14 details the calculation for determining the generator's electrical power output. The digestate liquid used in the scrubbing process is available after it is used in the scrubber for agricultural applications.

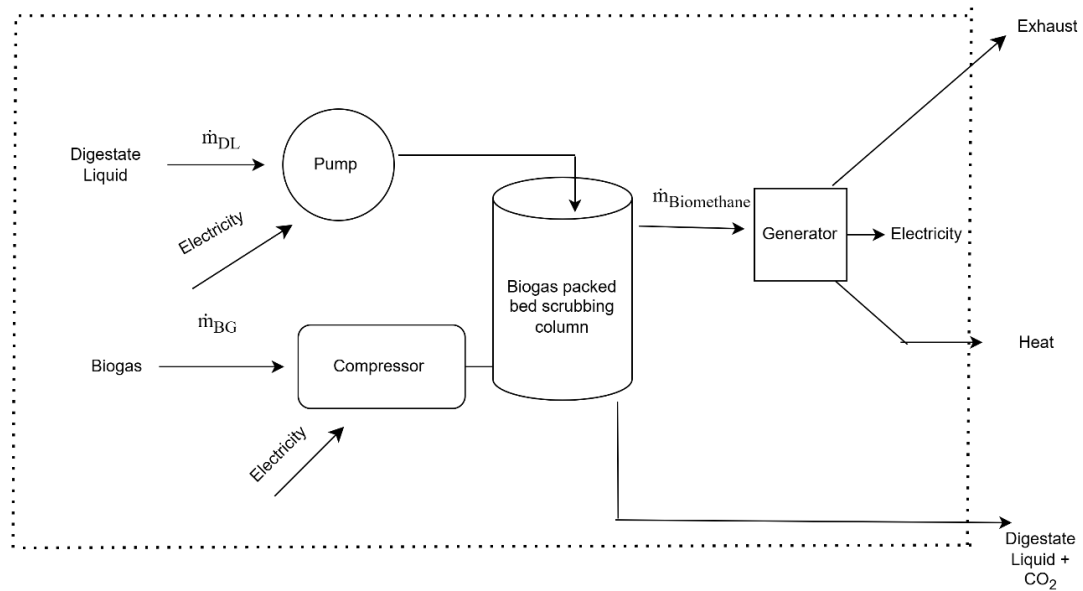


Figure 3-3: Process Flow Diagram (Source: Drawio).

3.4.3.1.- Assumptions

This model assumes a biogas production system with a herd size of 100 cows. The biogas consists solely of CH₄ (60%) and CO₂ (40%) by volume. Digestate liquid is used for scrubbing the biogas which is assumed to be available at no cost and a once-through process. The system is sized to achieve the removal of 95% of the CO₂ from the biogas.

3.4.3.2.- Calculation of Digestate Liquid Amount for Biogas Upgrading

As described in Chapter 2 the first step was to calculate the amount of liquid needed to attain the target scrubbing efficiency (95% CO₂ removal) using the mass balance equations (Wantz et al., 2022).

$$\dot{m}_{G1} + \dot{m}_{L1} = \dot{m}_{G0} + \dot{m}_{L0} \quad 3-5$$

Where:

$$\dot{m}_{G1} \text{ (mol/s)} = 0.60 \text{ CH}_4 + 0.40 \text{ CO}_2$$

$$\dot{m}_{G0} \text{ (mol/s)} = 0.95 * 0.6 \text{ CH}_4 + 0.05 * 0.4 \text{ CO}_2$$

Solving for liquid out

$$\dot{m}_{L0} = (\dot{m}_{G1} + \dot{m}_{L1}) - \dot{m}_{L1} \quad 3-6$$

3.4.3.3.- Production Calculation

Biogas production was estimated based on the number of cows on the farm, assuming a daily manure yield of 69 kg per cow. The manure had a total solids (TS) content of 12%, with volatile solids (VS) comprising 84% of the TS. The biogas production rate was calculated at 320 mL per gram of volatile solids (0.320 m³/kg VS), serving as the basis for determining the total biogas yield from the farm's manure resources.

$$\text{Total biogas produced} = N * M * TS * VS * BS \quad 3-7$$

Where:

N = Number of cows.

M= Manure yield per cow (kg/cow/day).

TS = Total solid (decimal).

VS = Volatile solid (decimal).

BS = Biogas specific production (m³/kg VS).

3.4.3.4.- Modeling of the Packed Bed Column (Scrubbing column)

As mentioned earlier, due to digestate liquid's weak alkalinity, its use for CO₂ absorption is limited to a once-through process (He et al., 2017). As a result, only a scrubbing column and generator system were modeled in this study with no recirculation or re-use of digestate liquid. The modeling was carried out using BioSTEAM software (version 2.38.6) with a Python interface (version 3.11.5) (Sanchis-Sebastiá et al., 2020). The height of the scrubber was calculated using mass transfer coefficients and Onda's correlation (Sinnott, 2005). The accuracy of the model was tested by changing various variables and observing the impact on the net present value (NPV).

3.4.3.5.- Estimation of Column's Diameter and Height

The density of digestate liquid (DL) was estimated based on its total solids (TS) content and temperature, following the method used for calculating the density of cattle manure (Gerber & Schneider, 2015). While Gerber & Schneider (2015) notes that this approach results in significant deviations between experimental and calculated values, it remains a viable estimation

method due to the availability of TS data. The density was determined using Equation 3-8 (Achkari-Begdouri & Goodrich, 1992; Gerber & Schneider, 2015).

$$\rho_{DL} = \rho_{H2O} * (1 - 0.004094 * \%TS)^{-1} \quad 3-8$$

The calculated density was then compared with values reported in Wang et al, (2019), which reports the density, TS, and VS content of pre-digested and post-digested dairy manure. Additionally, Schiavon et al. (2018) assumes a density of 990 kg/m³ for digestate, whereas a density of 998.88 kg/m³ was obtained using Equation 3-8.

The column area required for the system was calculated using Equation 2-10, and the diameter was then calculated using the area of a circle ($\frac{\pi d^2}{4}$) using Equation 2-11.

The effective area of the packed bed (A_p) was calculated as follows:

$$\frac{A_p}{a} = 1 - \exp \left[-1.45 \left(\frac{\sigma_p}{\sigma_{DL}} \right)^{0.75} * \left(\frac{l_{DL}}{a * \mu g} \right)^{0.2} * \left(\frac{l_{DL}^2 * a}{\rho_{DL}^2 * g} \right)^{-0.05} * \left(\frac{l_{DL}^2}{\sigma_{DL} * \rho_{DL} * a} \right)^{0.2} \right] \quad 3-9$$

Where:

A_p = Packed bed effective area (m²/m³)

σ_p = Surface tension of the packing bed (N/m)

σ_w = Surface tension of DL (N/m)

l_{DL} = (Digestate liquid flow rate (kg/s)/ column area (m²)) 3-10

a = surface area of packed bed (m²/m³)

The diffusion coefficient of DL was calculated using Equation 3-11 (Carlsson et al., 2006; Gendron et al., 2008), while the diffusion coefficient of biogas was calculated using Wilke and Lee correlation (Pérez Sánchez et al., 2016), with the assumption that biogas contains just CH₄ and CO₂, (Sindhuja et al., 2018) Equations 2-13 to 2-17 were used to calculate the diffusion coefficient of biogas.

$$D_{DL} = \frac{KT}{6\pi\eta r} \quad 3-11$$

Where:

D_{DL} = Diffusion coefficient of digestate liquid (m^2/s)

K = Boltzmann's constant $1.38 \times 10^{-23} J/K$ (NIST, 2022)

T = Temperature (K)

η = Dynamic viscosity of the solvent (Pa.s)

r = Hydrodynamic radius of the particle in digestate liquid (m)

The mass transfer coefficient of the liquid is calculated as follows:

$$K_L \left(\frac{\rho_{DL}}{\mu_{DL} g} \right)^{\frac{1}{3}} = 0.0051 \left(\frac{l_{DL}}{A p^* \mu_{DL}} \right)^{2/3} \left(\frac{\mu_{DL}}{\rho_{DL} * DL} \right)^{-\frac{1}{2}} (a * dp)^{0.4} \quad 3-12$$

Where:

K_L = Mass transfer coefficient of the liquid (m/s)

D_L = Diffusion coefficient of liquid (m^2/s)

dp = packing size of the packed bed (m)

The mass transfer coefficient for biogas was calculated using Equations 2-19 to 2-22 and the overall mass transfer coefficient and column height were calculated using Equations 2-23 to 2-24, parameters used for the modelling can be found in Table 3-1.

Table 3-1: Parameters for the Model.

Parameter	Unit	Value
Density of water @20°C	Kg/m ³	998.7
Density of biogas	Kg/m ³	1.158
Viscosity of methane	Pa.s	1.1e-5
Viscosity of CO ₂	Pa.s	1.47e-5
Viscosity of DI	Pa.s	300e-3
Collision diameter CO ₂	Angstroms	3.941
Collision diameter CH ₄	Angstroms	3.758
Diffusion coefficient of water	m ² /s	1.64e-9
Total solids in DL	%	4.46
Hydraulic radius	m	0.33e-6
Boltzmann constant		1.38e-23
Surface tension of DL	N/m	3e-3
The surface area of packing (a)	m ² /m ³	250
Lennard-Jones parameter (e/K) CO ₂	K	195.2
Lennard-Jones parameter (e/K) CH ₄	K	148
Henry's constant CO ₂	Bar	1650

Henry's constant CH ₄	Bar	40100
Biogas pressure	MPa (Bar)	0.1(1)
Packed bed column pressure	MPa (Bar)	1(10)
Packed bed column Temperature	°C	20
CEPCI 2023		802.9
CEPCI 2013		567.3

TSM- Total solid in manure

VSM -Volatile solid in manure

3.4.4- Generator

The generator was modeled using the method described in chapter 2. The calorific value was assumed to be the same since the assumption for this model was that DL absorbs CO₂ in the same manner as water. Experimental confirmation of this assumption would be valuable.

3.4.5- Economic Analysis

Modeling was conducted in BioSTEAM software (version 2.38.6) in Python 3.11.5. The base case scenario consisted of the following economic inputs and assumptions.

3.4.5.1- Equipment Cost

The pump and compressor's cost were obtained from an online vendor using BioSTEAM specifications. The cost of the scrubber was estimated based on its height and diameter, following the approach described by Scholz et al. (2013). The cost of the generator was estimated using the sixth-tenth rule, based on generator cost data reported in Sganzerla et al. (2023), which was used

to generate electricity in a small-scale anaerobic digestion of Jabuticaba by-product. The end-use application of the biomethane was electricity generation.

3.4.5.2- Total Fixed Capital Investment

The Fixed Capital Investment (FCI) includes the total costs of constructing the plant, encompassing expenses for equipment, installation, piping, electricity, and building infrastructure (Lawson et al., 2021). The equipment costs were calculated using the methodology outlined in Chapter 2. Maintenance (2%), administration (0.5%), property insurance (0.5%) and tax (0.1%) were calculated as a percentage of FCI.

3.4.5.3- Operating Cost

The costs associated with daily operations, such as digestate liquid (which is assumed to be free), electricity, and biogas, were calculated for this study. Biogas production cost was determined using data from the International Renewable Agency (IRENA), which estimated the total production cost in 2017 to range between \$0.22–\$0.39/m³. Applying a 2% inflation rate to adjust for present value at year 2024 (0.25-0.44 \$/m³), the cost was updated to \$0.35/m³.

3.4.5.4- Overall Project Assessment

The project's economic viability was evaluated using a Discounted Cash Flow (DCF) analysis with the NPV as the primary metric. NPV combines all the cash flows generated over the project timeline and converts them into their equivalent present value. A positive NPV indicates that the project is financially viable and suitable for implementation (i.e. Gupta et al., 2022). The

discount rate for this study was set at 10%, following methodologies outlined in Lawson et al. (2021) and Ghafoori et al. (2022). The project lifespan is 10 years, the operating time is assumed to be 342 days per year, and the construction cost is set to equal 40% in the first year and 60% in the second. Economic analysis parameters are summarized in Table 3-2.

Table 3-2: Summary of Economic Parameters.

Parameter	Value
Discount rate	10%
Project life	10 years
Depreciation method	MACRS
Depreciation years	7
Income tax	35%
Operation days	342 days per year
Construction period	2 years (0.4) (0.6)
Working capital over FCI (%)	5%

3.4.5.5- Revenue

The source of revenue in this production is the electricity produced by the generator. The assumed price of selling to the grid is 17.05 cents/kWh based on Central Electric Coop, Inc of PA. However, it should be noted that this price varies depending on various parameters. Also, BioSTEAM does not explicitly state electricity as revenue but instead calculates the energy required by the system and subtracts it from the energy generated by the system.

3.4.6- Model Testing

The model was tested by varying the input parameters effect on the NPV, as the predicted response is summarized in Table 3-3.

Table 3-3: Parameters for Model Testing.

Parameter	Expected Impact on NPV
Increase in biogas production cost	Negative
Decrease in biogas production cost	Positive
Increase in electricity cost	Negative
Decrease in electricity cost	Positive
Increase in number of Cows	Positive
Decrease in number of cows	Negative

3.4.7- Sensitivity Analysis

A sensitivity analysis was conducted on the model to assess the impact of key parameters (manure yield, biogas production cost, and electricity cost) on the NPV of the base case scenario. The electricity cost was analyzed using the highest and lowest rates from Pennsylvania utility companies, biogas production cost was tested using the lowest and highest cost from IRENA, while the manure methane yield was evaluated with a $\pm 20\%$ variation to determine their influence on the overall economic feasibility (Table 3-4).

Table 3-4: Inputs for Sensitivity Analysis.

Parameter	Low Value	Base Value	High Value	Units
Electricity	10.49	17.05	22.07	\$/kWh
Biogas Production Cost	0.25	0.35	0.44	\$/m ³
Manure Methane Yield	55.2	69	82.8	kg/cow/day

3.4.8- Scenario Analysis

The digestate liquid scenario was compared to the water scrubbing column model in Chapter 2. This system used the same flow as that of the base case scenario but used water for absorbing impurities rather than digestate liquid, hence providing a valid comparison.

An optimistic scenario was evaluated, assuming an electricity price of \$22.07/kWh, a biogas production cost of \$0.25/m³, and a manure yield of 82.8 kg/cow/day. In contrast, a pessimistic scenario considered an electricity price of \$10.49/kWh, an elevated biogas production cost of \$0.44/m³, and a lower manure yield of 55.2 kg/cow/day.

3.5- Results

This section presents the findings from both the experimental study and the techno-economic analysis model. It is structured into two parts: the first details the experimental results, while the second outlines the outcomes of the techno-economic analysis.

3.5.1- Experiment Result

The results from the laboratory analysis used to characterize the digestate liquid and Penn State water report of year 2023 are presented in Table 3-5.

Table 3-5: Characterization of the DL.

Parameter	Value	Unit	Parameter	Range of Detection	Units
Solids	4.46	%	Nitrate	1.48-1.575	ppm
Total Nitrogen	7.56	Ib/ton	Total Trihalomethane	1.39-2.39	ppb
Ammonium N (NH ₄ ⁺ N)	2.89	Ib/ton	Mercury	0.21	ppb
Calculated Organic N	4.67	Ib/ton	Chlorine	0.88-0.95	ppm
Total Phosphate (P ₂ O ₅)	3.15	Ib/ton			
Total Potash (K ₂ O)	3.76	Ib/ton			

Data Analysis

These data are displayed as box plot graphs for sorption vs temperature in Figures 3-4 to 3-11. The highest absorption for DL was at 4°C at 1440 minutes.

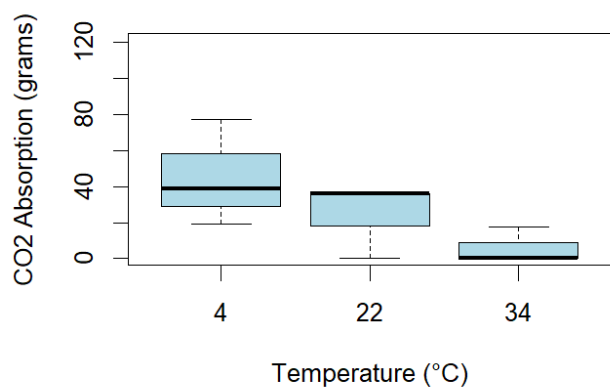


Figure 3-4: CO₂ Absorption of Water Using Volume Method At 30 Minutes.

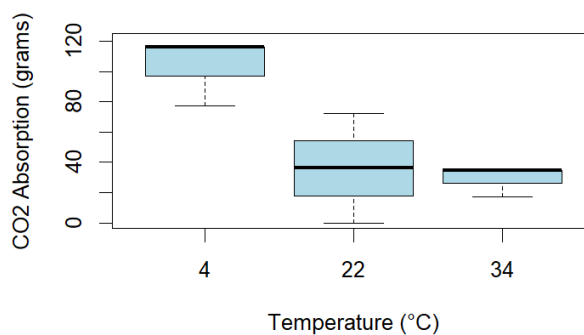


Figure 3-5: CO₂ Absorption of Water Using Volume Method At 1440 Minutes.

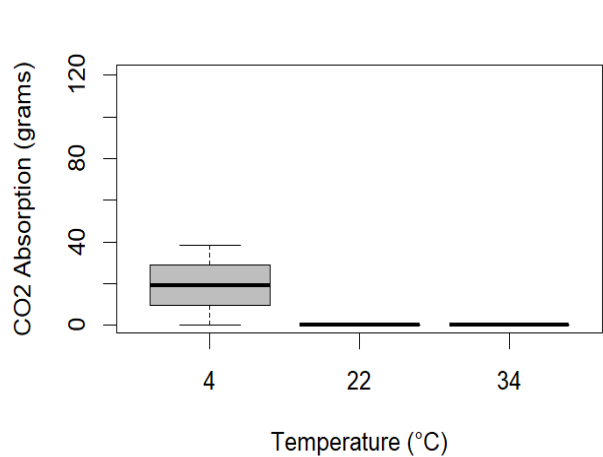


Figure 3-6: CO₂ Absorption of Digestate Liquid Using Volume Method At 30 Minutes.

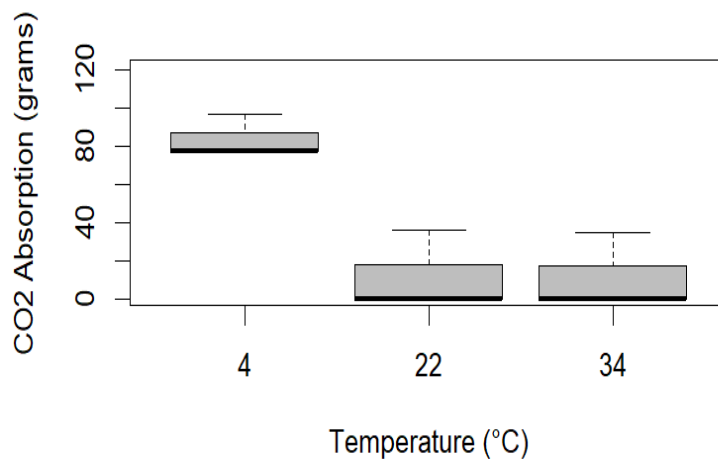


Figure 3-7: CO₂ Absorption of Digestate Liquid Using Volume Method At 1440 Minutes.

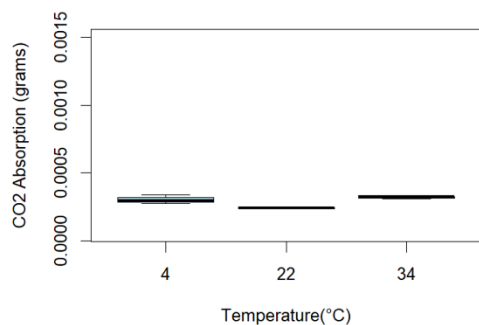


Figure 3-8: CO₂ Absorption of Water using pH Method At 30 Minutes.

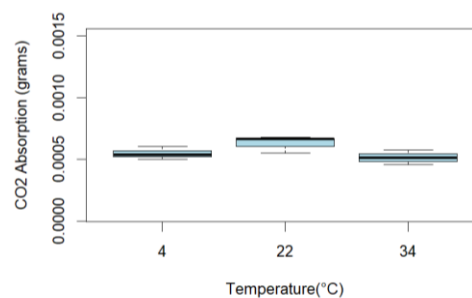


Figure 3-9: CO₂ Absorption of Water using pH Method At 1440 Minutes.

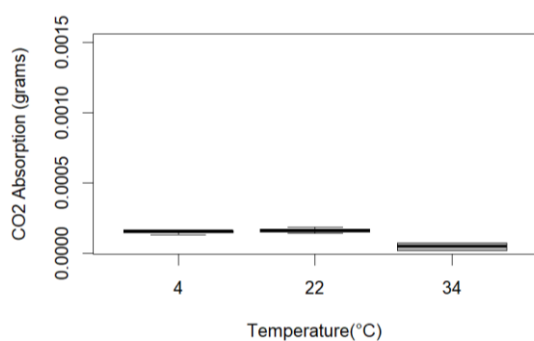


Figure 3-10: CO₂ Absorption of Digestate Liquid Using pH Method At 30 Minutes.

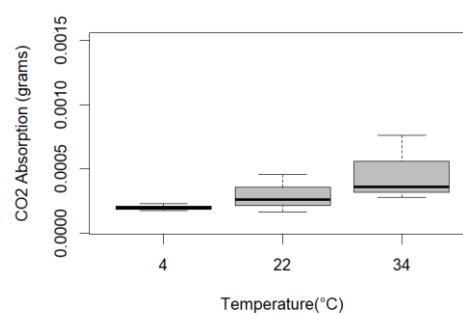


Figure 3-11: CO₂ Absorption of Digestate Liquid Using pH Method At 1440 Minutes.

The Shapiro-Wilk test is conducted to assess the normality of the data (Table 3-6). The water sample data at 30 minutes was analyzed using both the pH and volume methods, follows a normal distribution, allowing for the use of a parametric test (paired t-test). The paired t-test for water at 30 minutes yields a p-value of 0.01821, which is less than 0.05, indicating a statistically significant difference between the volume and pH methods. Similarly, for water at 1440 minutes, both datasets are normally distributed, and the paired t-test produces a p-value of 0.0037, showing a highly significant difference between the two methods. The volume method consistently provides significantly higher CO₂ absorption values than the pH method.

For the digestate sample data at 30 minutes, the volume method does not follow normal distribution. At 1440 minutes, neither method followed normally distributed data. Therefore, the Wilcoxon signed-rank test is used for comparison. The p-value for 30 minutes is 0.1953, and for 1440 minutes 0.1641, indicating no statistically significant difference between the pH and volume methods. However, the volume method yields higher CO₂ absorption values than the pH method, suggesting that the volume method provides greater sensitivity in measuring CO₂ absorption in digestate liquid. Higher values are recorded at 1440 minutes using the volume method, although the difference is not statistically significant.

Table 3-6: Normality Test Results for Water and Digestate Liquid Samples Across Time Intervals and Measurement Methods.

Sample	Time-interval (min)	Method	P-Value	Distribution Assumption
Water	30	Volume	0.1348	Normal
Water	30	pH	0.3664	Normal
Water	1440	Volume	0.3191	Normal
Water	1440	pH	0.8187	Normal
Digestate liquid	30	Volume	3.59e-05	Non-Normal
Digestate liquid	30	pH	0.0810	Normal
Digestate liquid	1440	Volume	0.0405	Non-Normal
Digestate liquid	1440	pH	0.01531	Non-Normal

3.5.2- Model Results

The model successfully simulated the performance of a digestate liquid scrubber, providing estimates of the system's physical and economic characteristics. The details of the model are presented below.

3.5.2.1- Digestate Liquid for Biogas Upgrading

The calculated size of the scrubber, and related design values are for digestate liquid as well as water scrubbing listed in Table 3-7.

Table 3-7: Calculated Result of the Model.

Parameter	Equation	Value for Digestate Liquid	Value for Water	Unit
Liquid required for scrubbing	3-5 and 3-6	0.017	0.0166	kg/s
Biogas volume	3-7	222.56	222.57	m ³ /day
Density	3-8	998.88	998	kg/m ³
Ap	3-9	249.82	118.41	m ² /m ³
$l_{DL/WI}$	3-10	0.61		kg/m ² s
Diffusion coefficient of liquid (D_{DI} and water)	3-11	1.31e-05	1.64e-093	m ² /s
Column diameter	2-11	0.39	0.35	m
Diffusion Coefficient of biogas (D_b)	2-13	1.74e-6	1.74e-6	m ² /s
M_{mb}	2-14	23.51	23.51	g/mol
ΩB	2-15	1.14	1.14	dimensionless
T^*	2-16	1.72	1.72	K
σ_{mb}	2-17	3.85	3.85	Å
K_L	3-12	1.67e-05	1.039 e-04	m/s
K_G	2-19	1.7e-04	2.1e-04	kmol/m ² sbar
μ_b	2-20	1.31e-05	1.31e-05	Pa.s
M_b	2-21	27.23	27.23	g/mol
V_b	2-22	0.609	0.811	kg/m ² s
K_L^*	2-23	1.7e-05	1.039 e-04	m/s
K_G^*	2-24	1.028e-8	6.297e-08	kmol/m ² sbar
HG	2-25	0.052	0.119	m
HL	2-26	1.23	0.366	m
Z	2-27	3.27	1.96	m

HOG	2-28	0.79	0.34	m
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3.5.2.2- Process Performance of Base Case Scenario

The process characteristics (mass and energy balance) of the scrubbing system are listed in Table 3-8.

Table 3-8: Mass and Energy Flow of the System.

Equipment	Liquid/ Gas In	Gas Out	Energy	Unit
Pump	Liquid 0.017	Liquid 0.017	0.00478kW	kg/s
Compressor	Methane – 0.232 Carbon dioxide- 0.155	Methane – 0.232 Carbon dioxide- 0.155	1.39kW	kmol/hr
Scrubber	Methane – 0.232 Carbon dioxide- 0.155	Methane – 0.223 Carbon dioxide- 0.0108		kmol/hr
Generator	Methane – 0.223 Carbon dioxide- 0.0108			

The digestate scrubbing column was modeled on BioSTEAM, the model was able to achieve a 93.03% CO₂ removal. The height of the column was calculated to be 3.27m (Equation 2-27), which is almost two times the height calculated using a pressurized water scrubber. The electricity produced is 17kW with electricity production of 139,646.25 kWh/year (349,115.61kWh).

3.5.3- Economic Analysis Results

3.5.3.1- Equipment Cost

Table 3-9 presents the installed equipment costs used in the model, using the same method as those used in chapter 2. The cost of the scrubbing column was higher than for water scrubbing because the height for CO₂ absorption using DL is greater.

Table 3-9: Cost of Installed Equipment.

Equipment	Cost (\$)	Size
Pump	731	96.6 ft by head
Compressor	4,080	0.78kW
Scrubbing column	4,330	3.27 m by height
Generator	21,800	17kW
Total	30,940	

3.5.3.2- Total Fixed Capital Investment

FCI which includes the total costs of constructing the plant, encompassing expenses for equipment, installation, piping, electricity, and building infrastructure for this scenario, calculated based on the parameters listed in the methods section is \$32,03739.

3.5.3.3- Operating Cost

The daily operations costs, such as digestate liquid (no cost associated with it), electricity, and biogas production cost, were calculated for this study. The annual operating cost excluding depreciation (USD/yr) is \$5,304.79/yr.

3.5.4- Model Testing

The impact of varying the biogas production cost, the number of cows, and electricity cost on the NPV is listed in Table 3-10. The effects of biogas production cost and electricity cost align with the expected outcomes. However, the outcome for the number of cows differs from expectations. As the number of cows increases, the cost of production also increases, but the resulting revenue is insufficient to offset the higher costs.

Table 3-10: Model Testing Results.

Parameter	Expected Impact on NPV	Result of Test
Increase in biogas production cost	Negative	✓
Decrease in biogas production cost	Positive	✓
Increase in number of cows	Positive	✗
Decrease in number of cows	Negative	✗
Increase in electricity cost	Negative	✓
Decrease in electricity cost	Positive	✓

3.5.5- Sensitivity Analysis

The NPV values from the sensitivity analysis are shown in Figure 3-12. Among the variables analyzed, the electricity sale price exhibited the greatest influence on the NPV (it is the revenue generated), followed by the biogas production cost, where reductions in production expenses improved the economic viability. In contrast, manure yield was the least impactful factor affecting the NPV.

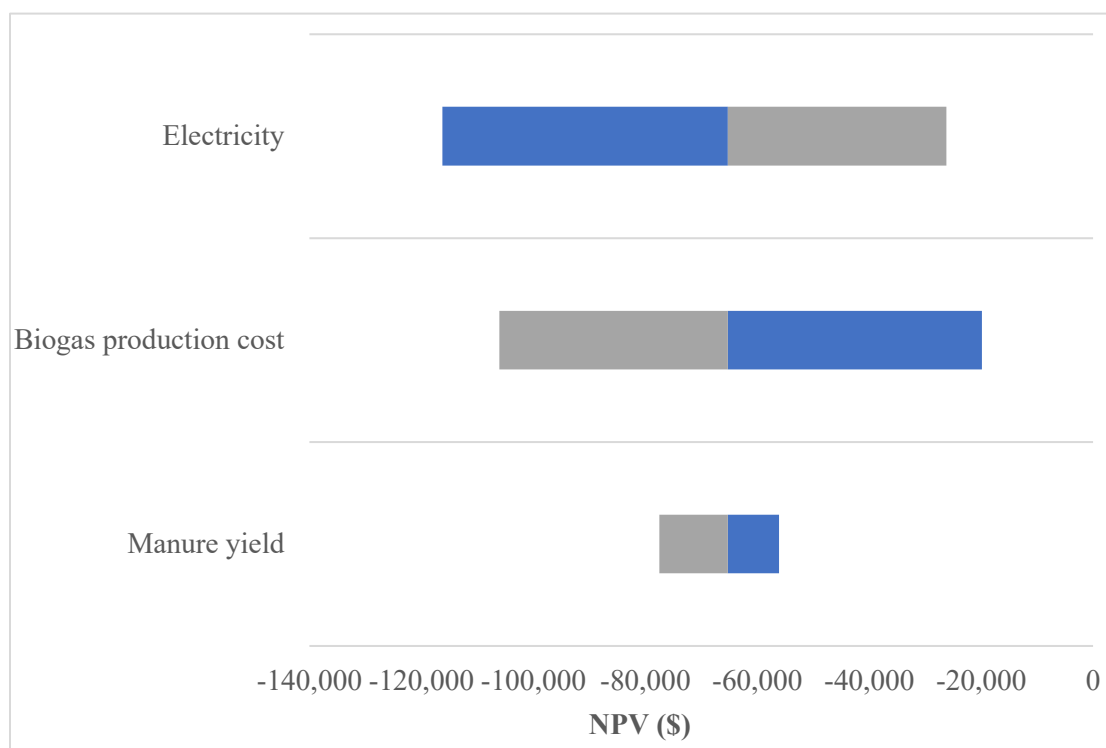


Figure 3-12: Sensitivity Analysis of the Model.

3.5.6- Scenario Analysis

The NPV for upgrading with digestate liquid is -\$65,240 (Table 3-11) and compares favorably to a water scrubbing system which has an NPV of -\$67,364. They both result in negative NPV. It should however be noted that there was no cost associated with the digestate liquid.

Table 3-11: Cash Flow for Digestate Liquid System.

	Depreciable capital [MMS]	Fixed capital investment [MMS]	Working capital [MMS]	Depreciation [MMS]	Net earnings [MMS]	Cash flow [MMS]	Net present value (NPV) [MMS]	Cumulative NPV [MMS]
2022	0.0128	0.0128	0	0	0	-0.00686	-0.00754	-0.00754
2023	0.0192	0.0192	0.0016	0	0	-0.0119	-0.0119	-0.0194
2024	0	0	0	0.00458	-0.012	-0.00746	-0.00678	-0.0262
2025	0	0	0	0.00785	-0.0158	-0.00799	-0.0066	-0.0328
2026	0	0	0	0.0056	-0.0136	-0.00799	-0.006	-0.0388
2027	0	0	0	0.004	-0.012	-0.00799	-0.00546	-0.0443
2028	0	0	0	0.00286	-0.0108	-0.00799	-0.00496	-0.0492
2029	0	0	0	0.00286	-0.0108	-0.00799	-0.00451	-0.0537
2030	0	0	0	0.00286	-0.0108	-0.00799	-0.0041	-0.0578
2031	0	0	0	0.00143	-0.00942	-0.00799	-0.00373	-0.0616
2032	0	0	0	0	-0.0053	-0.0053	-0.00225	-0.0638
2033	0	0	-0.0016	0	-0.0053	-0.0037	-0.00143	-0.0652

The optimistic scenario yielded a NPV of \$19,312, whereas the pessimistic scenario resulted in a negative NPV of −\$129,580.

3.6- Discussion

The objective of this study was to assess the feasibility of utilizing digestate liquid (DL) as an alternative to water for carbon dioxide absorption in biogas upgrading. This involved both an experimental evaluation of CO₂ absorption at varying temperatures and a techno-economic analysis, with the aim of using biomethane for electricity generation. This study provides insights into the feasibility and limitations of employing DL for biogas scrubbing.

The experimental findings for digestate liquid and water as CO₂ absorption absorbent indicated that absorption varies with temperature and time interval. The highest absorption of CO₂ in digestate liquid occurred at 4°C, aligning with the reference solubility curve of water. The pH method yielded conflicting results, showing minimal absorption across all three temperatures.

Given that the volume method aligns with theoretical solubility trends, this study primarily relies on this result; however, further experimental validation is necessary.

The discrepancy between volume-based and pH-based calculations CO₂ absorption measurements arises from the intrinsic equilibrium processes governing CO₂ dissolution in water. As detailed by Stumm and Morgan in *Aquatic Chemistry* (Chapter 4), dissolved CO₂ exists in several equilibrium forms: molecular CO₂(aq), carbonic acid (H₂CO₃), and its dissociation products, bicarbonate (HCO₃⁻) and carbonate (CO₃²⁻). The pH-based method relies on detecting the dissociated forms; however, a substantial portion of absorbed CO₂ may remain in its undissociated molecular form, particularly in buffered solutions, as discussed in Section 4.4 of the *Aquatic Chemistry* textbook. Consequently, the volume-based method, which captures total CO₂ uptake regardless of speciation tends to yield higher values than those derived from pH measurements.

Although DL showed potential and has been previously utilized (Yan et al., 2013), its performance was inferior to water's, particularly at 22°C and 34°C and at 30 minutes time interval. This disparity may be attributed to impurities present in DL, which could hinder absorption efficiency. Improving the absorption capacity of DL has been explored in prior studies (He et al., 2017), but its potential phytotoxicity must be considered if the digestate is intended for agricultural applications. In addition, more experiments should be carried out to ascertain the amount of CO₂ and the saturation capacity of CO₂ as this experiment was limited in scope.

The process model developed in BioSTEAM, yields 93.03% CO₂ removal efficiency, with a calculated scrubber height of 3.27 m nearly twice the height for water scrubbing reported in chapter 2.

The system's TEA indicates that sorption using DL is not financially viable under the conditions used in this study, with an NPV of -\$65,240 over a 10-year project lifespan. However,

the use of DL was more economically favorable compared to water due to the increased scrubber height required to achieve the desired purity, which subsequently raised equipment costs.

Sensitivity analysis identified electricity sales price as the most influential factor affecting NPV, highlighting the economic viability's dependency on market conditions.

3.7- Conclusions

This study investigated digestate liquid (DL) as a potential alternative absorbent to water for carbon dioxide (CO₂) removal in biogas upgrading. Through experimental evaluation and techno-economic modeling, the CO₂ absorption capacity of DL was assessed in comparison to water at temperatures of 4°C, 22°C, and 34°C. A process model was developed in BioSTEAM to evaluate system performance and economic viability.

The experimental results demonstrated that CO₂ absorption in DL is temperature-dependent, with the highest absorption occurring at 4°C. pH-based measurements of sorption showed minimal absorption across all temperatures, likely due to its measurement of CO₂ dissociation rather than direct CO₂ solubility. At longer absorption periods (1440 minutes), some CO₂ absorption occurs at 22°C and 34°C, suggesting time-dependent absorption behavior.

The process model designed achieves a simulated 93.03% CO₂ removal efficiency, however the required scrubbing column for DL was significantly taller than that of water, increasing system costs. The techno-economic analysis showed that DL-based scrubbing is not economically viable even as no cost was associated with the DL with a negative NPV of -\$65,240. However, the NPV is better than that of water.

Sensitivity analysis identified electricity price as the most significant factor influencing economic outcomes, emphasizing the dependency of economic feasibility on market conditions. Although DL presents an environmentally sustainable alternative, its absorption efficiency and economic performance require further optimization. Future research should focus on enhancing its absorption capacity, reducing equipment costs, and exploring its potential co-benefits to improve its viability for large-scale biogas upgrading.

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Chapter 4

TECHNO-ECONOMIC ANALYSIS OF BIOGAS UPGRADING IN NIGERIA

4.1- Abstract

The feasibility of biogas production and upgrading in Nigeria was evaluated, focusing on compressed biomethane gas (CBG) as a substitute for liquefied petroleum gas (LPG). A techno-economic analysis was carried out on the biogas upgrading system (water scrubbing), chosen for its cost-effectiveness and environmental benefits. This study assumed biogas production from a 60-cow agro-pastoral farm, with biogas composed of 60% methane and 40% carbon dioxide by volume, and an expected carbon dioxide removal efficiency of 90%. The analysis was performed using the BioSTEAM simulation system, incorporating equipment costs, operational expenses, and market pricing for CBG.

Results indicate that biogas upgrading to CBG is not economically viable under the base case scenario, with an estimated daily biogas yield of 46.49 m³/day yielding a negative net present value (NPV) of ₦10,253,874. Sensitivity analysis reveals that profitability strongly depends on biogas production cost, herd size and CBG sales price highlighting the necessity of a minimum scale for financial feasibility. In addition, for the scenario to be profitable a minimum biogas production cost should be about ₦398.5/m³. Grants, funding and subsidies can help this system be profitable and scalable in Nigeria.

4.2- Introduction

The population of Africa faces a significant energy crisis, with lacking access to essential energy resources such as electricity and clean cooking fuel (González-Eguino, 2015). Over 80% of African households depend on traditional biomass fuels for cooking, such as charcoal and firewood. This reliance accelerates deforestation and has significant health consequences, leading to an estimated 3.2 million premature deaths yearly from indoor air pollution (World Health Organization, 2024). Nigeria faces a severe energy crisis, with millions without access to electricity and clean cooking fuels (Somoye, 2023). Despite abundant organic waste, the country remains reliant on fossil fuels and traditional biomass, exacerbating environmental degradation and health risks. Biogas, produced through the anaerobic digestion of organic waste, presents a sustainable alternative that can help address this energy crisis, but challenges such as infrastructure gaps, financial constraints, and limited awareness hinder its adoption. Although Nigeria has vast energy potential, the country continues to struggle with power shortages and breakages, due in part to inadequate infrastructure and policy implementation (Adebayo et al., 2024).

Meanwhile, large volumes of organic waste accumulate annually, contributing to environmental degradation (Olugbemide & Likozar, 2022), as about 32 million tons of solid waste are generated per year about which 50% is organic waste (Ogunnaike, 2024) such as animal waste, food scraps, and agricultural residues (Lindkvist et al., 2019), which can be used to produce biogas.

Biogas is an alternative renewable energy source that can reduce dependence on fossil fuels in Nigeria. It can be used for multiple applications, including cooking, heating and electricity generation. When upgraded (i.e., removing impurities), it can be used as fuel for cars and generators (Nevzorova & Kutcherov, 2019).

Biogas can be compressed into gas cylinders and used as a substitute for LPG in homes, reducing a major limitation of the onsite use of biogas. However, the main challenges associated with the commercialization of biogas include its low energy content per unit volume, the difficulty in compressing it, and the predominance of small-scale production systems (Olugasa et al., 2014).

If properly utilized, biogas can create an energy source in communities. However, there are additional barriers to its adoption including infrastructural challenges (the required number of animals to produce feedstock), less awareness, inadequate waste collection, unavailability of locally made digesters and skilled operators for the digesters (Nevzorova & Kutcherov, 2019).

Although many African countries possess favorable geographic conditions for biofuel production, progress in this sector has remained slow (Ishola et al., 2013). Given the potential of biogas in addressing Nigeria's energy crisis, there is a need to assess the technical and economic feasibility of compressed and upgraded biogas as an alternative energy source to liquified petroleum gas in Nigeria, laying out the key barriers to its adoption, including technical, economic, and social challenges, and conduct a techno-economic analysis of biomethane (compressed biomethane gas) as a viable liquified petroleum gas substitute.

4.3- Biogas Technology: An Overview

4.3.1- What is Biogas?

Biogas is a renewable fuel produced from the anaerobic digestion of organic matter by microorganisms. This process occurs in a sealed, oxygen-free environment known as an anaerobic digester (i.e. Scarlat et al., 2018). It is a sustainable energy source with a wide range of

input materials, including landfills, wastewater treatment sludge, animal manure, and energy crops. The composition of raw biogas is influenced by the characteristics of the substrate and the performance of the biogas production process (Rafiee et al., 2021).

Biogas consists of combustible methane CH_4 (60–70%), which is the primary gas for energy production, carbon dioxide CO_2 (30–40%), and small amounts of other gases like hydrogen sulfide H_2S (Roopnarain & Adeleke, 2017). Factors such as pH, temperature, substrate type, loading rate, hydraulic retention time (HRT), and the carbon-to-nitrogen (C/N) ratio influence the efficiency of biogas production.

Biogas production in anaerobic digestion occurs through four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Different bacterial and archaeal communities work together in a syntrophic relationship to produce methane. In hydrolysis, complex carbohydrates, fats, and proteins are broken down into monomeric forms by exoenzymes and bacterial celluloses. During acidogenesis, these monomers are further degraded into short-chain acids, such as acetic acid, propionic acid, butyric acid, isobutyric acid, valeric acid, isovaleric acid, carbonic acid, as well as alcohols, hydrogen, and carbon dioxide. These short-chain acids are converted into acetate, hydrogen, and carbon dioxide in acetogenesis. Methanogens transform the intermediates created into carbon dioxide and methane during the final stage. Hydrogen-induced carbon dioxide reduction accounts for nearly one-third of the methane production process (Rajendran et al., 2012).

4.3.2- Biogas Technology in Africa

Different African countries have implemented biogas projects to provide sustainable energy solutions in reaction to the region's energy challenges. Governments, non-governmental organizations (NGOs), and private enterprises have promoted small-scale household digesters and

large-scale industrial biogas plants. Programs such as the Africa Biogas Partnership Program (ABPP) and the National Biogas Program of Ethiopia have demonstrated biogas technology's potential in rural and urban communities (Kamp & Bermúdez Forn, 2016).

Despite these efforts, biogas adoption remains limited due to technical, economic, and infrastructural barriers. The success of biogas technology depends on the availability of feedstock, type of digester, and local expertise, all of which influence the feasibility of implementation.

One of Africa's most widely used feedstocks for biogas production is cattle manure, mainly due to the high number of livestock in rural communities. In many African cultures, cattle ownership is an economic asset and a symbol of social status and wealth (Austin & Morris, 2012). This makes cattle dung an accessible and socially acceptable feedstock for anaerobic digestion. Additionally, manure-based biogas digesters provide a dual benefit by offering clean energy while reducing environmental pollution from unmanaged livestock waste.

4.3.3- Types of Biogas Anaerobic Digesters in Africa

Biogas digesters were initially introduced in Africa during the 1950s, with early installations recorded in South Africa and Kenya. The adoption came later to other African countries like Tanzania which began in 1975 and South Sudan in 2001 and has been adopted in other countries such as Nigeria, Burundi, Ghana, Guinea, Namibia, Lesotho, Botswana, Burkina



Figure 4-1: Balloon Digester in Uganda. (Orskov et al., 2014)

Faso, Ethiopia, Uganda, Cote d'Ivoire (Amigun & von Blottnitz, 2010). The most used types of digesters in Africa include fixed-dome, floating-drum, and balloon (Figure 4-1) digesters (Rajendran et al., 2012). Each type has advantages and limitations, as summarized in Table 4-1. Several important factors are relevant when selecting the type of digester to be used: the availability of feedstock, water supply, energy needs, local materials and labor, and the commitment level to efficiently operate and maintain the biodigester (Rupf et al., 2016).

Table 4-1: Digester Types Available in Africa and Their Characteristics Adapted from Abubakar (2022).

Parameter	Fixed dome digester	Floating-drum digester	Ballon digester
Life span	20 years or more	15 years	2-5 years
Size	5-200m ³	5-15m ³	4-100m ³
Investment costs	Low	High	Low
Gas pressure	60-130 mbar	20 mbar	Low gas pressure
Skill required	High	High	Low
Methane emission	High	Medium	Low

While digester type plays a critical role in biogas production, their efficiency depends on the quality and quantity of available feedstock. In Sub-Saharan Africa, biogas feedstock availability varies widely between rural and urban communities, influencing the feasibility of large-scale adoption.

4.3.4- Feedstock for Biogas Production

The feedstocks available to Sub-Saharan African (SSA) households for biogas production vary based on location and socio-economic status. In rural areas, agricultural feedstocks like

livestock manure, crop residues and municipal sources like night soil are commonly used. In contrast, urban households primarily rely on domestic sewage and the organic fraction of municipal solid waste (OFMSW) as their main feedstock (Rupf et al., 2016). However, domestic digesters in SSA mainly use animal excreta for energy production, cooking, and lighting (Mwirigi et al., 2014). The biogas yield per ton of different feedstocks is shown in Table 4-2, illustrating the variation in gas production efficiency.

Table 4-2: Biogas Yield from Potential Feedstock (Abubakar, 2022).

Type of feedstock	Biogas production (m ³ /ton fresh matter)
Cattle dung	55-68
Chicken	126.0
Litter/dung	826-1200
Fat	110
Food waste	74
Fruit waste	56
Horse manure	200-220
Maize silage	101.5

While biogas can be used on site, the opportunity exists to purify and compress the biogas, selling it as a replacement for LPG. This requires two processes, upgrading and compression.

4.3.5- Biogas Upgrading

Raw biogas contains methane (CH₄), ranging from 55% to 65%, and carbon dioxide (CO₂), which constitutes approximately 35% to 45%. Additionally, it contains trace amounts of nitrogen (N₂) (0–3%), oxygen (O₂) (0–2%), hydrogen (H₂) (0–1%), hydrogen sulfide (H₂S) (0–1%), and ammonia (NH₃) (0–1%) (Mohammadpour et al., 2025) which reduce its energy value. To enhance its usability, biogas upgrading is performed to increase CH₄ content, remove

contaminants (Bauer et al., 2013), increase compressibility and allow for usage as vehicle fuel or for injection into the pipeline grid. Different types of upgrading techniques are explained below.

4.3.5.1- Cryogenic Upgrading

In this upgrading method, impurities are separated from biogas by cooling the biogas under pressure, leading to the separation of CH₄ and CO₂ (Hoyer et al., 2016). Biogas is condensed into liquid after cooling to a temperature of -162°C, it produces CO₂ and CH₄ as byproducts in their purist form (Ahmad et al., 2018). An advantage of this upgrading technique is the liquefaction of CO₂ (Hoyer et al., 2016), and it does not require drying of biogas before upgrading. However, it requires high energy consumption (Golmakani et al., 2022).

4.3.5.2- Membrane Separation

Biogas upgrading using membrane technology uses the fact that gases have different permeability through a membrane (Vrbová & Ciahotný, 2017). During the separation of CO₂ and CH₄ in biogas upgrading, the membrane (polyimides, liquid membrane) preferentially allows the transport of impurities (Kárászová et al., 2015). Pressure in a membrane separation is classified as high and low, with high ranging from 8-20 bar (Gomes et al., 2019). Membrane technology continues to improve to gain better selectivity and higher permeability to achieve better separation and lower methane slip.

4.3.5.3- Pressure Swing Adsorption (PSA)

PSA utilizes differences in the physical properties of gases to selectively adsorb specific components under varying pressure conditions (Sánchez-Martín et al., 2023). The basic principle is that raw biogas is compressed to an elevated pressure and then fed into an adsorption column, which retains the carbon dioxide but not the methane. When the column material is saturated with carbon dioxide, the pressure is released, and the carbon dioxide can be desorbed and led into an off-gas stream. Several columns are needed for continuous production as they will be closed and opened consecutively (Svensson & Hulteberg, 2013). The typical setup contains four adsorption columns operated in parallel in 4 step cycles (the Skarstrom cycle), allowing for continuous operation. Adding more columns and optimizing advanced flow between the columns is a way to increase separation and potentially energy efficiency.

4.3.5.4- Amine Scrubbing

Amine scrubbing is a physical absorption scrubbing technique that uses a reagent that chemically binds to the CO₂ molecule, removing it from the biogas. The chemical reaction exhibits strong selectivity due to the high affinity of the chosen solvent for CO₂, resulting in the effective bonding of unwanted gas components with the scrubbing liquid. Commonly used amine-based solvents include monoethanolamine (MEA), diethanolamine (DEA), N-methyl-diethanolamine (MDEA), piperazine (PZ), and 2-amino-2-methyl-1-propanol (AMP), as well as various combinations of these compounds (Haider et al., 2022).

4.3.5.5- Organic Physical Scrubbing

This type of scrubbing involves physical absorption, using solvents such as polyethylene glycol-based solvents with a high affinity for CO₂ to absorb the gas (Golmakani et al., 2022).

Henry's law explains the absorption occurring in these organic physical scrubbers, like the absorption in a water scrubber. This results in the recirculating volume of the solvent being much lower when using the organic solvent, and thus, the required column diameter is much smaller. The biogas is compressed to a pressure of 7-8 bar, cooled, and then fed to the bottom of an absorption column. Here, CO₂ is absorbed into the liquid phase.

Genosorb is the most used solvent for biogas upgrading processes among organic physical scrubbers. The solvent consists of a mixture of dimethyl ethers and polyethylene glycol (Bauer et al., 2013; Ernst et al., 1990).

4.3.5.6- Water Scrubbing

Water scrubbing uses the higher solubility of CO₂ and H₂S in water than CH₄ (Islamiyah et al., 2015) to absorb impurities. The CO₂ in raw biogas also reacts with water, forming carbonic acid (Islamiyah et al., 2015) as shown in Equation 4.1.



It produces high methane purity (Qian et al., 2023) and is a relatively easy method of biogas upgrading, in which pressurized water is used as an absorbent. The raw biogas can be fed directly at storage pressure or can be compressed and fed to the scrubber column from the bottom, while pressurized water is sprayed through nozzles from the top of the column. The absorption process is thus a counter current one, which dissolves CO₂ as well as H₂S in water

(Islamiyah et al., 2015). Water scrubbing can also be used for selective removal of H_2S by further increasing the pressure of the biogas.

Among various biogas upgrading methods, Water Scrubbing emerges as the most cost-effective, environmentally friendly, and accessible technique for biomethane production. While alternative methods like PSA, membrane separation, and amine scrubbing offer higher efficiency, their high costs and energy demands make them less suitable for application in developing economies like Nigeria.

Given the advantages of low-cost operation, no chemical usage, and effective removal of CO_2 and H_2S , water scrubbing is the chosen upgrading method for this study.

4.3.6- Compressing Upgraded Biogas

To transport biogas to places of use other than the point of production, it can be stored in gas storage tanks with a pressure of about 5 bar or commercial gas cylinders of up to 200 bar (Kalita et al., 2023) to 240 bar (Yadav & Sircar, 2022). The pressure chosen depends on the end use of the biogas (Nallamothe et al., 2013). Compressed gas cylinders are a familiar product in many parts of Nigeria, and so compressed biogas should be a compatible product for many end users.

4.3.7- Challenges in Biogas Adoption in Nigeria

Although biogas offers a sustainable energy alternative, its adoption in many African countries, including Nigeria, remains limited. Despite abundant organic waste and growing energy needs, technical, financial, and socio-political barriers hinder its widespread implementation (Roopnarain & Adeleke, 2017). As discussed below, the key obstacles to biogas

adoption can be categorized into financial, infrastructural, technical, socio-cultural, and policy-related challenges.

4.3.7.1- Financial Barriers

One of the most significant challenges in biogas adoption is the high upfront investment cost required for digester construction and maintenance. Many rural households in Nigeria and other African nations rely on subsistence farming and lack access to financial support for biogas systems (Mwirigi et al., 2014). The average Nigerian in rural communities relies on subsistence farming for livelihood, but the income generated from such operations is insufficient to afford a biogas plant. Digesters require capital for construction and installation, making them unaffordable for low-income communities (Roopnarain & Adeleke, 2017). Consequently, one of Nigeria's most significant barriers to adopting and developing bioenergy technologies is inadequate financing, as loan facilities and government incentives for farmers are insufficient (Odejobi et al., 2024). Unlike fossil fuels, biogas adoption does not receive significant government subsidies or incentives, making it less attractive to investors and rural communities (Nevzorova & Kutcherov, 2019).

4.3.7.2- Infrastructural and Technical Constraints

The adoption of biogas technology depends on economic factors, technical feasibility, and infrastructure availability. Many African countries lack the necessary infrastructure for biogas collection, processing, and distribution, which limits scalability.

Biogas production, unlike other renewable energy sources, can be carried out at small and large scales both in remote and urban locations (Mwirigi et al., 2014). Most domestic livestock

are raised through extensive farming and pastoral systems, with only a small proportion managed under intensive or semi-intensive farming systems (Adeoti et al., 2014).

The major feedstock used for anaerobic digestion in Africa is livestock (Cow dung) waste. The method of animal rearing commonly observed in Nigeria does not allow for the economic utilization of animal waste. Allowing animals to roam freely in search of pasture is not conducive to the effective implementation of biogas technology (Attanda M.L et al., 2014). The free-range system is also practiced in some areas, allowing movement of the animals during the day and penning them at night preventing collection of the manure (Roopnarain & Adeleke, 2017). Urban areas also struggle with waste segregation. Household and municipal waste is often poorly sorted, reducing the efficiency of urban biogas systems (Nevzorova & Kutcherov, 2019).

Another contributing factor is water; the digester requires mixing water and feedstock, but a limitation in water availability poses a major constraint (Mwirigi et al., 2014).

4.3.7.3- Socio-Cultural and Awareness Challenges

Many rural households do not understand biogas technology, leading to low adoption rates due to misconceptions, social resistance, and a lack of education on its benefits.

In addition, socio-economic characteristics, such as the occupation of the family's breadwinner and the household income level, play a role in adopting biogas (Mwirigi et al., 2014). Low energy efficiency of biogas as utilization compared to fossil fuel, the presence of hydrogen sulfide, which corrodes engines and pipelines (Mukumba et al., 2016), lack of interest and unwillingness to change all play a role, all these factors contribute to the low adoption of anaerobic digesters in Africa.

4.3.8- Opportunities for Implementing Biogas in Nigeria

Biogas has the potential to provide sustainable energy while reducing reliance on fossil fuels, but its adoption remains limited due to financial, infrastructural, socio-cultural, and policy-related barriers. To increase biogas usage, a combination of financial incentives, technological improvements, awareness campaigns, and policy interventions is required. The following strategies outline the key solutions needed to enhance biogas adoption and commercialization in Nigeria and across Africa.

4.3.8.1- Financial Support and Incentives

Biogas adoption is hindered by high upfront investment costs and limited access to financing. Providing targeted financial incentives can significantly boost adoption, especially in rural communities. Financial assistance by the government and institutions to small-scale farmers and families can consist of loans with low interest rates, which will mobilize funds for the construction of digesters. The promotion of biogas technology should not only market biogas but also digestate. In addition, micro-financing institutions should be invited into the industry (Mwirigi et al., 2014). The government can also explore new models for providing carbon credits for rural households.

The rising price of LPG in Nigeria (Figure 4-2) provides an opportunity for biogas to be a cost-effective alternative, and high inflation (Figure 4-3) could help accelerate capital expense (CAPEX) recovery for biogas projects by increasing nominal revenues and reducing the real value of future repayments.

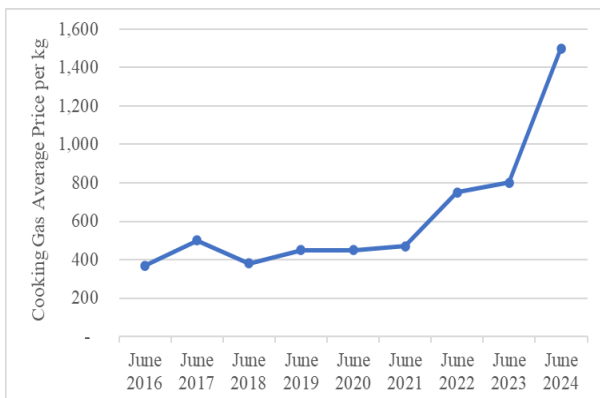


Figure 4-2: Average Price of LPG in Nigeria from 2016-2024. Adapted from Intelpoint (2024).

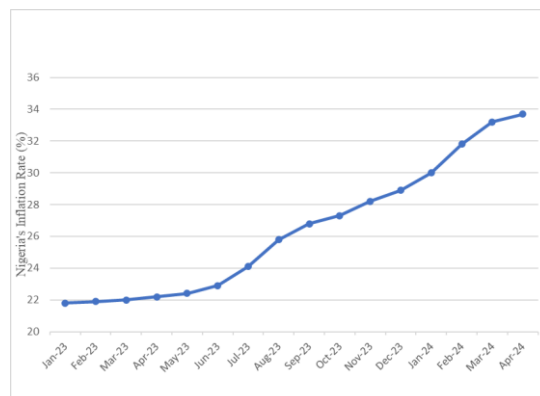


Figure 4-3: Inflation Rates in Nigeria. Adapted from Stears (2024).

4.3.8.2- Infrastructure and Technological Advancements

Inadequate infrastructure, poor waste collection systems, and lack of technical expertise hinder the efficient operation of biogas digesters. Investing in infrastructure and technical capacity will improve efficiency and reliability.

Increased awareness, education, and outreach on the proper use, maintenance, and repair have the potential to enhance the adoption and continual usage of biogas. Network formation of stakeholders with the communities can help improve adoption (Kamp & Bermúdez Forn, 2016). One example is the Ethiopian National Biogas Programme (NBPE) with the first stage of implementation launched in 2008-2013 (Kamp & Bermúdez Forn, 2016). Youth in the community should be integrated into this network to facilitate proper implementation and learning. A program involving the Africa Biogas Partnership Program (ABPP), conducted in Kenya, Tanzania, and Uganda, was established to aid the promotion of digesters in rural houses in Africa using the RE-AIM framework (Reach, Effectiveness, Implementation, Adoption, and Maintenance). With the main aim of creating a viable digester market, they were able to reach a

target of over 5 per cent by 2017 (Clemens et al., 2018). In Nigeria, established organizations such as the Biogas Practitioners Association of Nigeria (BPAN) and the Nigeria Biogas Association (NBA) have been actively operating for over five years (Nwankwo et al., 2024).

Technologies, such as biogas upgrading and compression, could encourage the expansion of biogas production by creating new income streams for digester owners.

4.3.8.3- Policy and Institutional Support

Promoting renewable energy has become a feasible strategy for mitigating energy problems in Africa (Jan & Akram, 2018). Government assistance, outreach and communications (Roopnarain & Adeleke, 2017), and incentives like soft loans and subsidies (Akinbami et al., 2001) can increase the adoption of digesters. Commercial banks and private entities could also issue loans, which can be implemented under policies and government regulations. Tax duty-free status of imported prefabricated digesters would be one approach to stimulating the biogas sector (Clemens et al., 2018).

Other barriers to adopting biogas are weak environmental policies and a poor institutional framework, such as a lack of program to create awareness of the use and benefit of biogas and governmental support. Supporting policies like renewable energy feed-in tariffs (FIT), tendering, and fiscal incentives exist (Kemausuor et al., 2018), but this does not happen in all African countries. Appropriate policy is required for the successful implementation of digesters in Africa. Currently, there is no policy or legal framework for biogas production and utilities in Nigeria (Nwankwo et al., 2024). There is potential for both private and public institutions to develop their own policies to promote the efficient use of energy (Odejobi et al., 2024). A significant challenge to the implementation of biogas technology in Nigeria is the inadequate grid network. The grid

infrastructure in Nigeria, as well as in other parts of Africa, lacks robustness, creating substantial difficulties for existing power plants. This also limits the grid's ability to integrate and access power from renewable energy sources (Odejobi et al., 2024).

4.3.9- Economic Sustainability

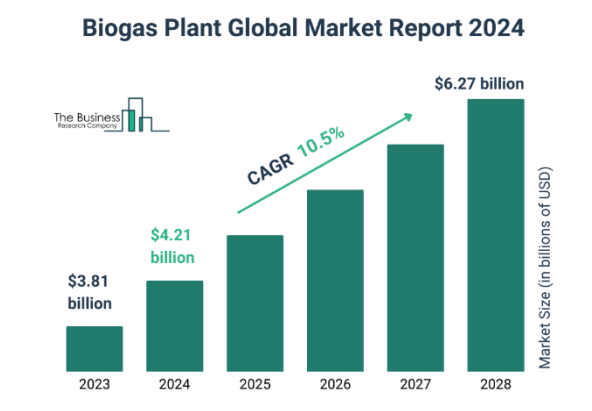


Figure 4-4: Projected Biogas Market Size Growth.
(The Business Research Company, 2024)

Generating energy from biogas offers a valuable opportunity for sustainable rural development. It boosts the farm's income from traditional activities and reduces the energy sector's overall environmental impact (Torquati et al., 2014). As an alternative to traditional biomass energy systems, biogas uses waste to produce energy, reducing the monetary cost and reliance on purchasing firewood, kerosene

or LPG. It also presents opportunities for economic sustainability as it provides a reliable source of energy for cooking, making cooking easy (Clemens et al., 2018). As shown in Figure 4-4, the global market of biogas is predicted to grow to a market size of \$6.27 billion, indicating colossal market potential. In addition, bio-slurry, a product from the digester, can be used as fertilizer (Clemens et al., 2018), as it has been seen to increase the production of crops and as a replacement for chemical fertilizers (Mengistu et al., 2015). Biogas used as fertilizer has potential to generate income and reduce the cost of inputs on the farm. Biogas technology has also played a role in job creation (i.e. Tanigawa, 2017).

4.4- Materials and Methods

Given the overall setting of Nigeria and Sub-Sahara Africa for biogas, biogas upgrading and compression for sale in transportable cylinders is a strategy that, if successful could play a role in enhancing biogas utilization, energy security and rural livelihood in the region.

4.4.1- A Description of The Overall Methodology

This study analyzed a hypothetical, representative Nigerian anaerobic digester that processes manure sourced from a cattle farm employing an agro-pastoral system, with a herd size of 60 cows, though herd sizes range from 20 to 100 (Food and Agriculture Organization, 2019). The system was simulated using BioSTEAM software, an open-source, object-oriented approach to model biorefinery processes (Cortes-Peña et al., 2020).

4.4.2- Assumptions

The facility is assumed to be served electricity by Ibadan Electricity Distribution Company (IBEDC), which is responsible for supplying power to Southwestern Nigeria (Oyo, Osun, Ogun, Kwara, parts of Niger, Ekiti and Kogi State) (Ibadan Electricity Distribution Company, n.d.) and is in Band B. The Nigeria's electricity pricing is categorized into five (A-E) different bands, based on the average number of hours of electricity supply within a day. Band B represents the category of customers that receive at least 16 hours of electricity per day. The biomethane is designated for use as compressed biomethane gas (CBG). For simplification, the biogas composition is assumed to consist of 60% methane (CH₄) and 40% carbon dioxide (CO₂) by volume.

The water scrubbing system is assumed to be a near-atmospheric water scrubbing process, selected due to its reliance on inexpensive water supply (Budzianowski et al., 2017), which is readily available in Nigeria. The absorber's height and diameter were adopted from an unpublished undergraduate study in Nigeria that focused on the development of a biogas scrubber. It was further assumed that the biomethane produced would achieve a 90% CO₂ removal efficiency (Noorain et al., 2019), and a 95% CH₄ recovery efficiency. This facility is assumed to be financed by personal savings and loans, and the construction schedule begins two years before the start of the business.

4.4.3- Base Case Scenario

In the base case scenario, the water scrubbing system operates under near-atmospheric pressure. The packed bed water scrubber is connected to a water tank at the top, supplying the water required for scrubbing, which is calculated using Equations 2-7 and 2-8. Biogas enters the scrubber from the bottom. After purification, the biomethane is compressed to a pressure of 200 bar using a compressor before being stored in a commercial gas cylinder (LPG tank) (Nallamothu et al., 2013).

Manure production was estimated based on the number of cows, assuming an average body mass of 450 kg per cow, with each producing 45 kg of manure per day (Netherlands East Africa Dairy Partnership, 2024). The manure contains total solids (TS) at 11.2% and volatile solids (VS) 61.5% of the total solids, Table 4-3 (Manyi-Loh et al., 2015). The biogas production rate is assumed to be 0.25 m³/kg of volatile solids (Hamid & Blanchard, 2018), biogas produced was calculated using Equation 2-5.

The biogas upgrading process utilizes a water scrubber with dimensions of 0.56 m in diameter and 0.87 m in height, derived from an earlier study conducted by the author (Akingbasote, 2021).

Table 4-3: Parameters for Calculating Biogas.

Parameter	Value	Unit
Manure yield	45	kg/day/cow
Total solids	11.2	%
VS	61.5	% of TS
Biogas production rate	0.250	m ³ /kg of VS

4.4.4- Model Development

BioSTEAM version 2.38.6, software, which uses Python 3.6 interface, was used to conduct the technical and economic analysis of this system, with modifications applied to its unit operations. Units are connected via pipe-notation, where the output of one-unit feeds into the input of another, collectively forming the system. The process flow diagram (Figure 4-5) shows the flow of biogas and water into the near atmospheric water scrubbing system, and the end use of the biomethane as compressed biomethane gas.

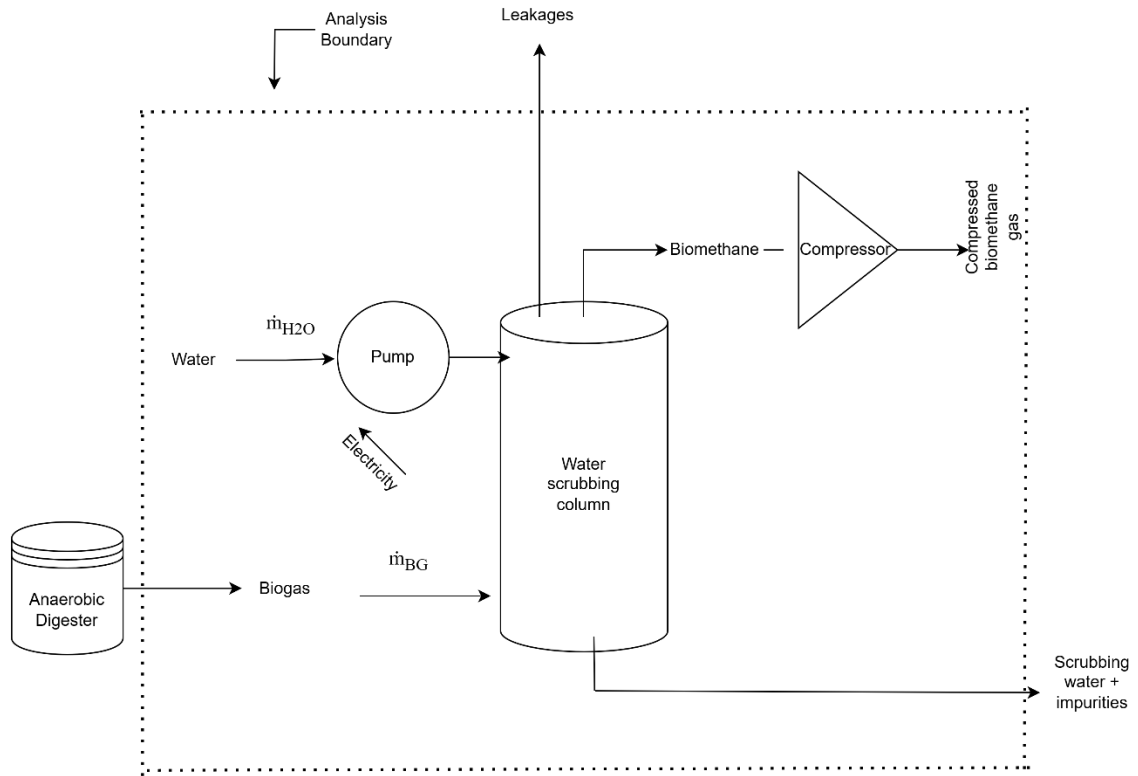


Figure 4-5: Process Flow Diagram of the Water Scrubbing System.

4.4.5- Economic Analysis

Economic analysis consisted of a discounted cash flow approach which was used to evaluate the profitability of the system by using the net present value (NPV) as the financial indicator as expressed in Equation 4-2. NPV is the difference between the present value of projected benefits and associated costs, measuring the project's financial viability. A positive NPV indicates a profitable and economically viable project, while a negative NPV indicates the project is not financially feasible (i.e. Adebimpe et al., 2002; Adeoti et al., 2000).

$$NPV = \sum_{t=0}^n \frac{(I_t - O_t)}{(1+r)^t} \quad (4-2)$$

Where:

NPV = Net present value (₦)

I_t = Discounted cash inflows (₦)

O_t = Discounted cash outflows (₦)

r = Discount rate (%)

t = time of the cash flow (years)

n = lifetime of investment (years)

4.4.5.1- Capital Costs

The cost of equipment was set based on market and industry pricing adjusted to reflect their actual market value in Nigeria. These modifications ensure that the model accurately represents the financial feasibility of the system within the local economic context. The equipment costs incorporated into the model are detailed in Table 4-4.

Table 4-4: Equipment Cost in Naira.

Equipment	Cost (₦)	Source
Pump	30,000	Assumption based on market price in Nigeria
Scrubbing Column	300,000	Assumption based on market price in Nigeria
Compressor	250,000	Personal communication with a compressor expert
Gas cylinder (50kg)	173,990	(Jumia, n.d.)

The Fixed Capital Investment (FCI) represents the total expenditure required for plant construction, covering costs related to equipment procurement, installation, piping, electrical systems, building construction, and other infrastructure expenses (Lawson et al., 2021). The FCI is estimated using the Lang factor method Equation 4-3 (i.e. Wild et al., 2024), with a 1.79 factor specific to biogas installation projects (Lawson et al., 2021).

$$FCI = L * \sum CE \quad 4-3$$

Where:

L = Lang factor (dimensionless)

$$\sum CE = \text{Sum of individual equipment (Naira)}$$

4.4.5.2- Operating Costs

The operating costs comprise of the total operational expenses associated with the system (i.e. Wild et al., 2024). Electricity costs in Nigeria were determined based on the tariff rates provided by the Ibadan Electricity Distribution Company Plc for Band B (Stears, 2024). Water cost was estimated at 3.5 ₦/kg as referenced from Victoria Garden City Water (n.d.). Labor costs were assumed to be ₦33,000, reflecting the minimum wage in Nigeria in the year 2024 (Juliet Nnaji, 2025). A detailed breakdown of the operating costs is presented in Table 4-5. The biogas production cost was calculated to be ₦512.75/m³ (\$0.35/m³), based on the biogas cost estimate provided by the International Renewable Energy Agency (IRENA) and converted to Naira using an exchange rate of \$1 = ₦1465.

Table 4-5: Assigned Prices for Utility and Operating Cost.

Parameter	Cost (N)	Unit
Water	3.5	₦/kg
Electricity	68.8	₦/kWh
Biogas production cost	512.75	₦/m ³
Labor	33,000	₦
Fringe benefit	40% of labor cost	
Maintenance	2% of FCI	
Land	0	

The plant is assumed to have a 10-year operational lifespan with 320 working days per year and a construction period of two years. The property tax, property insurance, supplies and administration fee are a percentage of the FCI.

The economic assumptions utilized in the BioSTEAM model are summarized in Table 4-6. Notably, income tax was excluded from the analysis, as it is a progressive tax dependent on

income levels. The techno-economic analysis also evaluated the Annual Operating Cost (AOC) excluding depreciation [USD/year], Variable Operating Costs (VOC) [USD/year], Total Capital Investment (TCI) [USD], Fixed Operating Costs (FOC) [USD/year], and Fixed Capital Investment (FCI), to identify the cost category with the highest financial burden.

Table 4-6: Economic Assumptions for Discounted Cash Flow Analysis.

Parameter	Value	Unit
Discount rate	10	%
Plant life	10	years
Depreciation	MACRS7	
Construction period	0.4 ,0.6	
Operating days	320	days
Working Capital over FCI	15	%
Lang factor	1.79	
Property tax	0.1	%
Property insurance	0.5	%
Supplies	20	%
Administration	0.5	%

4.4.5.3- Revenue

The end use of biomethane in this system is compressed biomethane gas (CBG), which serves as the sole source of revenue (a substitute for liquified petroleum gas LPG). The selling price of CBG was assumed to be ₦1,000/kg based on the current cost of LPG which is about ₦1250/kg and the need to sell for a lower value to be compete on the market. Additionally, the digestate produced as a byproduct of the anaerobic digestion process is returned to the farm at no cost.

4.4.6- Model Validation

The model was validated by testing the impact of several variables on the NPV and assessing whether it behaves as predicted, as shown in Table 4-7.

Table 4-7: Prediction of Model.

Parameter	Expected Impact on NPV
Increase in water cost	Negative
Decrease in water cost	Positive
Increase in CBG sales	Positive
Decrease in CBG sales	Negative
Increase in electricity cost	Negative
Decrease in electricity cost	Positive
Increase in CH ₄ recovery efficiency	Positive
Decrease in CH ₄ recovery efficiency	Negative
Increase in labor cost	Negative
Decrease in labor cost	Positive

4.4.7- Sensitivity Analysis

Sensitivity analysis was used to evaluate the impact of realistic variations in electricity costs, water costs, biogas production cost, number of cows and CBG sales price on the NPV. The herd size varied between 20 and 100 cows. Electricity costs were analyzed using the tariff rates for Band A and Band E in Nigeria. CBG sales prices are between 850-1250 ₦/kg, shown in Table 4-8. The effects of these variations will be assessed relative to the base case scenario to determine their influence on the financial viability of the system.

Table 4-8: Variables for Sensitivity Analysis.

Variable	Low Value	High Value
Number of cows	20	100
CBG sales price	₦850/kg	₦1250/kg
Water	₦2.8/kg	₦4.2/kg
Electricity cost	₦50.11/kWh	₦209.50kWh
Biogas production cost	₦366.25/m ³	₦644.60/m ³

4.4.8- Scenario Analysis

Two scenarios were compared an “optimistic” scenario, in which manure is sourced from 100 cows, with a CBG selling price of ₦1,250/kg, a water cost of ₦2.80/kg, an electricity cost of

₦50.11/kWh, and a biogas production cost of ₦366.25/m³ and a “pessimistic” scenario, in which manure is sourced from 20 cows, with a lower CBG selling price of ₦850/m³, a higher water cost of ₦4.20/kg, and an electricity cost of ₦209.50/kWh, and a biogas production cost of ₦644.60/m³.

4.5- Results and Discussion

This section presents the results of the techno-economic analysis of biogas upgrading using a water scrubbing system in Nigeria. The analysis evaluates biogas production and its conversion to CBG, enabling its use in households and enhancing the mobility of biogas as an energy source. The findings provide insights into the feasibility of implementing this upgrading technology, considering both technical performance and economic viability

4.5.1- Validation/Model Testing

The model was validated by varying the inputs to determine the effect on the NPV. The varied inputs are electricity cost, water cost, CBG sales price, labor cost and CH₄ recovery efficiency as shown in Table 4-9.

Table 4-9: Validation of Model.

Parameter	Expected Impact on NPV	Result of Test
Increase in water cost	Negative	✓
Decrease in water cost	Positive	✓
Increase in CBG sales	Positive	✓
Decrease in CBG sales	Negative	✓
Increase in electricity cost	Negative	✓
Decrease in electricity cost	Positive	✓
Increase in CH ₄ recovery efficiency	Positive	✓
Decrease in CH ₄ recovery efficiency	Negative	✓

Increase in labor cost	Negative	✓
Decrease in labor cost	Positive	✓

In all cases, the model behaved as expected, indicating that the model's output is likely to be reliable.

4.5.2- Base Case Mass and Energy Balance

Biogas production from 60 cows is estimated using the parameters outlined in Equation 2-1, yielding a production rate of 46.49 m³/day. The water for the scrubbing process is 0.69 kmol/hr, which is delivered to the water scrubber via a pump operating at an ideal power of 0.00471 horsepower (hp). The biogas, composed of 60% CH₄ and 40% CO₂ by volume, along with the water stream, enters the water scrubber column. As per BioSTEAM conventions, all streams are expressed in kmol/hr, with the inlet comprising 0.69 kmol/hr of water, 0.0484 kmol/hr of CH₄, and 0.0324 kmol/hr of CO₂.

Assuming a CO₂ removal efficiency of 90%, a CH₄ recovery efficiency of 95%, and 1% water retention in the biogas, the output streams are as follows: the biomethane stream consists of 0.0069 kmol/hr of H₂O, 0.046 kmol/hr of CH₄, and 0.00324 kmol/hr of CO₂; the scrubbing water stream contains 0.684 kmol/hr of H₂O, 0.00242 kmol/hr of CH₄, and 0.0292 kmol/hr of CO₂. The purified biomethane is subsequently compressed to a pressure of 200 bar using an electric compressor with a power requirement of 0.933 kW. The energy input for the system is utilized primarily for pumping water into the scrubber column and compressing the biomethane into LPG cylinders.

4.5.3- Base Case Mass Economic Analysis

The economic analysis of the system was conducted for a scale based on the base case scenario of 60 cows. The results indicate a negative Net Present Value (NPV) of -₦10,253,874, as shown in Table 4-10.

Table 4-10: Cash Flow for Base Case Nigerian Scenario.

Year	Depreciable capital [MM₦]	Fixed capital investment [MM₦]	Working capital [MM₦]	Depreciation [MM₦]	Net earnings [MM₦]	Cash flow [MM₦]	Net present value (NPV) [MM₦]	Cumulative NPV [MM₦]
2022	0.292	0.292	0	0	0	-0.292	-0.321	-0.321
2023	0.437	0.437	0.109	0	0	-0.547	-0.547	-0.867
2024	0	0	0	0.104	-1.64	-1.53	-1.39	-2.26
2025	0	0	0	0.179	-1.71	-1.53	-1.27	-3.53
2026	0	0	0	0.127	-1.66	-1.53	-1.15	-4.68
2027	0	0	0	0.091	-1.63	-1.53	-1.05	-5.73
2028	0	0	0	0.0651	-1.6	-1.53	-0.953	-6.68
2029	0	0	0	0.065	-1.6	-1.53	-0.866	-7.55
2030	0	0	0	0.0651	-1.6	-1.53	-0.787	-8.34
2031	0	0	0	0.0325	-1.57	-1.53	-0.716	-9.05
2032	0	0	0	0	-1.53	-1.53	-0.651	-9.7
2033	0	0	-0.109	0	-1.53	-1.43	-0.549	-10.3

The model is evaluated to determine the minimum biogas production cost at which the project becomes profitable, yielding a production cost of ₦398.5, as presented in Table 4-11.

Table 4-11: Cash Flow for Minimum Biogas Production Cost.

Year	Depreciable capital [MMN]	Fixed capital investment [MMN]	Working capital [MMN]	Depreciation [MMN]	Net earnings [MMN]	Cash flow [MMN]	Net present value (NPV) [MMN]	Cumulative NPV [MMN]
2022	0.292	0.292	0	0	0	-0.292	-0.321	-0.321
2023	0.437	0.437	0.109	0	0	-0.547	-0.547	-0.867
2024	0	0	0	0.104	0.0307	0.135	0.123	-0.745
2025	0	0	0	0.179	-0.0436	0.135	0.111	-0.633
2026	0	0	0	0.127	0.00738	0.135	0.101	-0.532
2027	0	0	0	0.091	0.0438	0.135	0.0921	-0.44
2028	0	0	0	0.0651	0.0698	0.135	0.0837	-0.356
2029	0	0	0	0.065	0.0698	0.135	0.0761	-0.28
2030	0	0	0	0.0651	0.0698	0.135	0.0692	-0.211
2031	0	0	0	0.0325	0.102	0.135	0.0629	-0.148
2032	0	0	0	0	0.135	0.135	0.0572	-0.0907
2033	0	0	-0.109	0	0.135	0.244	0.0941	0.00346

Based on the techno-economic analysis, the cost distribution across major economic indicators shows AOC and VOC constituting the largest portions, accounting for 45.7% and 45.3% of the total expenditure. In contrast, FCI, TCI, and FOC represent lower shares at 4.0%, 4.6%, and 0.4%, respectively (Figure 4-6). This highlights that operational expenses, rather than capital expenditure, contribute to the overall economic burden of converting biogas to CBG in Nigeria.

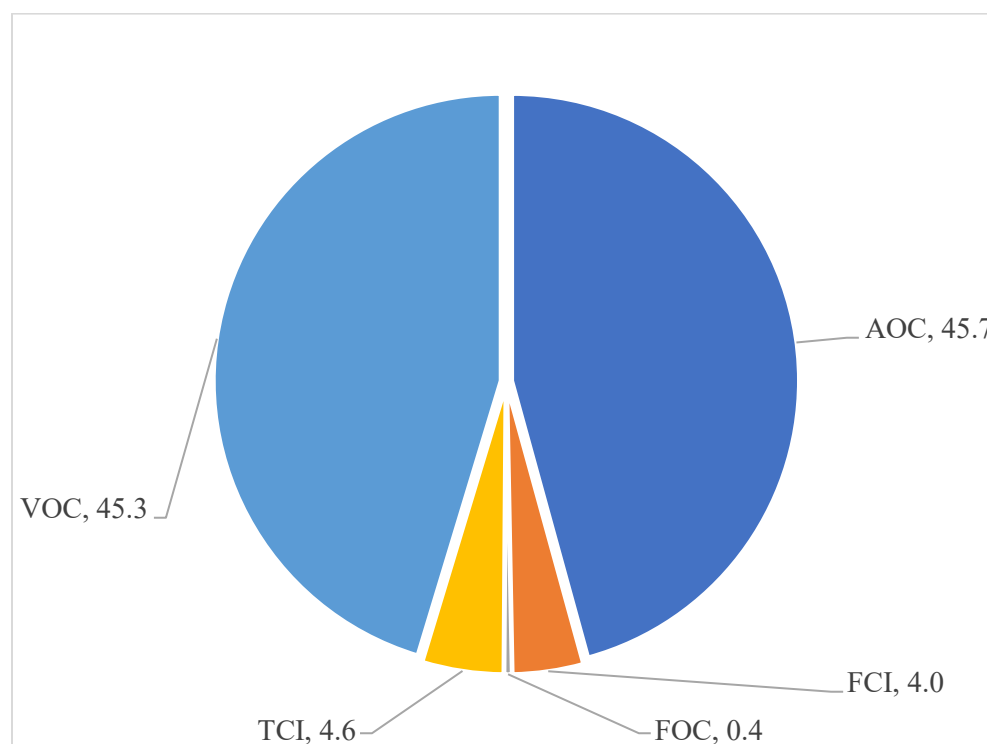


Figure 4-6: Breakdown of Biogas System Costs.

4.5.4- Sensitivity Analysis

The results indicate that the biogas production cost, CBG sales price and number of cows has the largest influence on NPV (Figure 4-7), suggesting that fluctuations in market price can greatly affect the system's profitability. The number of cows was expected to have a positive impact on the NPV. However, the opposite is the case, the economies of scale are not sufficient to compensate for the greater losses from the larger facility.

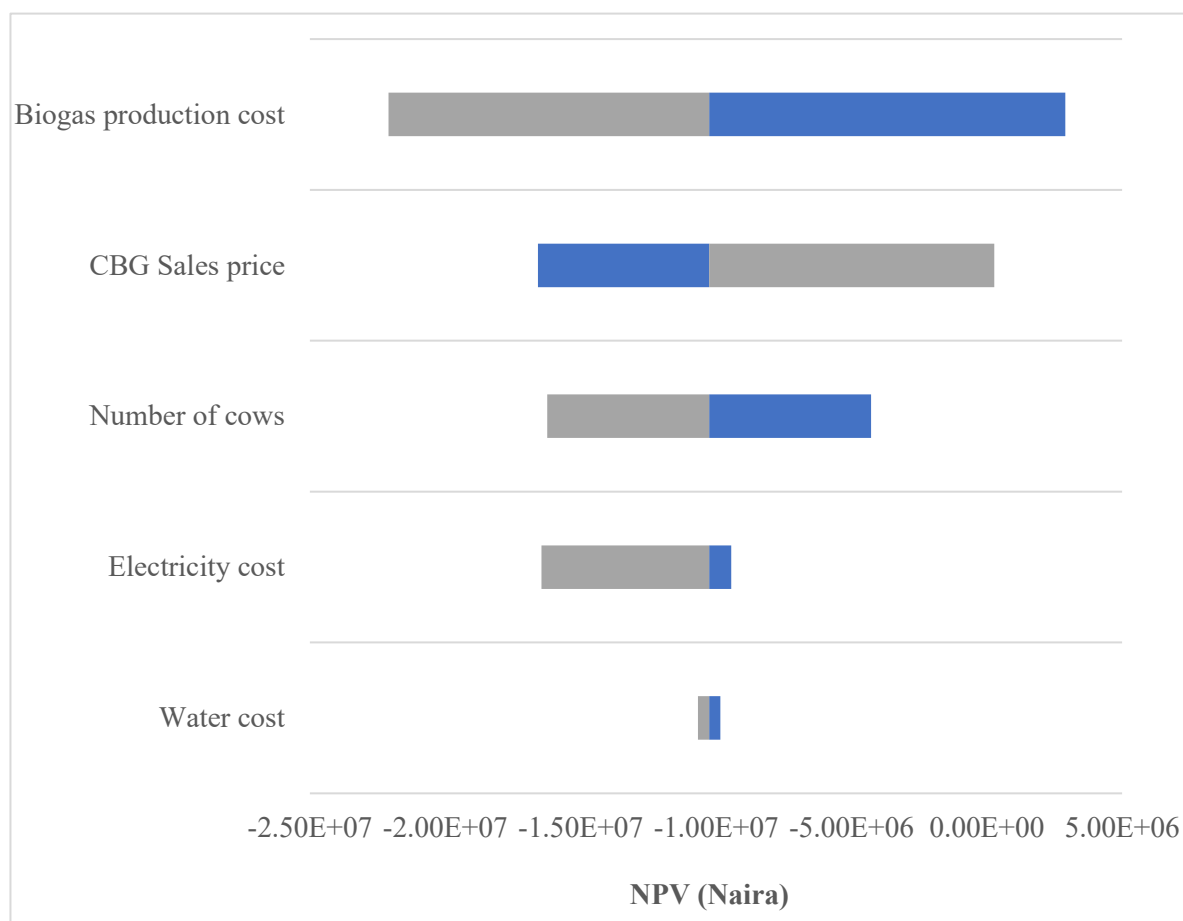


Figure 4-7: Sensitivity Analysis of the Model.

4.5.5- Scenario Analysis

The optimistic scenario with 100 cow manure, biogas production cost of 366.25 ₦/ m³, electricity cost of 50.11 ₦/kWh and CBG sales price of ₦1250 yields a positive NPV of 24,624,542, while the pessimistic scenario of 20 cows, biogas production cost of 644.60 ₦/m³, electricity cost of 209.5 ₦/kWh and CBG sales price of ₦850 yields a negative NPV of - ₦12,394,508. This shows that with less cost, a higher number of animals and sales price CBG, the system will be profitable.

4.6- Conclusions

This study assessed the feasibility of a biogas upgrading system using a techno-economic analysis based on water scrubbing technology for compressed biomethane gas (CBG) production in Nigeria as an alternate to liquid petroleum gas (LPG). Assessment of the economic, social and policy landscape in Nigeria suggests that while current conditions are not uniformly favorable to biogas development, new technologies and approaches such as upgrading and compression could play a role in increasing biogas production and use. The results show that biogas production from sixty cows, with upgrading to CBG, is not economically viable, yielding a negative NPV of - ₦10,253,874. However, sensitivity analysis revealed that variables such as the biogas production cost, sales price of CBG and number of cows play an important role in the profitability of the system. The method of farming in Nigeria also plays a role as all manure generated cannot be used for biogas production.

With a lower biogas production sales price of ₦398.5, the model can be profitable therefore grant, subsidies from the government can play an important role in the feasibility of this project, as cost tends to have high impact on the NPV. A combination of the optimistic scenario with possible input and output cost can also result in a positive NPV.

Ultimately, while biogas offers a promising path toward sustainable energy in Nigeria, strategic investments, policy support, and innovative approaches are required to overcome current barriers and maximize its potential for widespread implementation.

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Chapter 5

DISCUSSION AND CONCLUSIONS

5.1- Discussion

The techno-economic analysis of small-scale biogas upgrading in developing and developed economy, and the potential use of replacing water with digestate liquid was studied in this project. The findings suggest that biogas upgrading at a small scale is technically feasible but economically unviable without grants and support.

Chapter Two investigated a Pennsylvania case study for biogas upgrade, examining five biogas scenarios for a 100-cow farm. Except for the optimistic scenario, all other scenarios resulted in a negative NPV. The most economically limiting factors were biogas production costs and pipeline infrastructure, rendering options like pipeline injection unfeasible. Electricity generation using biomethane was more promising but would only be viable with financial incentives and high electricity sale prices. This reinforces the need for policy support and cooperative infrastructure models, especially in regions with high farm density.

Chapter Three investigated the use of digestate liquid (DL) as an absorbent for biogas upgrading, due to its availability as a by-product of the anaerobic digester. DL showed temperature and time-dependent CO₂ absorption characteristics, and the requirement for a significantly taller scrubbing column increased capital cost. Although no cost was attributed to DL itself, the system still results in a negative NPV, that is only slightly better than that of water scrubbing, highlighting the need for further optimization of absorption efficiency and equipment design. However, this area shows promise with further research, particularly in optimizing absorption properties and integrating co-benefits like fertilizer reuse.

Chapter Four extended the study to a developing economy (Nigeria). It explored biogas upgrading for compressed bottled gas (CBG) production from 60 cows using water scrubbing. The base case scenario proved economically infeasible, with biogas production cost as a factor greatly sensitive to the NPV. The model produced a negative NPV, but sensitivity analysis revealed that the system could become viable with a higher CBG sales price, reduced production costs, or increased herd size.

Although all the scenarios except the optimistic case, resulted in NPV, this outcome reflects only the economic dimension. It is important to also consider the broader social and environmental impacts. The incorporation of biogas into a community can lead to improved air quality, job creation, and a reduction in carbon emissions, which are beneficial not only to regions like Pennsylvania and Nigeria but also to the global environment. Rural areas in Nigeria with limited access to LPG could greatly benefit from biogas and biomethane as alternative cooking fuels. This transition has the potential to improve public health and reduce deforestation.

5.2- Limitations and Opportunities

Limitations

Some limitations were encountered during this study, and they include:

1. The study used BioSTEAM software for modeling. This software is built mainly for biorefineries but had to be configured for water scrubbing (absorption column), hence building the unit for the operation, unlike other process modeling tools with the column built into them. In addition, since BioSTEAM was built for biorefineries, the cost of equipment was tailored to large scale. These values were modified for the current study. Furthermore, the software did not permit the separation of electricity sales price and cost

(the amount sold to the grid and electricity cost), which hindered the ability to analyze the real effect of sales price of electricity back to the grid.

Despite these limitations, the model produced results that are consistent with published studies on water-scrubbing biogas upgrading. For example, the simulated methane recovery ranged around 93%, which aligns well with reported values of 89–95% in the literature. The accuracy of the model input was based on literature values, equations and market value.

2. This study shows the impact of temperature on absorption capacity in the use of digestate liquid for upgrading, hence reducing its usability in warmer climates or under uncontrolled temperatures. In addition, the variation between the method readings was wide, suggesting that additional careful assessment of sorption performance may be needed.
3. Lastly, the issue of lack of available data for the developing country was encountered in this study. For example, current and reliable costs of biogas production for Nigeria was not available, leading to the use of data not geographically bounded to Nigeria.

Opportunities for Further Research

Areas for further research include:

1. The role of policies and subsidies (financial incentives) should be investigated, as they tend to shift the economics towards profitability.
2. Further research into improving the absorption capacity of carbon dioxide in digestate liquid could lead to a solution for biogas upgrading.

5.3- Conclusions

The techno-economic feasibility of small-scale biogas upgrading systems across developing and developed economy and, the use of digestate liquid as an absorbent for CO₂ scrubbing was investigated in this project. Despite variations in geography, farm size, and energy infrastructure, a common conclusion emerged while that biogas upgrading is technically achievable with high CO₂ removal efficiencies, it remains economically unviable at small scales under current conditions.

In Pennsylvania, the high capital and operational costs associated with pipeline injection, combined with limited biogas volumes from small herds, result in consistently negative net present values (NPVs). Similarly, in Nigeria, CBG production is not feasible at the small farm level without significant financial support, due to factors such as manure collection, limited infrastructure, and high system costs.

The use of digestate liquid as an alternative absorbent showed promise and slightly improved economic performance compared to water, but also reveals limitations related to temperature sensitivity and system design complexity. The increased column height required for effective absorption significantly impacts capital costs, underscoring the need for further research and optimization.

Despite these economic challenges, this project highlights important opportunities. Biogas remains a sustainable and locally available energy resource particularly in agricultural settings, that with proper policy support, community-scale models, and innovative system designs, could play a meaningful role in transitioning toward low-carbon rural energy solutions. Strategic investments, financial incentives, and regional collaboration will be essential in unlocking the potential of biogas technologies in both developed and developing countries.

Ultimately, the findings underscore that while small-scale biogas upgrading is currently economically constrained, it holds significant promise if approached through cooperative frameworks, targeted subsidies, and continued technological refinement.

Appendix A

Electricity Cost

Table A-1: Electricity Cost for Utility Cost in Pennsylvania

Entity	Average price (Cents/kWh)
Duquesne Light Co	22.07
Tri-County Rural Elec Coop Inc (PA)	20.78
Pike County Light & Power Co	20.43
Wellsborough Electric Co	20.05
PPL Electric Utilities Corp	19.55
Pennsylvania Electric Co	19.07
UGI Utilities, Inc	18.68
Claverack Rural Elec Coop Inc	18.05
Citizens Electric Co - (PA)	17.41
Pennsylvania Power Co	17.29
Metropolitan Edison Co	17.24
Central Electric Coop, Inc - (PA)	17.05
PECO Energy Co	16.18
Sunrun Inc.	15.64
Tesla Inc.	15.34
SunPower Capital, LLC	15.28
Valley Rural Electric Coop Inc	15.01
West Penn Power Company	14.75
REA Energy Coop Inc	14.56
Northwestern Rural E C A, Inc - (PA)	14.3
Adams Electric Cooperative Inc	14.17
Bedford Rural Elec Coop, Inc	13.88
Somerset Rural Elec Coop, Inc	13.52
Sunnova	12.67
Borough of Chambersburg	10.49

Appendix B

Cash flows of Scenarios 2-5

The cash flow of the scenarios are listed in this section, and a table comparing the TCI, AOC, equipment cost of the five scenarios.

Table B-1: Scenario 2

	Depreciable capital [MMS]	Fixed capital investment [MMS]	Working capital [MMS]	Depreciation [MMS]	Net earnings [MMS]	Cash flow [MMS]	Net present value (NPV) [MMS]	Cumulative NPV [MMS]
2022	0.276	0.276	0	0	0	-0.148	-0.163	-0.163
2023	0.414	0.414	0.0345	0	0	-0.256	-0.256	-0.419
2024	0	0	0	0.0987	-0.154	-0.0548	-0.0498	-0.469
2025	0	0	0	0.169	-0.22	-0.0514	-0.0425	-0.511
2026	0	0	0	0.121	-0.172	-0.0514	-0.0386	-0.55
2027	0	0	0	0.0863	-0.138	-0.0514	-0.0351	-0.585
2028	0	0	0	0.0617	-0.113	-0.0514	-0.0319	-0.617
2029	0	0	0	0.0616	-0.113	-0.0514	-0.029	-0.646
2030	0	0	0	0.0617	-0.113	-0.0514	-0.0264	-0.672
2031	0	0	0	0.0308	-0.0822	-0.0514	-0.024	-0.696
2032	0	0	0	0	0.00646	0.00646	0.00274	-0.693
2033	0	0	-0.0345	0	0.00646	0.041	0.0158	-0.677

Table B-2: Scenario 3

	Depreciable capital [MMS]	Fixed capital investment [MMS]	Working capital [MMS]	Depreciation [MMS]	Net earnings [MMS]	Cash flow [MMS]	Discount factor	Net present value (NPV) [MMS]	Cumulative NPV [MMS]
2022	0.0358	0.0358	0	0	0	-0.0192	1.1	-0.0211	-0.0211
2023	0.0537	0.0537	0.00448	0	0	-0.0332	1	-0.0332	-0.0543
2024	0	0	0	0.0128	-0.0516	-0.0388	0.909	-0.0353	-0.0896
2025	0	0	0	0.0219	-0.0639	-0.0419	0.826	-0.0346	-0.124
2026	0	0	0	0.0157	-0.0576	-0.0419	0.751	-0.0315	-0.156
2027	0	0	0	0.0112	-0.0531	-0.0419	0.683	-0.0286	-0.184
2028	0	0	0	0.008	-0.0499	-0.0419	0.621	-0.026	-0.21
2029	0	0	0	0.00799	-0.0499	-0.0419	0.564	-0.0237	-0.234
2030	0	0	0	0.008	-0.0499	-0.0419	0.513	-0.0215	-0.256
2031	0	0	0	0.00399	-0.0459	-0.0419	0.467	-0.0196	-0.275
2032	0	0	0	0	-0.0344	-0.0344	0.424	-0.0146	-0.29
2033	0	0	-0.00448	0	-0.0344	-0.0299	0.386	-0.0115	-0.301

Table B-3: Scenario 4

	Depreciable capital [MMS]	Fixed capital investment [MMS]	Working capital [MMS]	Depreciation [MMS]	Net earnings [MMS]	Cash flow [MMS]	Net present value (NPV) [MMS]	Cumulative NPV [MMS]
2022	0.0118	0.0118	0	0	0	-0.00632	-0.00696	-0.00696
2023	0.0177	0.0177	0.00148	0	0	-0.011	-0.011	-0.0179
2024	0	0	0	0.00422	-0.0275	-0.0233	-0.0212	-0.0391
2025	0	0	0	0.00724	-0.0325	-0.0253	-0.0209	-0.06
2026	0	0	0	0.00517	-0.0304	-0.0253	-0.019	-0.079
2027	0	0	0	0.00369	-0.029	-0.0253	-0.0173	-0.0962
2028	0	0	0	0.00264	-0.0279	-0.0253	-0.0157	-0.112
2029	0	0	0	0.00264	-0.0279	-0.0253	-0.0143	-0.126
2030	0	0	0	0.00264	-0.0279	-0.0253	-0.013	-0.139
2031	0	0	0	0.00132	-0.0266	-0.0253	-0.0118	-0.151
2032	0	0	0	0	-0.0228	-0.0228	-0.00967	-0.161
2033	0	0	-0.00148	0	-0.0228	-0.0213	-0.00822	-0.169

Table B-4: Scenario 5

	Depreciable capital [MMS]	Fixed capital investment [MMS]	Working capital [MMS]	Depreciation [MMS]	Net earnings [MMS]	Cash flow [MMS]	Net present value (NPV) [MMS]	Cumulative NPV [MMS]
2022	0.00653	0.00653	0	0	0	-0.0035	-0.00385	-0.00385
2023	0.0098	0.0098	0.000817	0	0	-0.00606	-0.00606	-0.00991
2024	0	0	0	0.00233	-0.0249	-0.0226	-0.0205	-0.0304
2025	0	0	0	0.004	-0.0286	-0.0246	-0.0203	-0.0508
2026	0	0	0	0.00286	-0.0274	-0.0246	-0.0185	-0.0692
2027	0	0	0	0.00204	-0.0266	-0.0246	-0.0168	-0.086
2028	0	0	0	0.00146	-0.026	-0.0246	-0.0153	-0.101
2029	0	0	0	0.00146	-0.026	-0.0246	-0.0139	-0.115
2030	0	0	0	0.00146	-0.026	-0.0246	-0.0126	-0.128
2031	0	0	0	0.000729	-0.0253	-0.0246	-0.0115	-0.139
2032	0	0	0	0	-0.0232	-0.0232	-0.00984	-0.149
2033	0	0	-0.000817	0	-0.0232	-0.0224	-0.00863	-0.158

Table B-5: Table Comparing the TCI, Annual Operating Cost, Equipment Cost and Income

Parameter/scenarios	1	2	3	4	5
TCI	\$785,821.75	\$725,091.06	\$94,040.41	\$31,024.76	\$17,154.04
Annual Operating Cost	\$60,639.60	\$50,063.51	\$34,421.19	\$22,803.21	\$23,041.83
Equipment Cost	\$80,731.00	\$51,131.00	\$60,231.00	\$28,451.00	\$16,300.00
Income	\$57,521.00	\$56,522.38	-\$4,631.01	\$5,126.51	\$3,466.07

Appendix C

Experiment Result

This Appendix has the results from the volume and pH method for the experiment carried out to test CO₂ absorption.

Table C-1: Experiment Result for the pH Method.

Sample	Method	TimeInterval	Temperature	Replicate	change in H ⁺ (M)	Change in pH	CO2 absorbed in moles	CO2Absorption
Digestate liquid	pH change	30	22	1	8.06168E-09	-0.05	3.22467E-06	0.000141886
Digestate liquid	pH change	30	22	2	8.92714E-09	-0.06	3.57086E-06	0.000157118
Digestate liquid	pH change	30	22	3	1.05386E-08	-0.07	4.21545E-06	0.00018548
Digestate liquid	pH change	30	4	1	7.59823E-09	-0.06	3.03929E-06	0.000133729
Digestate liquid	pH change	30	4	2	8.96982E-09	-0.07	3.58793E-06	0.000157869
Digestate liquid	pH change	30	4	3	9.17875E-09	-0.07	3.6715E-06	0.000161546
Digestate liquid	pH change	30	34	1	4.21143E-09	-0.04	1.68457E-06	7.41211E-05
Digestate liquid	pH change	30	34	2	1.16742E-09	-0.01	4.66966E-07	2.05465E-05
Digestate liquid	pH change	1440	4	1	1.2949E-08	-0.09	5.17959E-06	0.000227902
Digestate liquid	pH change	1440	4	2	1.11153E-08	-0.08	4.4461E-06	0.000195629
Digestate liquid	pH change	1440	4	3	1.00643E-08	-0.07	4.02572E-06	0.000177132
Digestate liquid	pH change	1440	22	1	2.5869E-08	-0.13	1.03476E-05	0.000455294
Digestate liquid	pH change	1440	22	2	1.46528E-08	-0.08	5.86111E-06	0.000257889
Digestate liquid	pH change	1440	22	3	9.5656E-09	-0.06	3.82624E-06	0.000168355
Digestate liquid	pH change	1440	34	1	4.34163E-08	-0.29	1.73665E-05	0.000764126
Digestate liquid	pH change	1440	34	2	2.03605E-08	-0.16	8.14421E-06	0.000358345
Digestate liquid	pH change	1440	34	3	1.59506E-08	-0.12	6.38025E-06	0.000280731
Water	pH change	30	4	1	7.36298E-07	-2.17	0.000294519	0.012958851
Water	pH change	30	4	2	8.46126E-07	-2.23	0.00033845	0.014891821
Water	pH change	30	4	3	6.87941E-07	-2.25	0.000275176	0.012107753
Water	pH change	30	22	1	6.25462E-07	-2.06	0.000250185	0.01100813
Water	pH change	30	22	2	5.97548E-07	-2.08	0.000239019	0.01051684
Water	pH change	30	22	3	5.83832E-07	-2.07	0.000233533	0.010275439
Water	pH change	30	34	1	7.70081E-07	-2.10	0.000308032	0.013553429
Water	pH change	30	34	2	8.06224E-07	-2.09	0.000322489	0.014189535
Water	pH change	30	34	3	8.06224E-07	-2.09	0.000322489	0.014189535
Water	pH change	1440	22	1	1.69398E-06	-2.60	0.000677591	0.02981401
Water	pH change	1440	22	2	1.65532E-06	-2.59	0.000662128	0.029133652
Water	pH change	1440	22	3	1.37537E-06	-2.44	0.000550149	0.024206554
Water	pH change	1440	4	1	1.50976E-06	-2.60	0.000603904	0.026571765
Water	pH change	1440	4	2	1.34498E-06	-2.53	0.000537993	0.02367168
Water	pH change	1440	4	3	1.25485E-06	-2.49	0.000501941	0.022085388
Water	pH change	1440	34	1	1.1386E-06	-2.08	0.000455441	0.020039425
Water	pH change	1440	34	2	1.27974E-06	-2.18	0.000511895	0.022523392
Water	pH change	1440	34	3	1.44E-06	-2.29	0.000575211	0.025309269

Table C-2: Experiment Result for the Volume Method.

Sample	Method	Time Interval	Temperature	Replicate	Change in volume	CO2 absorbed in moles	CO2Absorption
Digestate liquid	Volume Change	30	34	1	0.00	0.00	0.00
Digestate liquid	Volume Change	30	34	2	0.00	0.00	0.00
Digestate liquid	Volume Change	30	34	3	0.00	0.00	0.00
Digestate liquid	Volume Change	30	22	1	0.00	0.00	0.00
Digestate liquid	Volume Change	30	22	2	0.00	0.00	0.00
Digestate liquid	Volume Change	30	22	3	0.00	0.00	0.00
Digestate liquid	Volume Change	30	4	1	0.00	0.00	0.00
Digestate liquid	Volume Change	30	4	2	10.00	0.44	19.34
Digestate liquid	Volume Change	30	4	3	20.00	0.88	38.67
Digestate liquid	Volume Change	1440	34	1	0	0.00	0.000
Digestate liquid	Volume Change	1440	34	2	0	0.00	0.000
Digestate liquid	Volume Change	1440	34	3	20	0.79	34.897
Digestate liquid	Volume Change	1440	22	1	0	0.00	0.000
Digestate liquid	Volume Change	1440	22	2	0	0.00	0.000
Digestate liquid	Volume Change	1440	22	3	20	0.82	36.071
Digestate liquid	Volume Change	1440	4	1	40	1.76	77.349
Digestate liquid	Volume Change	1440	4	2	40	1.76	77.349
Digestate liquid	Volume Change	1440	4	3	50	2.20	96.686
Water	Volume Change	30	34	1	10.00	0.40	17.45
Water	Volume Change	30	34	2	0.00	0.00	0.00
Water	Volume Change	30	34	3	0.00	0.00	0.00
Water	Volume Change	30	22	1	20.00	0.82	36.07
Water	Volume Change	30	22	2	0.00	0.00	0.00
Water	Volume Change	30	22	3	20.00	0.82	36.07
Water	Volume Change	30	4	1	20.00	0.88	38.67
Water	Volume Change	30	4	2	10.00	0.44	19.34
Water	Volume Change	30	4	3	40.00	1.76	77.35
Water	Volume Change	1440	34	1	10	0.40	17.449
Water	Volume Change	1440	34	2	20	0.79	34.897
Water	Volume Change	1440	34	3	20	0.79	34.897
Water	Volume Change	1440	22	1	40	1.64	72.143
Water	Volume Change	1440	22	2	30	1.23	0.000
Water	Volume Change	1440	22	3	20	0.82	36.071
Water	Volume Change	1440	4	1	60	2.64	116.023
Water	Volume Change	1440	4	2	40	1.76	77.349
Water	Volume Change	1440	4	3	60	2.64	116.023