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Energy Performance Analysis of Biogas-Fueled Combined Heat and Power (CHP) Production for Kaliti Wastewater Treatment Plant, replacing the existing Biogas Flare System and Recovering Energy

A thesis Submitted for the in partial fulfillment for the degree of masters of Science in Mechanical and Industrial Engineering (Thermal Engineering), in College of Technology and Built Environment (CTBE)

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Table of content

List of figures

List of tables

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CERTIFICATION

I, the undersigned, certify that I have read and heard by recommending for acceptance by College of Technology and Built Environment, Mechanical and Industrial Engineering (Thermal Engineering Stream) of a thesis titled " Energy Performance Analysis of Biogas-Fueled Combined Heat and Power (CHP) Production for Kaliti Wastewater Treatment Plant, replacing the existing Biogas Flare System and Recovering Energy)". This certificate used as a partial fulfillment of the requirement for the thermal engineering of Masters of Science in Mechanical Engineering.

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Declaration

I, Tigist Gebrekidan declare that this thesis is the result of my work, hence all relevant data, resources and materials used during the work has been properly collected and cited. This thesis has partially presented however, it will be made available at the university's library for thermal engineering studies duty. I hereby swear unequivocally that this thesis has not been submitted to any other university or institution for the ward or research paper.

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ACRONYMS AND ABBREVIATIONS

- UASB – Anaerobic Sludge Blanket
- CHP – Combined Heat and Power
- WWTP – Waste Water Treatment Plant
- TVS – Total Volatile Solids
- WWTW – Waste water Treatment Work
- AD – Anaerobic Digestion
- CH_4 – Methane
- CO_2 – Carbondioxide
- CO – Carbon monoxide
- H_2S – Hydrogen Sulfide
- H – Hydrogen
- N- Nitrogen

Abstract

The Kaliti Wastewater Treatment Plant in Addis Ababa, Ethiopia, currently underutilizes biogas produced during wastewater treatment by flaring it off, the flare system can handle a maximum daily methane production of 13,000 Nm^3, operating within a pressure range of 10-65 mbar and managing biogas flow rates between 40-600 Nm^3/h. This inefficiency contributes to environmental pollution and missed opportunities for energy independence. The plant wastes valuable renewable energy by flaring biogas instead of capturing and utilizing it,. This thesis aims to investigate the feasibility of implementing a biogas-fueled combined heat and power (CHP) system at the Kaliti Wastewater Treatment Plant to address the underutilization of biogas and improve energy efficiency. The study involved data collection on biogas production rates, plant energy consumption, and biogas characteristics. A site assessment evaluated existing infrastructure and potential CHP system locations. A biogas CHP system was designed and modeled using collected data and industry benchmarks. Energy performance analysis assessed electricity generation and heat recovery potential, followed by sensitivity analysis to explore parameter variations. Biogas production at the plant exhibits notable seasonal fluctuations, likely influenced by varying biological processes within the digester. Implementing a CHP system offers a substantial improvement in energy utilization compared to flaring, with stable electric and thermal efficiencies across different biogas flow rates. The modeled CHP system demonstrates potential to generate significant electricity and thermal energy, reducing reliance on external energy sources and providing economic benefits through cost savings. The performance analysis of CHP system shows, the total electric energy production (1672 MWh/a) and total thermal energy production (1964 MWh/a). The implementation of a biogas-fueled CHP system presents a viable solution for enhancing energy efficiency, leveraging renewable energy sources, and achieving environmental sustainability at the Kaliti Wastewater Treatment Plant. Utilizing biogas for combined electricity and heat generation offers a sustainable approach to waste management while reducing environmental impact and operating costs. Investment in renewable energy technologies is crucial for long-term sustainability and resilience in wastewater treatment operations.

Keywords: Biogas, Combined Heat and power (CHP), Energy Efficiency, Renewable Energy, Waste Water Treatment, Environmental Sustainability.

CHAPTER ONE

1. Introduction

The Kaliti Wastewater Treatment Plant, situated in Addis Ababa, Ethiopia, plays a pivotal role in managing the city's sanitation needs. As one of the largest treatment facilities in the region, Kaliti is tasked with treating vast quantities of toilet waste collected from households and industries, thereby safeguarding public health and environmental integrity. Central to its operations is the anaerobic digestion process, which converts organic matter in the waste into biogas - a renewable energy source rich in methane. However, despite the potential for energy recovery, the biogas produced at Kaliti has thus far been underutilized, with the majority being flared off without harnessing its energy content. This oversight represents a significant missed opportunity for sustainable energy generation and environmental stewardship.

The focus of this thesis is to address this gap by conducting an energy performance analysis of biogas-fueled combined heat and power (CHP) systems at the Kaliti Wastewater Treatment Plant. By replacing the existing biogas flare system with a more efficient energy recovery solution, this research aims to unlock the untapped potential of biogas as a renewable energy source. Specifically, the recovered biogas will be utilized for electric power and heat production, thereby reducing the facility's reliance on non-renewable energy sources and contributing to its overall energy efficiency. Additionally, the digestate - a byproduct of the anaerobic digestion process -will be repurposed as fertilizer, providing a sustainable solution for agricultural needs in the nearby areas.

Ethiopia, like many developing countries, faces significant challenges in managing its wastewater and sanitation infrastructure. Rapid urbanization, population growth, and industrialization have placed immense pressure on existing treatment facilities, leading to concerns about water pollution, public health risks, and environmental degradation. In this context, the Kaliti Wastewater Treatment Plant stands as a critical asset in the nation's efforts to address these challenges and meet its sustainable development goals.

At the heart of the Kaliti facility lies the anaerobic digestion process—a proven technology for treating organic waste and producing biogas. Anaerobic digestion involves the breakdown of organic matter by microorganisms in the absence of oxygen, resulting in the release of biogas as a byproduct. Biogas is primarily composed of methane (CH4) and carbon dioxide (CO2), with methane being the key component that can be utilized as a renewable energy source.

Despite its potential, the biogas produced at Kaliti has historically been flared off, largely due to logistical, technical, and operational challenges. The absence of a robust energy recovery system has meant that valuable energy resources are being wasted, contributing to environmental pollution and missed opportunities for sustainable development.

The Kaliti Wastewater Treatment Plant utilizes a comprehensive process to treat septic wastewater, ensuring the removal of contaminants and the safe discharge of treated water as shown in figure 1.1. The plant processes 100,000 cubic meters of wastewater per day, employing various stages of mechanical, biological, and chemical treatments to handle waste effectively.

The treatment process begins with the septic wastewater entering the inlet chamber. From there, it passes through a coarse screen to remove large debris and a perforated band screen to filter out smaller particles. The wastewater then enters the aerated grit and grease removal system to eliminate grit and grease.

The next stage involves the Up flow Anaerobic Sludge Blanket (UASB) reactor, where anaerobic digestion occurs, producing biogas that is flared off. Excess sludge from the UASB reactor is managed separately, while the treated water flows to trickling filters for further purification. Secondary clarifiers then separate the sludge from the water, with the sludge being recycled back to the UASB reactor and trickling filters.

Following this, the treated water undergoes chlorination and dichlorination to ensure it is safe for discharge into the river. Additionally, the plant handles sludge drying in a dry bed and provides latrine water stations. Percolated water from this process is also managed effectively to prevent contamination.

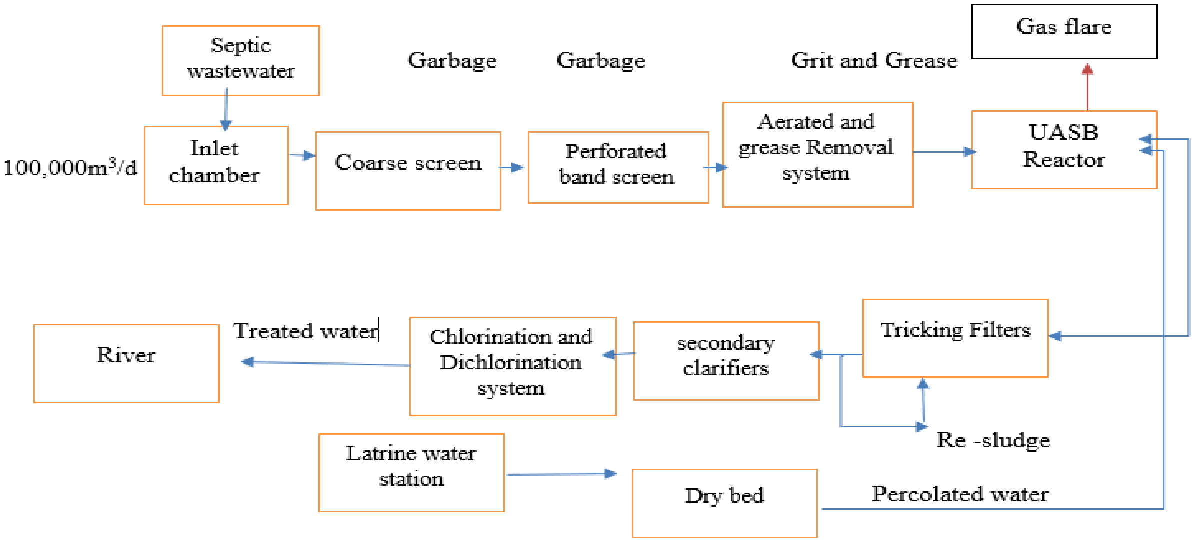


Figure 1.1 Kaliti Waste Water Treatment Plant Process Flow Diagram

The Akaki Wastewater Treatment Plant features an advanced biogas flare system, integral to managing the biogas produced during the anaerobic digestion process. This system ensures the safe and efficient handling of biogas, primarily composed of methane, generated in the Upflow Anaerobic Sludge Blanket (UASB) reactor. In the UASB reactor, organic matter in the wastewater undergoes anaerobic digestion, producing biogas—a mixture of methane (CH_4), carbon dioxide (CO_2), and trace gases.

Figure 1.2 UASB reactor

The collected biogas is channeled from the reactor to the flare system, ensuring continuous and controlled handling of the gas.

The biogas flare system is designed to combust the collected biogas safely. The system can handle a maximum daily methane production of 13,000 Nm^3, operating within a pressure range of 10-65 mbar and managing biogas flow rates between 40-600 Nm^3/h. The biogas is fed into a combustion chamber where it is ignited and burned, converting methane into carbon dioxide and water vapor. This combustion process significantly reduces the environmental impact by mitigating the release of methane, a potent greenhouse gas

Key features of the biogas flare system include a robust combustion system, supporting pipes for the safe transport of biogas, pressure relief valves to maintain system safety by preventing overpressure, and an automatic alarm system to alert operators to any irregularities. These components ensure the system's efficiency and reliability.

By flaring the biogas, the Akaki Wastewater Treatment Plant minimizes the release of methane into the atmosphere, converting it into less harmful carbon dioxide and water vapor. This process not only reduces greenhouse gas emissions but also ensures compliance with environmental safety standards. The biogas flare system exemplifies effective waste management and environmental protection at the plant. Through the safe and efficient combustion of biogas, the plant significantly mitigates its environmental footprint, showcasing its commitment to sustainability.

Figure 1.3 Existing Biogas Flare System

1.2 Problem Statement

The Kaliti Wastewater Treatment Plant serves the city of Addis Ababa, Ethiopia, handles large amount of liquid waste but currently underutilizes the biogas produced during treatment. Instead of harnessing this valuable renewable energy resource, the biogas is flared off, resulting in wasted energy and environmental pollution. To address this inefficiency, the implementation of combined heat and power (CHP) systems is proposed. By transitioning from flaring to energy recovery through CHP systems, the research aims to improve the plant's sustainability and efficiency.

The study's objectives include assessing biogas energy potential, evaluating CHP system feasibility, estimating economic and environmental benefits, and exploring digestate repurposing for agriculture. Through these efforts, the research aims to guide the adoption of sustainable energy practices at Kaliti, benefiting both the facility and the wider community.

1.3 Objectives

1.3.1 Main Objectives

The primary objective of this thesis is to conduct a comprehensive energy performance analysis of biogas-fueled CHP systems at the Kaliti Wastewater Treatment Plant.

1.3.2 Specific Objectives

The specific objective of the study is:

- Assess the potential for recovering energy from biogas produced at the Kaliti facility.
- Evaluate the feasibility and effectiveness of implementing CHP systems for electric power and heat production.
- Estimate the economic and environmental benefits of transitioning from biogas flaring to energy recovery.

1.4 Scope of the Study

This study will focus specifically on the Kaliti Wastewater Treatment Plant and its biogas production system. Data collection will involve gathering information on the quantity and quality of biogas generated, as well as the operational parameters of the treatment facility. Energy performance modeling will be conducted to simulate the operation of CHP systems and assess their potential for electric power and heat generation.

The economic analysis will include cost-benefit assessments, payback period calculations, and sensitivity analyses to determine the financial viability of implementing CHP systems. Environmental impacts, such as greenhouse gas emissions reductions and air quality improvements, will also be evaluated to provide a holistic understanding of the benefits associated with energy recovery. Recommendations for optimizing the utilization of biogas and digestate will be provided based on the research findings, with the aim of promoting sustainable energy practices and enhancing the overall efficiency and environmental performance of the Kaliti Wastewater Treatment Plant.

CHAPTER TWO

2. Literature review

2.1 Biogas Based energy Recovery System

The potential for energy recovery from wastewater treatment plants (WWTPs) is substantial, particularly through biogas recovery. This is highly pertinent to the Kaliti Wastewater Treatment Plant, where replacing the existing biogas flare system with a more efficient energy recovery system could yield significant benefits. The current system at Kaliti can be upgraded to enhance energy self-sufficiency and operational efficiency.

Biogas recovery primarily involves the anaerobic digestion process, where organic matter in wastewater is broken down by microorganisms, producing biogas rich in methane. This biogas can be harnessed for energy production, reducing reliance on external energy sources and decreasing greenhouse gas emissions. Specifically, the implementation of co-digestion processes, where additional organic waste materials are added to the digesters, can significantly boost biogas yields [1]. This approach has been identified as a viable measure to increase the energy self-sufficiency of WWTPs [2].

Furthermore, integrating fuel cell systems can offer a more efficient means of converting biogas into electricity. Fuel cells operate with higher efficiency compared to traditional internal combustion engines and have lower emissions. The use of biogas in combined heat and power (CHP) devices is another effective strategy to maximize energy efficiency. CHP systems simultaneously generate electricity and useful heat from the same energy source, offering a high overall efficiency [2].

However, the performance and efficiency of biogas-powered systems are influenced by several factors. The combination of substrates used in the digestion process can affect biogas production rates and methane content. Additionally, ambient temperature variations can impact the stability and efficiency of

the anaerobic digestion process [3]. To address these challenges and optimize energy recovery, it is crucial to implement efficient biogas treatment methods.

One key aspect of biogas treatment is the removal of hydrogen sulfide (H2S), a common contaminant in biogas that can corrode equipment and reduce the efficiency of energy recovery systems. Effective H_2S removal technologies, such as chemical scrubbers, biological filters, and activated carbon adsorption, are essential for maintaining the longevity and efficiency of biogas utilization systems [4].

It has to be noted that enhancing the energy recovery capabilities of the Kaliti Wastewater Treatment Plant involves upgrading the existing biogas flare system to a more advanced energy recovery system. By adopting co-digestion processes, integrating fuel cell systems, and utilizing combined heat and power devices, the plant can significantly improve its energy self-sufficiency and operational efficiency. Addressing factors such as substrate combinations and ambient temperatures, alongside implementing efficient biogas treatment methods like H_2S removal, is critical for optimizing the performance of biogas-powered systems. The transition towards more efficient energy recovery systems at WWTPs not only enhances sustainability but also contributes to broader environmental and economic benefits.

A range of studies have explored the potential of biogas-based heat and power production using cogeneration. Magó [5] emphasizes the integration of solar energy and biomass utilization in scalable co-generation power plants, while Solarte-Toro [6] compares the use of biogas and syngas as energy vectors for heat and power generation. Norouzi [7] provides a comprehensive review of different biogas-based power generation technologies, including single generation, cogeneration, and multi-generation systems. Schneider [8] focuses on small-scale cogeneration of heat and power using solid biomass fuels, highlighting the challenges and potential solutions in this area. These studies collectively underscore the importance of biogas as a renewable energy source and the need for further research to optimize its utilization in cogeneration systems.

Table 2.1 summarizes 13 papers focused on various aspects of energy production and utilization in wastewater treatment plants (WWTPs) and the integration of biogas and other renewable energy sources into these systems. "Techno-Economic Assessment of CHP Systems in Wastewater Treatment Plants" [9] employs techno-economic modeling, life cycle cost analysis (LCCA), and sensitivity analysis, demonstrating that combined heat and power (CHP) systems offer significant cost savings and energy efficiency improvements compared to traditional systems, yet real-world validation of simulation results is needed. Another paper [10], "Techno-economic Analysis of Solid Oxide Fuel Cell-Based CHP Systems for Biogas Utilization at Wastewater Treatment Facilities," utilizes similar methods to show that solid oxide fuel cell (SOFC)-based CHP systems provide higher efficiency and lower emissions. However, there's a lack of long-term operational data to validate techno-economic models. "Optimization Strategies for Mixing Ratio of Biogas and Natural Gas Co-Firing in a Cogeneration of Heat and Power Cycle" [11] employs optimization modeling and scenario analysis to determine optimal biogas-natural gas mixing ratios, yet real-world validation and long-term performance data are needed. "An overview of biogas production and utilization at full-scale wastewater treatment plants in the United States" [12] identifies the potential for biogas production to achieve energy neutrality in WWTPs, highlighting the need for comprehensive techno-economic assessments. Several other papers explore various aspects of energy production and utilization in WWTPs, including case studies, comparative analysis, and environmental assessments, emphasizing the need for further research on real-world performance validation, long-term data collection, and comprehensive techno-economic assessments across different WWTPs and regions.

Table 2.1 Summary Table: Biogas-Fueled CHP for Wastewater Treatment Plants

No	Title of Paper	Methodology Used	Key Findings	Research Gap
1	Techno-Economic Assessment of CHP Systems in Wastewater Treatment Plants [9]	Techno-economic modeling, LCCA (Life Cycle Cost Analysis), and sensitivity analysis	CHP systems provide significant cost savings and energy efficiency improvements compared to traditional systems	Need for real-world validation of simulation results.
2	Techno-economic analysis of solid oxide fuel cell-based combined heat and power systems for biogas utilization at wastewater treatment facilities [10]	Techno-economic modeling, LCCA (Life Cycle Cost Analysis), and sensitivity analysis	SOFC-based CHP systems provide higher efficiency and lower emissions compared to traditional systems	Need for long-term operational data to validate techno-economic models
3	Optimization Strategies for Mixing Ratio of Biogas and Natural Gas Co-Firing in a Cogeneration of Heat and Power Cycle [11]	Optimization modeling, computational simulations, and scenario analysis	Optimal biogas-natural gas mixing ratios can significantly enhance efficiency and	Need for real-world validation of optimal mixing ratios and

			reduce emissions in CHP systems	long-term performance data
4	An overview of biogas production and utilization at full-scale wastewater treatment plants (WWTPs) in the United States: Challenges and opportunities towards energy-neutral WWTPs [12]	Literature review and case study analysis	Identifies significant potential for biogas production and utilization to achieve energy neutrality in WWTPs; highlights key challenges including variability in biogas production and regulatory hurdles	Need for comprehensive techno-economic assessments and long-term performance data for various WWTPs across different regions
5	A Case Study on the Electricity Generation Using a Micro Gas Turbine Fueled by Biogas from a Sewage Treatment Plant [13]	Case study and performance monitoring	Implementation of a micro gas turbine fueled by biogas demonstrates feasibility and energy recovery	Further exploration needed on long-term performance and scalability of such systems.
6	Comparative analysis of different CHP systems using biogas for the cassava starch plants[14]	Comparative economic analysis	Various CHP systems show different economic viability and performance for cassava starch plants	Need for detailed assessment of technical feasibility and environmental impact of each CHP system
7	Environmental and techno-economic analysis of the integration of biogas and solar power systems into urban wastewater treatment plants [15]	Environmental impact assessment and economic analysis	Significant environmental benefits and potential for cost savings with biogas CHP systems.	Research on integrating renewable energy sources with biogas CHP systems is lacking.
8	Energy Performance Analysis of Biogas CHP in Large-Scale Wastewater Treatment Plants [16]	Literature review and synthesis	Identifies key factors influencing energy performance in wastewater treatment plants	Need for more empirical studies to quantify the impact of various factors on energy performance

9	Analytical Study to Use the Excess Digester Gas of Wastewater Treatment Plants [17]	Analytical study	Utilization options for excess digester gas: energy recovery, flaring	Need for empirical data validation and cost-benefit analysis.
10	Energy Management in Wastewater Treatment Systems: Biogas Energy Recovery Management Application [18]	Energy management strategies and biogas utilization analysis	Effective biogas energy recovery management enhances energy efficiency and reduces costs	Need for comprehensive analysis of long-term performance and economic benefits of energy management
11	Advances, challenges, and perspectives of biogas cleaning, upgrading, and utilization [19]	Literature review and analysis of technological advancements	Highlights advancements in biogas cleaning, upgrading, and utilization; Identifies challenges	Need for more empirical studies validating technological advancements; Future research directions
12	Techno-economic analysis and case study of combined heat and power systems in a wastewater treatment plant [20]	Case study analysis and techno-economic modeling	Implementation of CHP systems resulted in cost savings and improved energy efficiency	Limited generalizability due to single case study, need for broader data from various facilities.
13	Performance analysis and economic assessment of a combined cooling heating and power (CCHP) system in wastewater treatment plants (WWTPs) [21]	Empirical Data collection, performance testing, techno-economic modeling, cost-benefit analysis	CCHP systems offer improved energy efficiency and cost savings through integrated heat and power generation	Need for long-term performance data and validation in real-world WWTP settings

Due to the fluctuating cost and the environmental effects of conventional sources (especially crude oil) of energy, there is an emergent interest in the use of renewable energy. As such, the adoption of renewable energy is gradually becoming significant due to the negative effects of greenhouse gas emissions on the environment [22].

At present, modern anaerobic technologies are widely applied for industrial wastewater treatment; however, their applications for domestic and municipal sewage treatment are still very limited. Biological wastewater treatment plant (WWTP) is a facility for removal of mainly organic pollution from wastewaters. Organic pollution is partly trans- formed into sludge that, with the use of up-to-date technologies, represents an important energy source [23].

Over the last few years, the interest in bio-energy production has increased significantly. A number of different technologies and processes are used to recycle organic waste and one of them is biogas production. Biogas typically refers to gas containing mainly methane and produced by anaerobic decomposition of organic material. The composition of biogas largely depends on the type of substrate. Human excreta-based biogas contains 65-66% CH4, 32-34% CO_2 by volume and the rest is H_2S and other gases in traces whiles the biogas composition for a municipal solid waste is composed of 68-72% CH_4, 18-20% CO_2, and 8% H_2S.

Table 2.2 Average Composition of biogas from different organic residues

Gases	**Percentage (%)**
Methane (CH4)	40-75
Carbon Dioxide (CO2)	25-40
Nitrogen(N)	0.5-2.5
Oxygen(O)	0.1-1

Hydrogen Sulfide(H2S)	0.1-0.5
Carbon Monoxide (CO)	0.1-0.5
Hydrogen(H)	1-3

Theoretically every organic material can be digested. The feedstock for anaerobic digestion includes cattle dung and manure, goat dung, chicken droppings, abattoir by-products, kitchen waste, food processing factory wastes and human excreta. Wastewater and sludge are important carriers of valuable resources, comprising mainly of water, nitrogen, phosphorous, organic carbon, and the embedded energy potential. The embedded minerals are important as agricultural fertilizers, and the organic carbon can be used as a soil revitalizer or to generate clean energy [24] . Energy recovery, alongside water, organic matter, and nutrient retrieval, presents significant value relative to associated costs. Feedstock selection for anaerobic digestion hinges on factors like substrate temperature and availability, with availability being paramount. Biogas potential also relies on gas yield per kg of Total Volatile Solids (TVS). Anaerobic Digestion (AD) of agricultural and industrial residues, municipal organic waste, sewage sludge, etc., emerges as a highly appealing renewable energy avenue. Wastewater harbors chemical, thermal, and hydraulic energies, with chemical energy locked in organic molecules, release able through microbial metabolism. Biogas from sewage sludges in mesophilic AD consists mainly of methane (60–67%) and carbon dioxide (30–40%), with traces of nitrogen, hydrogen sulfide, and other constituents.

In wastewater treatment, biogas is generated during sludge decomposition within anaerobic digesters, where oxygen is absent. This process, known as Anaerobic Digestion, was pioneered by South Africa in wastewater treatment works (WWTW) [26]. These works feature large, sealed, heated tanks housing anaerobic bacteria to break down wastewater sludge. The resulting biogas, rich in methane, offers a promising energy source. However, in many small to medium-sized municipal treatment plants, biogas is simply vented, contributing to greenhouse gas emissions. Anaerobic municipal sewage treatment may not be deemed an energy producer unless processing a significant wastewater flow. Yet, there's considerable potential for energy recovery from WWTPs to enhance efficiency and reduce emissions. Unfortunately, in numerous wastewater treatment plants, especially in developing nations, biogas remains untapped, with no thermal energy recovery or electricity generation, often being flared and wasted [27].

The energy released from biogas renders it suitable for heating and cooking purposes worldwide. Additionally, biogas can fuel anaerobic digesters, converting its energy into electricity and heat using gas engines. Notable properties of biogas as a fuel (assuming a 60 % CH_4 content) include a minimal calorific value of 21.5 MJ/m^3, stochiometric air-to-fuel ratio of 5.71, and flame velocity of 25 cm/s.

In France, the majority of biogas is generated through anaerobic digestion, primarily used in Combined Heat and Power (CHP) plants. As of 2014, the country boasted 502 biogas plants with a total installed capacity of 293 MW, generating around 1,500 GWh of electricity and 1,600 GWh of heat annually [28].

Compared to other renewable energy sources in heating, bioenergy offers the highest mitigation potential, avoiding around 31.2 million tons of greenhouse gases. In 2014, electricity and heat production from biogas using Combined Heat and Power (CHP) systems held a prominent position among available bioenergy technologies [29]. CHP allows simultaneous generation of electricity and heat from a single fuel source, enhancing efficiency and cleanliness. It's adaptable to various energy needs, replacing or complementing separate heat and power systems. Market forces and energy product requirements influence the choice of technology, with CHP offering high efficiency and significant waste heat recovery, unlike conventional power plants where much of the heat is lost.

Cogeneration, also known as Combined Heat and Power (CHP), offers advantages over separate heat and electricity production by facilitating electrical network balancing. The technologies employed in cogeneration systems aim to optimize primary energy savings. Figure 2 demonstrates the cogeneration principle, contrasting it with conventional separate thermal and electrical energy production [30].

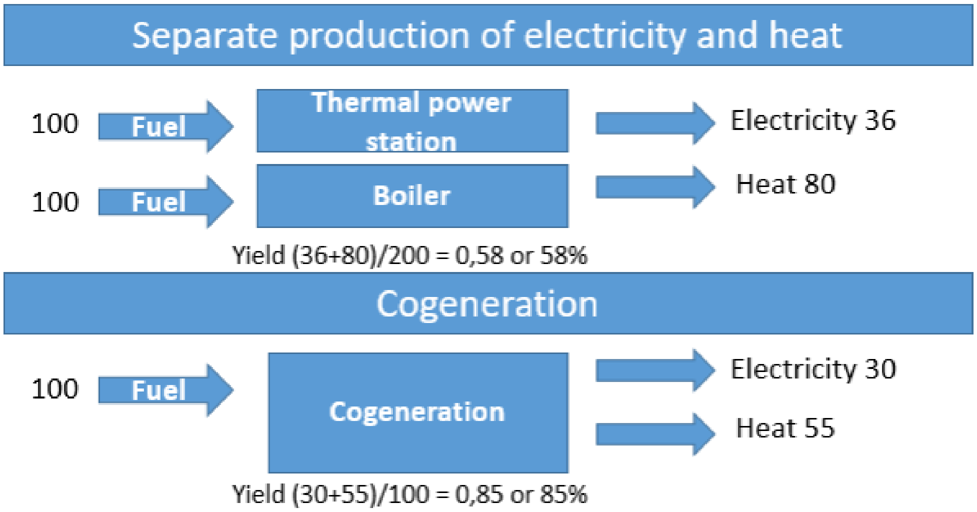


Figure 2.1 Cogeneration

CHP technology garners global attention for its superior energy supply performance, lower fuel consumption, and reduced CO2 emissions per MWh. By elevating steam power efficiency from 36-45% to over 80-90%, CHP plants significantly enhance overall efficiency. Integration with gas turbine plants and/or flue gas-condensing units further boosts efficiency. CHP systems enhance energy security by producing energy on-site and greatly improving efficiency.

The key advantage of CHP over separate electricity and heat production lies in its remarkable efficiency gains through utilizing a single process for both energy types. CHP can operate in topping or bottoming cycles. In topping cycles, fuel combustion in a prime mover generates electricity or mechanical power, with recovered waste heat providing additional thermal energy. Bottoming cycles, or waste heat to power, utilize rejected heat from industrial processes for power production.

CHP, also known as cogeneration, is recognized for its energy-saving capabilities and consequent reduction in CO2 emissions. For instance, a 5-MW gas-turbine CHP unit with 75% efficiency can cut annual CO2 emissions by roughly 50% compared to an 80% efficient system. CHP systems offer fuel flexibility, utilizing fossil fuels as well as renewable sources like landfill gas, biomass, or digester gas.

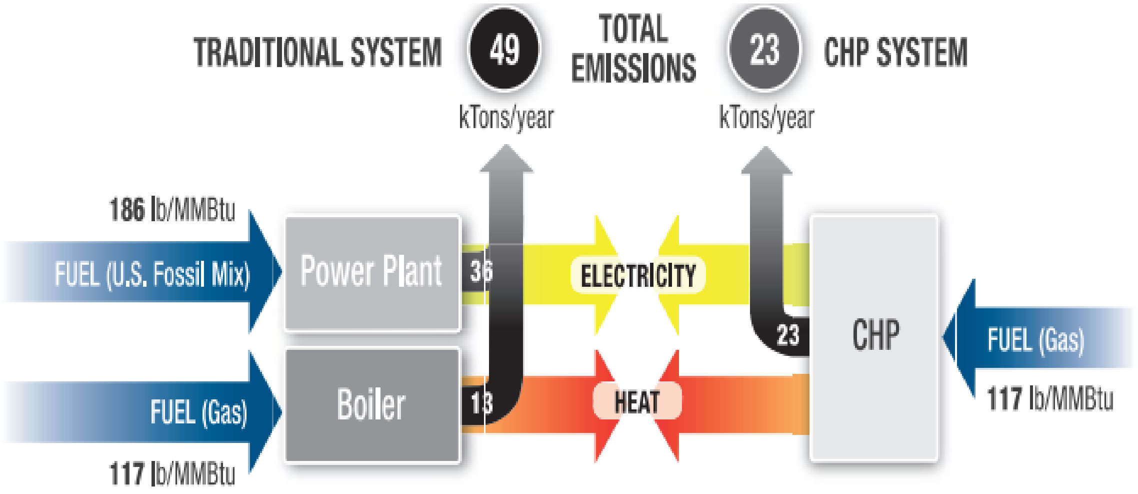


Figure 2.2 Cogeneration Vs Stand Alone System

CHP is the sequential or simultaneous generation of multiple forms of useful energy (usually mechanical and thermal) in a single, integrated system. CHP systems consist of a number of individual components—prime mover (heat engine), generator, heat recovery, and electrical interconnection— configured into an integrated whole. The type of equipment that drives the overall system (i.e., the prime mover) typically identifies the CHP system. Prime movers for CHP systems include steam turbines, gas turbines (also called combustion turbines), spark ignition engines, diesel engines, microturbines, and fuel cells.[31] One of the critical factors in the WWTF CHP project is the selection of a prime mover , the device that converts fuel to energy . prime mover include internal combustion engine , combustion gas turbine, micro gas turbine, advanced lean burn engine , recuperated gas turbine & fuel cell.[32].

2.2 Energy recovery options for Biogas

Gas turbine CHP

The growing concern over climate change and the depletion of traditional energy sources has led to a surge in interest in renewable energy alternatives. Among these, bio-gas stands out as a promising candidate due to its abundant availability and relatively low environmental impact. Bio-gas, produced through the anaerobic digestion of organic waste, contains a significant amount of methane and can be a valuable source of energy if properly utilized.

Traditionally, bio-gas generated from waste treatment processes has been flared, resulting in the release of greenhouse gases into the atmosphere. However, with advancements in technology and a growing emphasis on sustainability, there is a shift towards harnessing this energy for productive use. Gas turbines emerge as a key player in this endeavor, offering a reliable and efficient means of converting bio-gas into electricity.

Gas turbines operate by burning fuel to produce hot gases, which then drive a turbine to generate electricity. When coupled with bio-gas, these turbines offer a sustainable energy solution that not only reduces greenhouse gas emissions but also provides a reliable source of power. Unlike intermittent renewable energy sources like wind and solar, bio-gas energy from gas turbines can be generated consistently, making it suitable for baseload power generation.

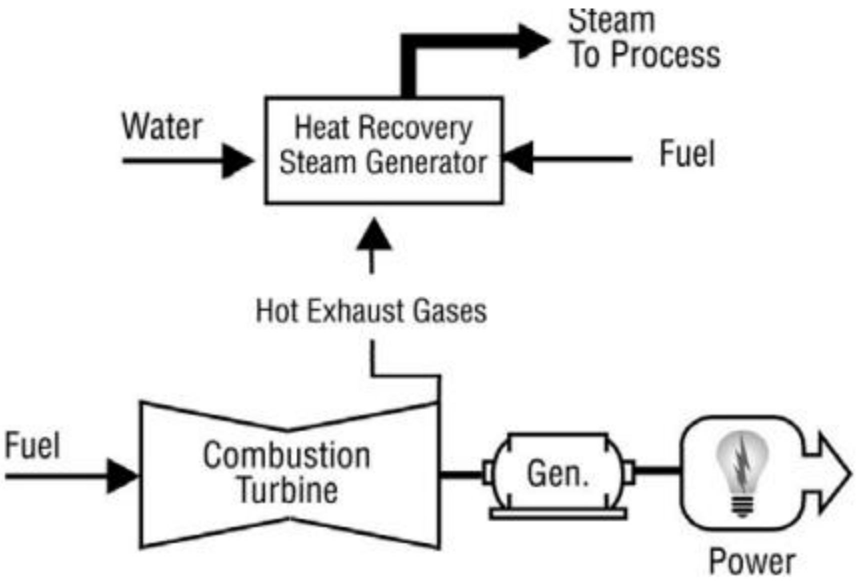


Figure 2.3 Gas turbine CHP

Reciprocating Internal combustion engine CHP

Reciprocating internal combustion engines, commonly used in Combined Heat and Power (CHP) applications, excel in scenarios with low-pressure steam or hot water demand. They are particularly practical for facilities where engine power output can be adjusted based on demand. Found in institutions like universities, hospitals, and industrial facilities, as well as residential and commercial buildings, these engines provide both power and heat, meeting thermal loads such as hot water requirements and space heating.

Internal combustion engines are prevalent in sectors where thermal demands are modest, such as the tertiary sector and small industries. These engines operate through a conventional piston-driven combustion process, comprising a cylinder, piston, inlet port, and exhaust port. While offering superior thermal efficiency compared to technologies like gas and steam turbines, they face limitations in heat recovery due to lower temperature levels.

The feasibility of using engines in cogeneration depends on specific cases where a substantial amount of heat at low temperatures is required. The recoverable heat varies depending on factors like engine type (turbocharged or naturally aspirated) and operating regime. Reciprocating IC engines, available in sizes ranging from kilowatts to over 5 MW, function by burning fuel in a combustion chamber, driving a piston that generates power. Heat recovery from exhaust and jacket water enhances overall efficiency.

In Otto engines, a mixture of air and fuel is compressed in each cylinder, ignited externally. Conversely, Diesel engines compress only air in the cylinder, with fuel injected during compression's final phase, leading to spontaneous ignition due to compressed air's high temperature.

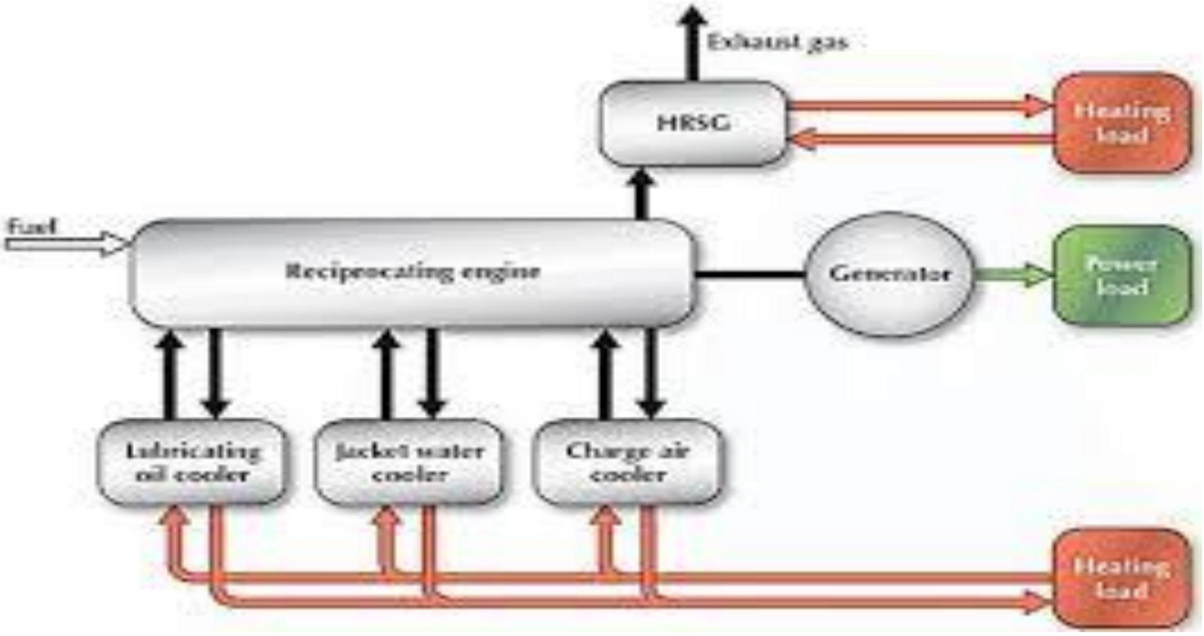


Figure 2.4 Reciprocating Internal Combustion Engine CHP

Micro turbines CHP

The term "micro-turbine" typically refers to a compact system comprising a small compressor, combustion chamber, turbine, and electric generator, usually generating less than 250 kW [33].

Micro-turbines essentially function as gas turbines, but on a smaller scale. To enhance efficiency, they often incorporate a heat recovery system, utilizing exhaust heat to preheat incoming air before combustion.

In operation, fresh air is drawn into the turbine at high speed and pressure, mixed with fuel, and combusted in the chamber under controlled conditions for optimal efficiency and low emissions. The expanding gases drive the turbine's vanes, producing work, before being expelled into the atmosphere [34].

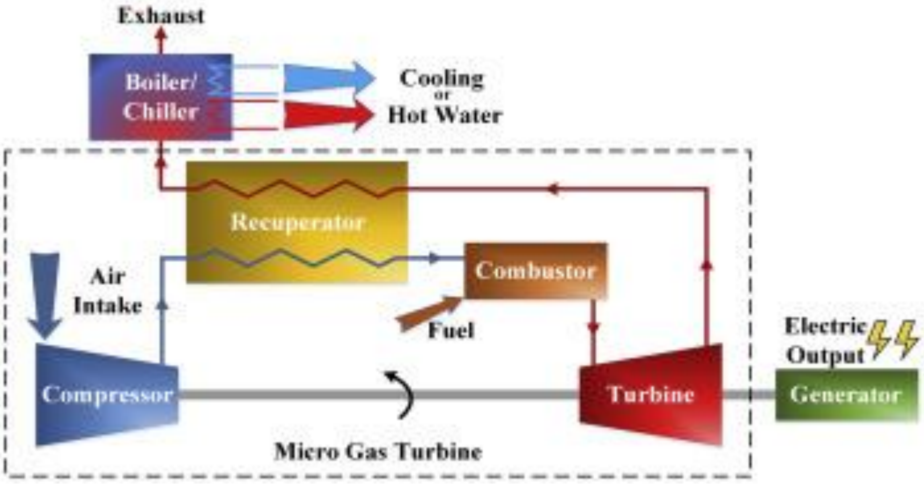


Figure 2.5 Micro turbine CHP

Micro-turbines are well-suited for distributed power generation, offering flexibility and the ability to operate in parallel to meet increased demand. They provide stable energy output and boast low greenhouse gas emissions. However, they also come with drawbacks such as high costs, relatively low electrical efficiency, and sensitivity to environmental conditions.

Fuel cells CHP

Fuel cell CHP (Combined Heat and Power) applications offer high efficiency, low emissions, and reliable power generation, utilizing waste heat for heating purposes. These systems operate quietly and come in various sizes, making them scalable to meet diverse energy needs. However, challenges such as high initial costs, limited fuel availability, infrastructure constraints, maintenance requirements, and efficiency issues at partial loads hinder widespread adoption. Despite these challenges, ongoing technological advancements and supportive policies are driving the growth of fuel cell CHP applications, positioning them as promising solutions for decentralized power generation and energy efficiency improvements.

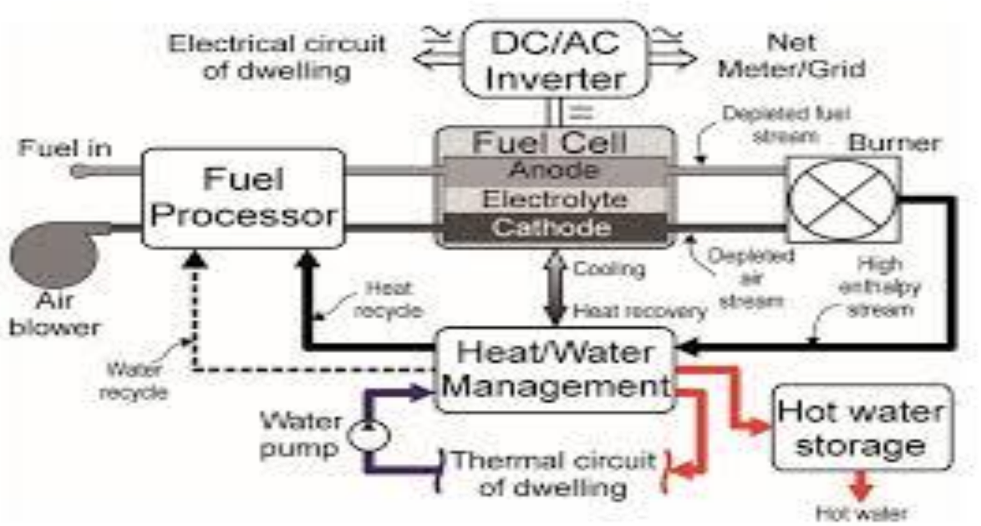


Figure 2.6 Fuel Cell CHP

Steam turbines-based CHP

Utilizing biogas in steam turbine-based Combined Heat and Power (CHP) systems at wastewater treatment plants offers an efficient and sustainable energy solution. Biogas, produced through the anaerobic digestion of sewage sludge, is cleaned to remove impurities and then burned in a boiler to generate high-pressure steam. This steam drives a turbine to produce electricity while the residual heat is captured for further use, such as heating the treatment plant or nearby buildings. This process not only reduces greenhouse gas emissions by capturing methane but also enhances energy efficiency and lowers operating costs. The on-site generation of electricity and heat improves energy security and supports the facility's energy needs, making wastewater treatment plants more sustainable and cost-effective.

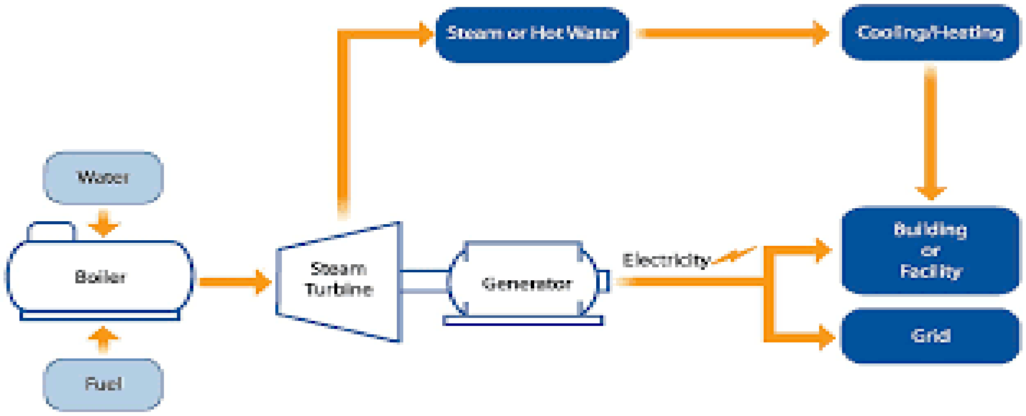


Figure 2.7 Steam turbines-based CHP

2.3 Literature review gap

The existing literature on biogas utilization in wastewater treatment plants offers valuable insights, yet there remains a notable gap concerning the specific circumstances of the Kaliti Wastewater Treatment Plant in Addis Ababa, Ethiopia. Despite its prominence as one of the region's largest treatment facilities, studies addressing the underutilization of biogas at Kaliti are scarce. While existing research often focuses on theoretical models and case studies from other locales, it fails to provide a thorough understanding of the unique logistical, technical, and operational challenges facing Kaliti. Moreover, there is a dearth of research exploring the feasibility and effectiveness of implementing combined heat and power (CHP) systems to recover energy from biogas at this facility. Therefore, there is a pressing need for empirical studies and data-driven analyses to bridge this gap and offer actionable insights for enhancing Kaliti's energy performance.

CHAPTER THREE

3. Methodology

This section will outline the methodological approach used to evaluate the feasibility and energy Wastewater Treatment Plant. The methodology will address the following aspects: The following methods were adopted:

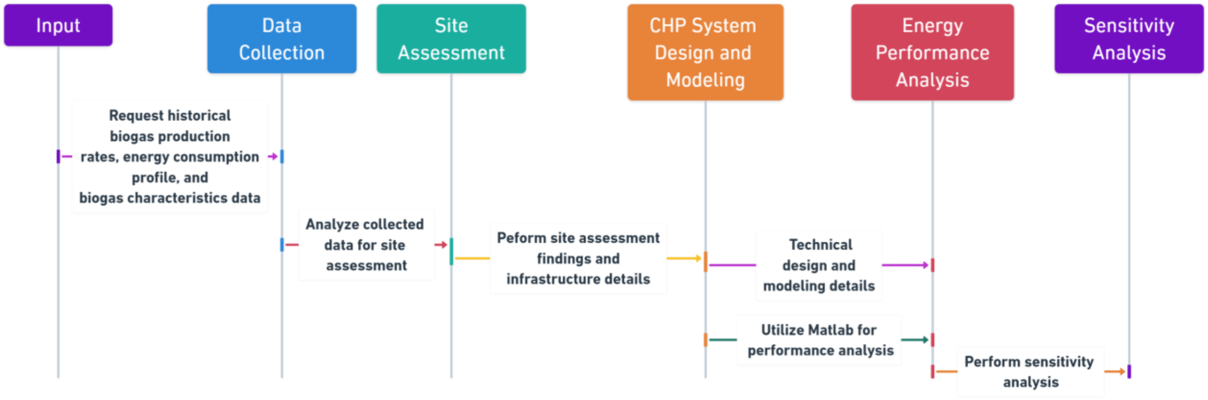


Figure 3.1 Overall Methodology with sequence diagram

3.1 Data collection

Three years biogas production rates were collected from the Kaliti Wastewater Treatment Plant, spanning the years 2021 to 2023. This data provided a comprehensive understanding of the fluctuations in biogas production over this period. Additionally, a detailed analysis of the plant's current energy consumption profile was conducted. This analysis encompassed both electricity and thermal energy consumption, broken down by department or process, to present a clear and detailed picture of the plant's energy requirements.

3.2 Site Assessment

The site visit was conducted at the Kaliti plant to assess several key factors relevant to the integration of a Combined Heat and Power (CHP) system. The evaluation focused on existing infrastructure, such as biogas storage capacity and the electrical grid connection point, to determine their suitability for handling additional power generation. Potential locations for the CHP system installation were identified, considering factors like proximity to biogas storage, existing electrical and thermal distribution systems, and ease of maintenance. Furthermore, the assessment explored the availability of waste heat utilization opportunities, examining potential applications for the heat generated by the CHP system within the treatment plant to reduce reliance on conventional heating sources.

3.3 Biogas CHP System Design

A technical design for a biogas-fueled Combined Heat and Power (CHP) system was developed, specifically tailored to the Kaliti plant's biogas production capacity and energy requirements. This design accounted for factors such as average and peak biogas flow rates to ensure the system could handle variations. The CHP system's performance was analyzed using Matlab, considering the biogas flow rate and composition based on collected data, the electrical and thermal efficiency of the CHP system according to manufacturer specifications and industry benchmarks, and the heat demand profile of the Kaliti plant throughout the year to optimize heat generation for maximum utilization.

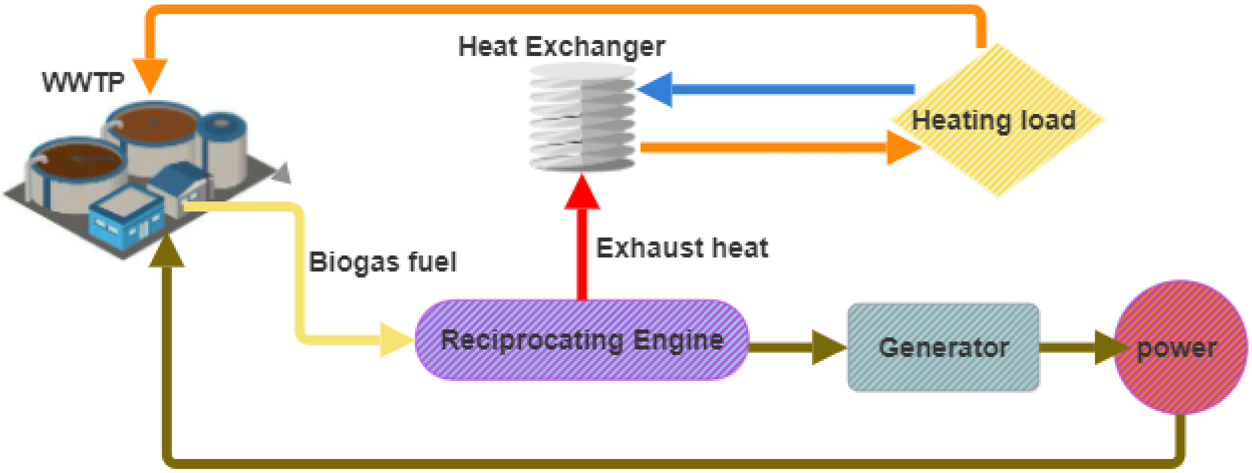


Figure 3.2 Selected Reciprocating Engine CHP system for this Research

3.4 Performance analysis

The performance analysis of a CHP system unit typically involves evaluating its efficiency in producing both electrical and thermal energy from a single fuel source. The general approach to derive the mathematical equations used in the performance analysis of a cogeneration unit is as follows:

Overall Energy Efficiency ($\eta_{Overall}$)

The overall energy efficiency of a CHP system unit is defined as the ratio of the useful energy outputs (electrical and thermal) to the total energy input from the fuel.

$$\eta_{Overall} = \frac{W_{el} + Q_{th}}{Q_{in}}$$

Where:

- W_{el} = Electrical power output (in kW)
- Q_{th} = Useful thermal energy output (in kW)
- Q_{in} = Total fuel energy input (in kW)

Electrical Efficiency (η_{el})

The electrical efficiency is the ratio of the electrical power output to the total fuel energy input

$$\eta_{el} = \frac{W_{el}}{Q_{in}}$$

Where:

- W_{el} = Electrical power output (in kW)
- Q_{in} = Total fuel energy input (in kW)

. Thermal Efficiency (η_{el})

The thermal efficiency is the ratio of the useful thermal power output to the total fuel energy input

$$\eta_{th} = \frac{Q_{th}}{Q_{in}}$$

Where:

- Q_{th} = Useful thermal energy output (in kW)
- Q_{in} = Total fuel energy input (in kW)

Heat-to-Power Ratio (HPR)

The heat-to-power ratio is the ratio of the useful thermal energy output to the electrical power output:

$$\eta_{el} = \frac{Q_{th}}{W_{in}}$$

Energy Balance

In a cogeneration system, the total energy input must equal the sum of all energy outputs and losses.

$$Q_{in=} W_{el} + Q_{th} + Q_{loss}$$

Where

Q_{loss} represents the energy losses, typically due to inefficiencies and heat losses in the system.

Sensitivity Analysis: Sensitivity analyses were performed to assess the impact of variations in key parameters on the overall performance and economic viability of the CHP system.

CHAPTER FOUR

4. Results and Discussion

4.1 Performance Analysis

This section presents the data analysis and sensitivity analysis conducted for the "Energy Performance Analysis of Biogas-Fueled CHP for the Kaliti Wastewater Treatment Plant." Through comprehensive data analysis and sensitivity analysis, this study aims to provide valuable insights into the energy performance potential of biogas-fueled CHP systems at the Kaliti Wastewater Treatment Plant.

Table 4.1 Biogas Plant Performance 2021

Months	[Text]	July	Aug	Sep	Oct	Nov	Overall
Year	[Number]	2021	2021	2021	2021	2021	2021
Methane Content in the Biogas	[%]	60%	60%	60%	60%	60%	60%
Average Hourly Biogas Gas flow	(Nm3/hr)	65.9	45.1	52.88	120.71	175.30	92.0
Maximium Hour Biogas Flow	(Nm3/hr)	125.0	63.0	101	177	240	240.0
Average Hourly Methane Flow	(Nm3/hr)	39.5	27.1	31.7	72.4	105.2	55.2
Maximium Hourly Methane Flow	(Nm3/hr)	75.0	37.8	60.6	106.2	144.0	144.0
Standard value for the heat value of methane	[kWh/m³]	9.97	9.97	9.97	9.97	9.97	9.97
Average Fuel input power	[kW]	394	270	316	722	1048	550

Max Fuel Input Power	***[kW]***	***748***	***377***	***604***	***1059***	***1435***	***1436***
Average CHP input power	***[kW]***	***400***	***270***	***200***	***400***	***600***	***300***
Partial load	[%]	98%	98%	98%	98%	98%	98%
Electric efficiency CHP 1	**[%]**	**38%**	**37%**	**36%**	**38%**	**39%**	**37%**
Thermal efficiency CHP 1	**[%]**	**52%**	**53%**	**54%**	**52%**	**51%**	**53%**
Losses	[%]	10%	10%	10%	10%	10%	10%
El. Power CHP 1	***[kWe]***	***150***	***99***	***72***	***150***	***232***	***111***
Th. Power CHP 1	***[kWth]***	***210***	***144***	***108***	***210***	***308***	***159***
El. Energy	***[kWhe/a]***	***1317029***	***864851***	***626975***	***1317029***	***2030890***	***968137***
Th. Energy	***[kWhth/a]***	***1836571***	***1263829***	***949825***	***1836571***	***2699510***	***1397063***
Total Electric Energy	[MWhe/a]	1317	865	627	1317	2031	968
Total Thermal Energy	[MWhth/a]	1837	1264	950	1837	2700	1397

Table 4.2 Biogas Plant Performance 2022

Months	[Text]	July	Augest	Sep	Oct	Nov	Overall
Year	[Number]	2022	2022	2022	2022	2022	2022
Methane Content in the Biogas	[%]	60%	60%	60%	60%	60%	60%
Average Hourly Biogas Gas flow	(Nm3/hr)	146.1	126.2	98.63	150.35	312.00	166.7
Maximium Hour Biogas Flow	(Nm3/hr)	231.0	224.0	199	286	312	312.0
Average Hourly Methane Flow	(Nm3/hr)	87.7	75.7	59.2	90.2	187.2	100.0
Maximium Hourly Methane Flow	(Nm3/hr)	138.6	134.4	119.4	171.6	187.2	187.2

Standard value for the heat value of methane	[kWh/m³]	9.97	9.97	9.97	9.97	9.97	9.97
Average Fuel input power	[kW]	874	755	590	899	1866	997
Max Fuel Input Power	***[kW]***	***1382***	***1340***	***1190***	***1711***	***1866***	***1866***
Average CHP input power	***[kW]***	***900***	***800***	***300***	***500***	***1000***	***500***
Partial load	[%]	98%	98%	98%	98%	98%	98%
Electric efficiency CHP 1	**[%]**	**40%**	**39%**	**37%**	**38%**	**40%**	**38%**
Thermal efficiency CHP 1	**[%]**	**50%**	**51%**	**53%**	**52%**	**50%**	**52%**
Losses	[%]	10%	10%	10%	10%	10%	10%
El. Power CHP 1	***[kWe]***	***357***	***315***	***111***	***191***	***400***	***191***
Th. Power CHP 1	***[kWth]***	***453***	***405***	***159***	***259***	***500***	***259***
El. Energy	***[kWhe/a]***	***3129357***	***2760213***	***968137***	***1671669***	***3501033***	***1671669***
Th. Energy	***[kWhth/a]***	***3966243***	***3546987***	***1397063***	***2270331***	***4382967***	***2270331***
Total Electric Energy	[MWhe/a]	3129	2760	968	1672	3501	1672
Total Thermal Energy	[MWhth/a]	3966	3547	1397	2270	4383	2270

Table 4.3 Biogas Plant Performance 2023

Months	[Text]	July	Augest	Sep	Oct	Nov	Overall
Year	[Number]	2023	2023	2023	2023	2023	2023
Methane Content in the Biogas	[%]	60%	60%	60%	60%	60%	60%
Average Hourly Biogas Gas flow	(Nm3/hr)	130.4	101.9	101.53	244.81	310.84	137.6
Maximium Hour Biogas Flow	(Nm3/hr)	155.0	159.0	158	316	351	351.0
Average Hourly Methane Flow	(Nm3/hr)	78.3	61.2	60.9	146.9	186.5	82.5

Maximium Hourly Methane Flow	(Nm3/hr)	93.0	95.4	94.8	189.6	210.6	210.6
Standard value for the heat value of methane	[kWh/m³]	9.97	9.97	9.97	9.97	9.97	9.97
Average Fuel input power	[kW]	780	610	607	1464	1859	823
Max Fuel Input Power	***[kW]***	***927***	***951***	***945***	***1890***	***2099***	***2100***
Average CHP input power	***[kW]***	***800***	***700***	***400***	***800***	***1000***	***500***
Partial load	[%]	98%	98%	98%	98%	98%	98%
Electric efficiency CHP 1	**[%]**	**39%**	**39%**	**38%**	**39%**	**40%**	**38%**
Thermal efficiency CHP 1	**[%]**	**51%**	**51%**	**52%**	**51%**	**50%**	**52%**
Losses	[%]	10%	10%	10%	10%	10%	10%
El. Power CHP 1	***[kWe]***	***315***	***273***	***150***	***315***	***400***	***191***
Th. Power CHP 1	***[kWth]***	***405***	***357***	***210***	***405***	***500***	***259***
El. Energy	***[kWhe/a]***	***2760213***	***2393921***	***1317029***	***2760213***	***3501033***	***1671669***
Th. Energy	***[kWhth/a]***	***3546987***	***3124879***	***1836571***	***3546987***	***4382967***	***2270331***
Total Electric Energy	[MWhe/a]	2760	2394	1317	2760	3501	1672
Total Thermal Energy	[MWhth/a]	3547	3125	1837	3547	4383	2270

The analysis of the raw data shows in the appendices shows that Between July 2021 and November 2023, the Akaki Waste Water Treatment Facility kept track of how much biogas it made every hour and every day. This biogas is measured in cubic meters. Sometimes, the facility made a lot of biogases, like over 300 cubic meters per hour or over 7000 cubic meters per day. Other times, it made very little, even none. The highest biogas production happened in late 2021 and most of 2022, but in early 2021 and some parts of 2022, it was lower. For examples in November 2022, the facility made the most biogas, 7704 cubic meters. Some other days in 2022 also had much of biogas. Summer months usually had more biogas considering the biogas generation. This is due to warmer days as it helps bacteria make more gas. Winter months had less, this is because it's colder and there's less waste to make gas from. Sometimes, the facility didn't make any biogas, probably because it was closed for maintenance. Overall, the facility made more biogas each year, especially in 2022, showing that it's getting better at it. This biogas can be used as a clean energy source, which helps manage waste and protects the environment.

In this analysis of a biogas plant's performance from 2021 - 2023 as shown in table 4.1, it has been observed that significant seasonal variations in several key metrics. The average hourly biogas flow rate exhibited a cyclical pattern, peaking in November (312 Nm^3/hr) and October (245 Nm^3/hr.) before dipping to its lowest point in September (52.9 Nm^3/hr). This trend mirrored the average hourly methane flow rate, which also reached its highs in October (146.9 Nm^3/hr) and November (186.5 Nm^3/hr.) and fell to a minimum in September (60.9 Nm^3/hr). This suggests a potential correlation between seasonal factors and the efficiency of the biological processes within the digester.

Interestingly, the average fuel input power followed a similar seasonal pattern as the biogas flow rate. The plant required the most fuel input power in November (1859kW) to keep up with the high biogas production, while September saw the lowest fuel input power requirement (607 kW) due to the decreased biogas flow. However, despite these variations, the electric efficiency (ranging from 39% to 40%) and thermal efficiency (between 43% and 45%) of the CHP system remained relatively stable throughout the year. This indicates that the CHP system performed consistently in converting the biogas into usable energy forms regardless of the seasonal fluctuations in biogas flow rate.

The total electric energy production (1672 MWh/a) and total thermal energy production (1964 MWh/a) for the year also reflected the seasonal variations in biogas flow. As expected, the highest electricity and thermal energy production occurred in November (3501 MWh/a and 3770 MWh/a, respectively) when the biogas flow was at its peak. Conversely, September witnessed the lowest electricity and thermal output (627 MWh/a and 950 MWh/a, respectively) due to the diminished biogas flow during that period.

These findings suggest that seasonal factors likely influence the biological activity within the digester, impacting the biogas production rate. Further investigation is recommended to pinpoint the specific seasonal elements that contribute to these variations. Additionally, analyzing the composition of the biogas beyond just methane content could provide valuable insights. Understanding the presence of other components, such as hydrogen sulfide or volatile fatty acids, might help identify areas for improvement in the digestion process or potential limitations on CHP efficiency. By taking a more comprehensive look at the seasonal factors and the biogas composition, we can optimize plant operations and ensure the biogas plant functions at its maximum potential throughout the year.

Table 4.4 Biogas Plant Performance Summary (2021 - 2023)

Months	[Text]	Month 1-3	Month 4-6	Month 7-9	Month10-12	Average
Year	[Number]	2021-2023	2021-2023	2021-2023	2021-2023	2021-2023
Average of the three years						
Methane Content in the Biogas	[%]	60%	60%	60%	60%	60%
Average Hourly Biogas Gas flow	(Nm3/hr)	299	329	171	332.00	282.75

Maximium Hour Biogas Flow	(Nm3/hr)	352	334	231	444	444
Average Hourly Methane Flow	(Nm3/hr)	179.4	197.4	102.6	199.2	169.7
Maximium Hourly Methane Flow	(Nm3/hr)	211.2	200.4	138.6	266.4	266.4
Standard value for the heat value of methane	[kWh/m^3]	9.97	9.97	9.97	9.97	9.97
Average Fuel input power	[kW]	1788	1968	1023	1986	1861
Max Fuel Input Power	***[kW]***	***2105***	***1998***	***1382***	***2655***	***2922***
Average CHP input power	***[kW]***	***1800***	***2000***	***600***	***1000***	***1000***
Partial load	[%]	98%	98%	98%	98%	98%
Electric efficiency CHP 1	**[%]**	**41%**	**37%**	**36%**	**38%**	**40%**
Thermal efficiency CHP 1	**[%]**	**49%**	**53%**	**54%**	**52%**	**50%**
Losses	[%]	10%	10%	10%	10%	10%
El. Power CHP 1	***[kWe]***	***747***	***835***	***232***	***400***	***400***
Th. Power CHP 1	***[kWth]***	***873***	***965***	***308***	***500***	***500***
El. Energy	***[kWhe/a]***	***6542565***	***7317456***	***2030890***	***3501033.1***	***3501033***
Th. Energy	***[kWhth/a]***	***7648635***	***8450544***	***2699510***	***4382966.9***	***4382967***
Total Electric Energy	[MWhe/a]	6542.56	7317.46	2030.89	3501.03	3501.03
Total Thermal Energy	[MWhth/a]	7648.64	8450.54	2699.51	4382.97	4382.97

4.2 Sensitivity analysis

The amount of biogas generated at the Kaliti wastewater treatment plant varies throughout the months and years. To understand how the system's performance is affected by these fluctuations in biogas production, sensitivity analyses have been conducted, as shown in Table 4.2

Table 4.5 Sensitivity Analysis

Biogas flow rate (Nm^3/h)	**Methane Flow rate (Nm^3/h)**	**Heating Value of Mathane (kWh/m^3)**	**CHP input power in kW**	**Partial load efficiency**	**Electric efficiency CHP**	**Thermal Losses**	**Thermal Efficiency CHP**	**Net Electric Power (kW)**	**Net Thermal Power (kW)**	**Overall Efficiency (%)**
40	24.0	9.98	240	98%	**36.3%**	10.00%	53.7%	86.84	128.73	90.0%
50	30.0	9.98	299	98%	**36.8%**	10.10%	53.1%	110.28	158.88	89.9%
60	36.0	9.98	359	98%	**37.3%**	10.20%	52.5%	134.04	188.59	89.8%
70	42.0	9.98	419	98%	**37.7%**	10.30%	52.0%	158.06	217.93	89.7%
80	48.0	9.98	479	98%	**38.1%**	10.40%	51.5%	182.30	246.92	89.6%
90	54.0	9.98	539	98%	**38.4%**	10.50%	51.1%	206.73	275.60	89.5%
100	60.0	9.98	599	98%	**38.6%**	10.60%	50.8%	231.34	303.99	89.4%
110	66.0	9.98	659	98%	**38.9%**	10.70%	50.4%	256.11	332.09	89.3%
120	72.0	9.98	719	98%	**39.1%**	10.80%	50.1%	281.01	359.94	89.2%
130	78.0	9.98	778	98%	**39.3%**	10.90%	49.8%	306.05	387.54	89.1%
140	84.0	9.98	838	98%	**39.5%**	11.00%	49.5%	331.20	414.90	89.0%
150	90.0	9.98	898	98%	**39.7%**	11.10%	49.2%	356.47	442.03	88.9%
160	96.0	9.98	958	98%	**39.9%**	11.20%	48.9%	381.84	468.93	88.8%
170	102.0	9.98	1018	98%	**40.0%**	11.30%	48.7%	407.31	495.62	88.7%
180	108.0	9.98	1078	98%	**40.2%**	11.40%	48.4%	432.87	522.10	88.6%
190	114.0	9.98	1138	98%	**40.3%**	11.50%	48.2%	458.52	548.37	88.5%
200	120.0	9.98	1198	98%	**40.4%**	11.60%	48.0%	484.24	574.44	88.4%

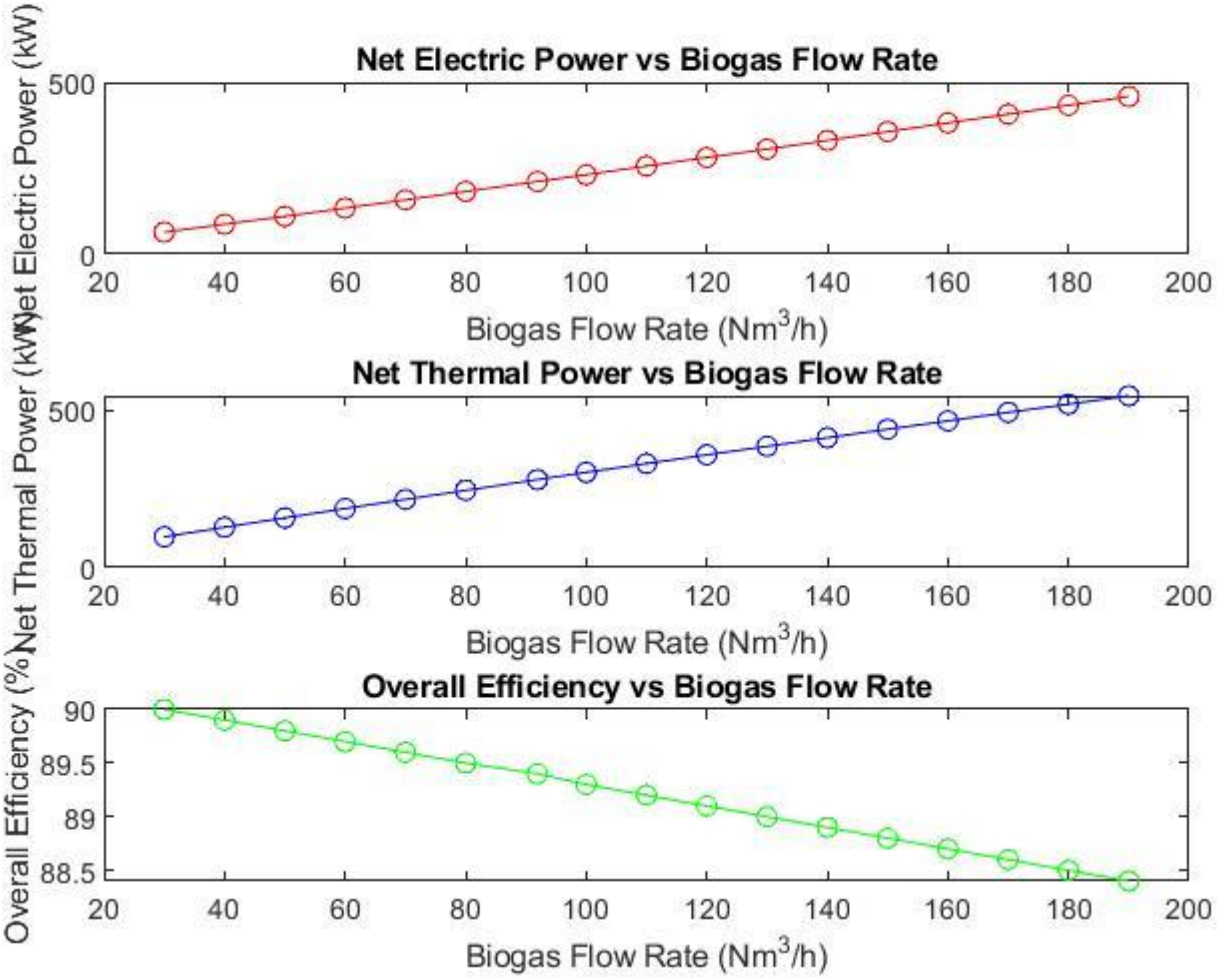


Figure 4.1 Sensitivity Analysis

Table 4.2 and figure 4.1 provides a detailed analysis of the performance metrics for a Combined Heat and Power (CHP) system at varying biogas flow rates. The biogas flow rate ranges from 40 Nm³/h to 200 Nm³/h, the methane flow rates range from 24 Nm³/h to 120 Nm³/h, indicating a consistent methane composition in the biogas. The heating value of methane remains steady at 9.98 kWh/m³, except for the last data point where it slightly increases to 10.98 kWh/m³, suggesting a minor variation in methane quality at higher flows.

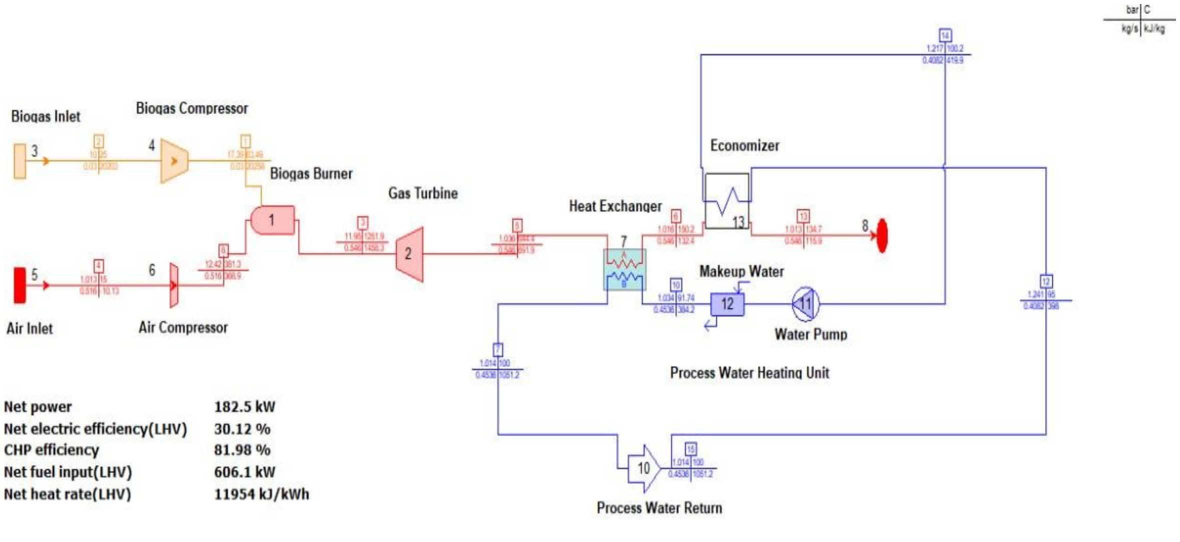
CHP input power increases linearly with the biogas flow rate, from 240 kW at 40 Nm³/h to 1198 kW at 200 Nm³/h, directly proportional to the methane flow rate and its heating value. The electric efficiency of the CHP system gradually improves from 36.3% at 40 Nm³/h to 40.4% at 200 Nm³/h, indicating better electrical conversion efficiency at higher biogas flow rates. Thermal losses show a slight increase from 10% to 11.60% as the biogas flow rate rises. However, thermal efficiency decreases from 53.7% at 40 Nm³/h to 48% at 200 Nm³/h, reflecting a minor decline in the system's ability to convert energy into useful thermal output at higher flows.

Net electric power generated rises significantly from 86.84 kW to 484.24 kW with increasing biogas flow rates, while net thermal power also increases from 128.73 kW to 574.44 kW. This increase in thermal power generation corresponds to the rising input power, despite the decreasing thermal efficiency. Overall efficiency shows a marginal decline from 90.0% at 40 Nm³/h to 88.40% at 200 Nm³/h

Key findings include the improvement in electric efficiency with higher biogas flow rates, reaching up to 40.4% at the highest flow rate, and a slight decrease in thermal efficiency, indicating more energy is lost as heat at higher flow rates. The overall efficiency remains relatively high, with a minor downward trend, highlighting the system's effectiveness but also the diminishing returns on efficiency with increased biogas input. Balancing power outputs is crucial as both net electric and thermal power outputs increase with biogas flow rate, reflecting the system's capacity to generate more power with higher biogas inputs, although with varying efficiency rates. This analysis provides valuable insights for optimizing strategies to balance electric and thermal outputs and maximize overall system performance.

Simulation Result

To analyze the biogas cogeneration unit, Thermoflex software was used due to its suitability for modeling thermodynamic systems, particularly those involving complex energy interactions like biogas-based cogeneration. Thermoflex provides a user-friendly interface and a comprehensive set of components to accurately simulate the entire cogeneration process, including biogas production, gas engines, heat exchangers, and auxiliary equipment. Its ability to handle various fuel types, including biogas, and simulate multiple operational scenarios, such as varying loads and environmental conditions, makes it ideal for optimizing performance. Additionally, Thermoflex offers detailed thermodynamic and economic analyses, which are essential for evaluating system efficiency, power output, thermal behavior, and economic feasibility. Its compatibility with other modules like PEACE further enhances its utility for an integrated technical and economic assessment of biogas cogeneration projects.



Net power	182.5 kW
Net electric efficiency(LHV)	30.12 %
CHP efficiency	81.98 %
Net fuel input(LHV)	606.1 kW
Net heat rate(LHV)	11954 kJ/kWh

		1	2	3	4	5	6	7	8	10	11	12	13	14	15
p	bar	17.39	10	11.95	1.013	1.036	1.016	1.014	12.42	1.034	1.034	1.241	1.013	1.217	1.014
T	C	63.49	25	1251.9	15	644.4	150.2	100	381.3	91.74	100.2	95	134.7	100.2	100
m	kg/s	0.03	0.03	0.546	0.516	0.546	0.546	0.4536	0.516	0.4536	0.4082	0.4082	0.546	0.4082	0.4536
h	kJ/kg	20258	20203	1458.3	-10.13	691.9	132.4	1051.2	368.9	384.2	419.9	398	115.9	419.9	1051.2

Figure 4.2 Biogas based Cogeneration at Design Condition with a Biogas flow rate

Based on the Thermoflex Simulation results, the biogas-based cogeneration system demonstrates higher efficiency in generating both electricity and useful heat by utilizing biogas as the primary fuel source. The system operates by compressing biogas and air, which are then mixed and combusted in a biogas burner. This combustion process generates high-temperature gases that drive the gas turbine, leading to a net electrical power output of 182.5 kW. The system's net electric efficiency is recorded at 30.12%, which, while moderate for electricity production alone, is significantly enhanced by the combined heat and power (CHP) functionality.

After the gas turbine extracts energy, the exhaust gases, still at a high temperature of 631.9°C, pass through a heat exchanger, where much of the remaining energy is recovered and transferred to a process water-heating unit. This heat recovery is crucial in improving the overall system efficiency. Additionally, the system employs an economizer that further extracts heat from the gases, reducing their temperature to 134.7°C while preheating the makeup water to 95°C. This step reduces the fuel required to heat the process water, making the system more fuel-efficient and contributing to the overall CHP efficiency of 81.98%.

The simulation highlights that the system requires a net fuel input of 606.1 kW (LHV), and the net heat rate is calculated to be 11,954 kJ/kWh. These figures reflect the energy input necessary to produce one unit of electricity while also accounting for the significant heat recovery that occurs during operation. This heat recovery is especially valuable for industrial applications or district heating systems, where both electricity and thermal energy are required.

From an environmental perspective, the use of biogas as the primary fuel source adds a sustainability dimension to the system. Biogas, often produced from organic waste, is a renewable energy source that can help reduce greenhouse gas emissions compared to conventional fossil fuels. The system effectively maximizes energy recovery, reducing waste and improving overall fuel utilization.

In conclusion, the results underscore the cogeneration system's robust performance. Its moderate electrical efficiency is complemented by excellent CHP efficiency, thanks to thorough heat recovery mechanisms. With its ability to efficiently convert biogas into both electricity and heat, the system is an ideal solution for energy-intensive industries or communities with district heating networks, offering a balance of economic and environmental benefits.

Sensitivity Analysis

To evaluate the impact of varying biogas flow on system performance, a sensitivity analysis was conducted using flow rates ranging from 30 m^3/hour to 200 m^3/hour, based on raw data collected from the site. Given that the density of biogas is approximately 1.15 kg/m^3, this corresponds to biogas flows of about 0.0096 kg/s at the lower end (30 m^3/hour) and 0.0639 kg/s at the upper end (200 m^3/hour). The analysis explores how these variations in biogas flow rates affect overall system efficiency and performance outputs.

Table 4.6 Sensitivity Analysis of Thermoflex

Mass flow rate of biogas (kg/s)	Volumetric Flow Rate of Biogas (m^3 /h)	Net Electric Power (kw)	Net Electric Efficiency (LHV), %	CHP Efficiency (%)
0.01	30	59.18	29.29	85.04
0.02	60	120.6	29.85	82.73
0.03	90	182.5	30.12	81.97
0.04	120	245.7	30.41	81.82

0.05	160	308.9	30.58	81.7
0.06	200	372.3	30.71	81.6

The above table presents a sensitivity analysis of a biogas-based cogeneration plant, simulated using Thermoflex software, highlighting how varying the mass flow rate of biogas impacts key performance metrics. The mass flow rate of biogas ranges from 0.01 to 0.06 kg/s, with corresponding volumetric flow rates increasing proportionally from 30 to 200 m³/h. As the mass flow rate increases, the net electric power output also rises, starting at 59.18 kW and reaching 372.3 kW. This indicates that higher biogas input leads to greater power generation. The net electric efficiency, based on the lower heating value (LHV) of the biogas, shows a slight improvement with increasing mass flow rates, from 29.29% to 30.71%, suggesting marginally better conversion efficiency at higher inputs. However, the Combined Heat and Power (CHP) efficiency, which considers both electricity and useful heat produced, decreases slightly from 85.04% to 81.6%. This minor decline could be due to increased thermal losses or other inefficiencies at higher biogas flow rates. Overall, the analysis demonstrates that while increasing the biogas mass flow rate enhances net electric power and slightly improves electric efficiency, it results in a small reduction in CHP efficiency, providing valuable insights for optimizing the performance of biogas-based cogeneration plants.

Biogas Flaring Vs Biogas Energy recovery using cogeneration

The comparison in table 5 highlights the significant benefits of cogeneration over flaring biogas at wastewater treatment plants. Cogeneration at the Akaki Wastewater Treatment Plant stands out for its efficient utilization of biogas, generating both electric power and heat. This approach not only reduces reliance on non-renewable energy sources but also creates additional revenue streams through the potential sale of excess electricity. Conversely, the flaring method at the Kaliti Wastewater Treatment Plant results in wasted energy resources and environmental pollution, representing a missed opportunity for sustainable energy generation and revenue generation.

Table 4.7 Biogas Flaring Vs Biogas Energy recovery using cogeneration

Aspect	**Flaring at Kaliti Wastewater Treatment Plant**	**Biogas Cogeneration at Akaki Wastewater Treatment Plant**
Purpose	Currently used to dispose of excess biogas without energy recovery, resulting in wasted energy resources and environmental pollution	Utilized for both environmental protection and energy gene ration, converting biogas into useful energy for electricity and heat production
Biogas Utilization	Biogas is primarily flared off without harnessing its energy content, contributing to environmental pollution	Biogas is efficiently utilized for electricity and heat production, reducing reliance on non-renewable energy sources
Energy Recovery System	Currently lacks a robust energy recovery system	Features an advanced biogas flare system, designed for safe combustion and efficient energy recovery
Environmental Impact	Contributes to environmental pollution by releasing methane, a potent greenhouse gas, into the atmosphere	Minimizes environmental impact by converting methane into less harmful carbon dioxide and water vapor through safe combustion
Efficiency and	Relies on a	Features a comprehensive system

Reliability	basic flaring mechanism without additional features for efficiency and reliability	with pressure relief valves, supporting pipes, and an automatic alarm system for enhanced efficiency and reliability
Compliance with Standards	May not fully comply with environmental safety standards due to the release of methane into the atmosphere	Ensures compliance with environmental safety standards by safely and efficiently managing biogas through combustion
Overall Environmental Footprint	Contributes to environmental degradation and missed opportunities for sustainable development	Mitigates environmental footprint by effectively managing biogas and reducing greenhouse gas emissions through efficient combustion
Potential for Sustainable Development	Represents a significant missed opportunity for sustainable energy generation and environmental stewardship	Demonstrates a commitment to sustainability by utilizing biogas for energy generation and environmental protection

4.3 Economic analysis (Gross)

Biogas flaring systems, currently in use, are designed to combust collected biogas, releasing methane—a potent greenhouse gas—into the atmosphere. While these systems mitigate immediate safety concerns, they fail to harness the energy potential of biogas effectively. In contrast, biogas cogeneration systems offer significant benefits by utilizing biogas for electricity and heat production. This not only reduces environmental impact but also generates substantial revenue through electricity and heat sales. Although the initial investment for cogeneration systems is higher, the long-term return on investment and sustainability make them a more economically viable and environmentally friendly option compared to flaring systems.

Table 4.8 Biogas Management Comparison: Flaring vs. Cogeneration (Gross Economic Analysis)

Aspect	Biogas Flaring System	Biogas Cogeneration System
Maximum Daily Methane Production (Nm³)	13,000	13,000
Biogas Flow Rates (Nm³/h)	40-600	40-600
Operating Pressure Range (mbar)	10-65	10-65
Revenue Generation	None	Estimated annual revenue from electricity and heat sales: $200,000
Environmental Impact	Moderate - Releases methane, a potent greenhouse gas	Reduced - Methane converted into carbon dioxide and water vapor
Energy Utilization	Low - Wastes biogas energy potential	High - Biogas used for electricity and heat production
Investment and Operational Costs	Initial setup cost for flare system: $50,000	Initial setup cost for cogeneration system: $300,000
Return on Investment	N/A - No revenue generated	Estimated ROI within 5 years with

(ROI)		potential for continued profit
Long-term Sustainability	Limited - Relies on continuous supply of biogas for flaring	High - Utilizes biogas efficiently, contributing to sustainable energy production

Economic Assessment for CHP system

Cost data for various Combined Heat and Power (CHP) technologies were collected and summarized as follows:

- **Reciprocating** engines typically range in size from less than 65kW-15MW and have an average installed cost of $1,433-2900 per kWh. These engines offer a total average CHP system efficiency of 78% and require operation and maintenance (O&M) costs ranging from $0.0177 per kWh.
- **Micro turbines,** with a typical size range of 30-2000 kW, have an average installed cost of $2500-4300 per kW. These systems boast a total average CHP system efficiency of 66.8% and incur O&M costs ranging from $0.013 per kWh.
- **Gas turbines** cover a broader size range, from 1-50 MW, and have an average installed cost of $1250-3,30000 per kW. They exhibit a total average CHP system efficiency of 69% and require O&M costs ranging from $0.0111 per kWh.
- **Fuel cells**, ranging in size from 200-2000 kW, have a higher average installed cost of $4600-10,000 per kW. However, they offer superior total average CHP system efficiency of 82% and have O&M costs ranging from $0.040 per kWh.

Table 4.9 Cost data for various Combined Heat and Power (CHP) technologies [35,36]

CHP Technology	Typical Size Range	Average Installed Cost ($/kW) \$	Total Average CHP System Efficiency (%)	O&M Cost (/kWh)

Reciprocating Engine	65Kw-15Mw	1,433-2,900	78	0.0177
Microturbine	30-200kw	2,500-4,300	66.8	0.013
Gas Turbine	1-50Mw	1,250-3,300	69	0.0111
Fuel Cell	200-2000Kw	4600-10,000	82	0.040

There are major assumptions have taken to asses reciprocating CHP system, cost, life cycle of the equipment, discount rate and so on.

- Life time of operating CHP system 10-20 years
- Installed cost current value average for 65kwh - 15MW costs 1400-2900 $/kwh
- Operating and maintenance cost 0.0177$/kwh
- Reduction of CHP system 30-50%
- Discount rate of CHP 3%

Electrical energy input from biogas :600kwh

- To select CHP system of 6ookwh energy the price would be 1800$/kwh we multiply to get the price: 1800$/kwh*600kwh = 1,080,000$
- Maintenance cost: 0.0177$/kwh*600kwh= 10.62$
- Investment cost included every cost related to CHP system materials transportation and other costs we have lamp sum 10% added: 1,188,000$
- Net return or useful energy per year has calculated as
- Net value: 600kwh*0.067 $/kwh (EEPCo)*24hr*365days

Net return = 352,152 $

Net Present value (NPV)

NPV analysis is used to help determine how much an investment, project, or any series of cash flows is worth. It is an all-encompassing metric, as it takes into account all revenues, expenses, and capital costs associated with an investment in its Free Cash Flow (FCF)In addition to factoring all revenues and costs, it also takes into account the timing of each cash flow that can result in a large impact on the present value of an investment. For example, it's better to see cash inflows sooner and cash outflows later, compared to the opposite.

The formula for Net Present Value is:

$$\text{NPV} = 1 + \frac{Z1}{1+r} + \frac{Z2}{(1+r)2} - Xo$$

Where:

Z1 = Cash flow in time 1

Z2 = Cash flow in time 2

r = Discount rate

X0 = Cash outflow in time 0 (i.e., the purchase price / initial investment)

Discounted payback period

The payback period, or payback method, is a simpler alternative to NPV. The payback method calculates how long it will take to recoup an investment. One drawback of this method is that it fails to account for the time value of money. For this reason, payback periods calculated for longer-term investments have a greater potential for inaccuracy.

To find the discounted payback period, the discounted cash inflow for each period is determined as given in equation. Discounted cash flow = actual cash inflow

$$\text{period Discount cash flow } = \frac{actual\ cash\ flow(Z)}{(1+r)n}$$

$$\text{payback period } = \frac{Total\ Investment}{Net\ return\ per\ year}$$

$$\text{payback period } = \frac{1{,}188{,}000}{352{,}152-10.62}$$

PBP = 3.4 years

CHAPTER FIVE

5. Conclusions and Recommendations

5.1 Conclusions

In this study a detailed analysis has been done on a biogas-fueled combined heat and power (CHP) system at the Kaliti Wastewater Treatment Plant, several key findings have emerged. The analysis revealed notable seasonal fluctuations in biogas production, likely influenced by varying biological processes within the digester. This underscores the importance of understanding and addressing seasonal variations to optimize energy utilization effectively. Comparing our results, the implementation of a CHP system demonstrated a significant improvement in energy utilization compared to traditional biogas flaring practices. The stable electric and thermal efficiencies across different biogas flow rates indicate the effectiveness of the CHP system in harnessing biogas for both electricity and thermal energy generation. The importance of these findings lies in their potential to enhance energy efficiency, leverage renewable energy sources, and achieve environmental sustainability at the Kaliti Wastewater Treatment Plant. By utilizing biogas for combined electricity and heat generation, the CHP system offers a sustainable approach to waste management while reducing environmental impact and operating costs. However, it is important to acknowledge certain limitations of this study. The analysis was based on available data and assumptions, which may not capture all nuances of the system's performance. Additionally, the study focused primarily on technical feasibility, leaving out aspects related to regulatory frameworks, socio-economic factors, and community engagement. Future work in this area could explore these aspects in more detail, integrating multidisciplinary perspectives to develop comprehensive strategies for implementing biogas-fueled CHP systems in wastewater treatment plants. Additionally, further research could delve into optimizing system design, enhancing biogas production efficiency, and investigating innovative financing models to overcome barriers to implementation. Overall, the findings of this study provide a foundation for advancing sustainable energy solutions in wastewater treatment operations.

5.2 Recommendations

In the future, it will be essential to test various types of cogeneration units from multiple perspectives, including efficiency, economic viability, and environmental impact. This comprehensive evaluation will help in selecting the most suitable technology tailored to specific needs and purposes. Additionally, exploring the potential for converting existing diesel generators to biogas generators presents a promising alternative. Given that biogas generators are scarce in Ethiopia and importing them from abroad incurs prohibitively high costs, this conversion could provide a cost-effective and locally sustainable solution. Therefore, a thorough investigation into the feasibility and practical implementation of such conversions could significantly benefit the energy sector in Ethiopia.

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Appendixes

Raw data

Date	Hourly Average biogas amount Nm^3/h)	Daily average biogas amount (Nm^3/d)
7/1/2021	89	2136
7/2/2021	95	2280
7/3/2021	106	2544
7/4/2021	125	3000
7/5/2021	121	2904
7/6/2021	119	2856
7/7/2021	101	2424
7/8/2021	49	1176
7/9/2021	58	1392
7/10/2021	51	1224
7/11/2021	65	1560
7/12/2021	76	1824
7/13/2021	35	840
7/14/2021	53	1272
7/15/2021	37	888
7/16/2021	25	600
7/17/2021	41	984
7/18/2021	47	1128
7/19/2021	59	1416
7/20/2021	78	1872
7/21/2021	53	1272
7/22/2021	59	1416
7/23/2021	80	1920
7/24/2021	96	2304
7/25/2021	60	1440
7/26/2021	23	552
7/27/2021	35	840
7/28/2021	45	1080
7/29/2021	61	1464

7/30/2021	59	1416
7/31/2021	41	984
8/1/2021	37	888
8/2/2021	60	1440
8/3/2021	47	1128
8/4/2021	58	1392
8/5/2021	45	1080
8/6/2021	48	1152
8/7/2021	54	1296
8/8/2021	58	1392
8/9/2021	58	1392
8/10/2021	39	936
8/11/2021	45	1080
8/12/2021	22	528
8/13/2021	22	528
8/14/2021	40	960
8/15/2021	63	1512
8/16/2021	58	1392
8/17/2021	51	1224
8/18/2021	18	432
8/19/2021	38	912
8/20/2021	41	984
8/21/2021	43	1032
8/22/2021	54	1296
8/23/2021	38	912
8/24/2021	48	1152
8/25/2021	45	1080
8/26/2021	58	1392
8/27/2021	36	864
8/28/2021	40	960
8/29/2021	53	1272
8/30/2021	43	1032

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9/5/2021	37	896
9/6/2021	47	1124
9/7/2021	36	864
9/8/2021	32	768
9/9/2021	25	600
9/10/2021	20	480
9/11/2021	28	672
9/12/2021	3	72
9/13/2021	0	0
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9/15/2021	4	96
9/16/2021	35	840
9/17/2021	47	1128
9/18/2021	64	1536
9/19/2021	77	1848
9/20/2021	84	2016
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9/22/2021	94	2256
9/23/2021	84	2016
9/24/2021	0	0
9/25/2021	67	1608
9/26/2021	101	2424
9/27/2021	93	2232
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9/29/2021	99	2376
9/30/2021	99	2376
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10/7/2021	87	2088
10/8/2021	79	1896

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10/12/2021	103	2472
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10/14/2021	76	1824
10/15/2021	98	2352
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10/17/2021	129	3096
10/18/2021	137	3288
10/19/2021	139	3336
10/20/2021	133	3192
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11/15/2021	240	5760
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11/19/2021	197	4728
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11/22/2021	206	4944
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11/27/2021	203	4872
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12/14/2021	184	4416
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12/16/2021	186	4464
12/17/2021	190	4560
12/18/2021	198	4752
12/19/2021	199	4776
12/20/2021	197	4728
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12/22/2021	185	4440
12/23/2021	183	4392
12/24/2021	183	4392

12/25/2021	184	4416
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12/27/2021	219	5256
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12/29/2021	219	5256
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1/22/2022	188	4512
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2/21/2022	217	5208
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4/10/2022	188	4512
4/11/2022	191	4584
4/12/2022	190	4560
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5/14/2022	283	6792
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5/24/2022	275	6600
5/25/2022	228	5472
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5/27/2022	282	6768
5/28/2022	323	7752
5/29/2022	334	8016
5/30/2022	331	7944
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6/3/2022	319	7656
6/4/2022	329	7896
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6/15/2022	257	6168
6/16/2022	240	5760
6/17/2022	233	5592
6/18/2022	272	6528
6/19/2022	229	5496
6/20/2022	168	4032
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6/22/2022	212	5088
6/23/2022	222	5328
6/24/2022	137	3288
6/25/2022	159	3816
6/26/2022	194	4656
6/27/2022	232	5568
6/28/2022	200	4800
6/29/2022	184	4416
6/30/2022	177	4248
7/1/2022	143	3432
7/2/2022	187	4488
7/3/2022	231	5544
7/4/2022	196	4704
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7/6/2022	190	4560
7/7/2022	204	4896
7/8/2022	214	5136
7/9/2022	223	5352
7/10/2022	132	3168
7/11/2022	195	4680
7/12/2022	118	2832
7/13/2022	116	2784
7/14/2022	115	2760
7/15/2022	80	1920
7/16/2022	144	3456
7/17/2022	146	3504
7/18/2022	168	4032
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7/20/2022	77	1848
7/21/2022	103	2472
7/22/2022	133	3192
7/23/2022	112	2688
7/24/2022	82	1968
7/25/2022	104	2496
7/26/2022	176	4224
7/27/2022	123	2952
7/28/2022	97	2328
7/29/2022	105	2520
7/30/2022	154	3696
7/31/2022	69	1656
8/1/2022	46	1104
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8/26/2022	122	2928
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9/8/2022	98	2352
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9/15/2022	116	2784
9/16/2022	129	3096
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9/20/2022	162	3888
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9/23/2022	179	4296
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9/26/2022	12	288
9/27/2022	16	384
9/28/2022	14	336
9/29/2022	13	312
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10/8/2022	61	1464
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10/12/2022	164	3936
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11/26/2022	179	4296
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11/29/2022	176	4224
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12/13/2022	153	3672
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12/15/2022	156	3744
12/16/2022	155	3720
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4/22/2023	271	6504
4/23/2023	266	6384
4/24/2023	255	6120
4/25/2023	228	5472
4/26/2023	219	5256
4/27/2023	179	4296
4/28/2023	202	4848
4/29/2023	197	4728
4/30/2023	158	3792
5/1/2023	105	2520
5/2/2023	93	2232
5/3/2023	102	2448
5/4/2023	131	3144
5/5/2023	119	2856
5/6/2023	135	3240
5/7/2023	97	2328
5/8/2023	84	2016
5/9/2023	0	0
5/10/2023	0	0
5/11/2023	103	2472
5/12/2023	106	2544
5/13/2023	105	2520
5/14/2023	113	2712
5/15/2023	102	2448
5/16/2023	123	2952

5/17/2023	123	2952
5/18/2023	120	2880
5/19/2023	95	2280
5/20/2023	93	2232
5/21/2023	71	1704
5/22/2023	85	2040
5/23/2023	125	3000
5/24/2023	122	2928
5/25/2023	106	2544
5/26/2023	79	1896
5/27/2023	125	3000
5/28/2023	154	3696
5/29/2023	173	4152
5/30/2023	183	4392
5/31/2023	192	4608
6/1/2023	196	4704
6/2/2023	205	4920
6/3/2023	213	5112
6/4/2023	213	5112
6/5/2023	212	5088
6/6/2023	214	5136
6/7/2023	214	5136
6/8/2023	204	4896
6/9/2023	176	4224
6/10/2023	186	4464
6/11/2023	190	4560
6/12/2023	152	3648
6/13/2023	128	3072
6/14/2023	139	3336
6/15/2023	155	3720
6/16/2023	180	4320
6/17/2023	186	4464
6/18/2023	184	4416
6/19/2023	171	4104
6/20/2023	155	3720
6/21/2023	145	3480
6/22/2023	157	3768
6/23/2023	177	4248
6/24/2023	180	4320
6/25/2023	164	3936
6/26/2023	178	4272
6/27/2023	193	4632
6/28/2023	152	3648
6/29/2023	163	3912
6/30/2023	166	3984

7/1/2023	152	3648
7/2/2023	125	3000
7/3/2023	94	2256
7/4/2023	128	3072
7/5/2023	149	3576
7/6/2023	128	3072
7/7/2023	136	3264
7/8/2023	122	2928
7/9/2023	151	3624
7/10/2023	148	3552
7/11/2023	144	3456
7/12/2023	155	3720
7/13/2023	122	2928
7/14/2023	114	2736
7/15/2023	116	2784
7/16/2023	146	3504
7/17/2023	152	3648
7/18/2023	140	3360
7/19/2023	150	3600
7/20/2023	152	3648
7/21/2023	98	2352
7/22/2023	100	2400
7/23/2023	91	2184
7/24/2023	122	2928
7/25/2023	146	3504
7/26/2023	140	3360
7/27/2023	151	3624
7/28/2023	137	3288
7/29/2023	100	2400
7/30/2023	114	2736
7/31/2023	120	2880
8/1/2023	123	2952
8/2/2023	108	2592
8/3/2023	131	3144
8/4/2023	159	3816
8/5/2023	153	3672
8/6/2023	135	3240
8/7/2023	138	3312
8/8/2023	85	2040
8/9/2023	79	1896
8/10/2023	65	1560
8/11/2023	78	1872
8/12/2023	99	2376
8/13/2023	108	2592
8/14/2023	92	2208

8/15/2023	74	1776
8/16/2023	96	2304
8/17/2023	76	1824
8/18/2023	80	1920
8/19/2023	92	2208
8/20/2023	136	3264
8/21/2023	90	2160
8/22/2023	85	2040
8/23/2023	98	2352
8/24/2023	80	1920
8/25/2023	99	2376
8/26/2023	112	2688
8/27/2023	120	2880
8/28/2023	125	3000
8/29/2023	73	1752
8/30/2023	82	1968
8/31/2023	89	2136
9/1/2023	110	2640
9/2/2023	133	3192
9/3/2023	147	3528
9/4/2023	156	3744
9/5/2023	130	3120
9/6/2023	111	2664
9/7/2023	109	2616
9/8/2023	76	1824
9/9/2023	90	2160
9/10/2023	68	1632
9/11/2023	90	2160
9/12/2023	86	2064
9/13/2023	68	1632
9/14/2023	77	1848
9/15/2023	54	1296
9/16/2023	52	1248
9/17/2023	77	1848
9/18/2023	96	2304
9/19/2023	97	2328
9/20/2023	69	1656
9/21/2023	77	1848
9/22/2023	106	2544
9/23/2023	123	2952
9/24/2023	107	2568
9/25/2023	106	2544
9/26/2023	86	2064
9/27/2023	99	2376
9/28/2023	141	3384

9/29/2023	147	3528
9/30/2023	158	3792
10/1/2023	172	4128
10/2/2023	169	4056
10/3/2023	180	4320
10/4/2023	181	4344
10/5/2023	195	4680
10/6/2023	193	4632
10/7/2023	189	4536
10/8/2023	199	4776
10/9/2023	236	5664
10/10/2023	228	5472
10/11/2023	236	5664
10/12/2023	229	5496
10/13/2023	255	6120
10/14/2023	259	6216
10/15/2023	258	6192
10/16/2023	256	6144
10/17/2023	238	5712
10/18/2023	239	5736
10/19/2023	235	5640
10/20/2023	276	6624
10/21/2023	265	6360
10/22/2023	256	6144
10/23/2023	267	6408
10/24/2023	271	6504
10/25/2023	284	6816
10/26/2023	275	6600
10/27/2023	300	7200
10/28/2023	309	7416
10/29/2023	316	7584
10/30/2023	309	7416
10/31/2023	314	7536
11/1/2023	311	7464
11/2/2023	301	7224
11/3/2023	306	7344
11/4/2023	318	7632
11/5/2023	319	7656
11/6/2023	336	8064
11/7/2023	317	7608
11/8/2023	312	7488
11/9/2023	324	7776
11/10/2023	309	7416
11/11/2023	340	8160
11/12/2023	351	8424

11/13/2023	307	7368
11/14/2023	302	7248
11/15/2023	310	7440
11/16/2023	308	7392
11/17/2023	322	7728
11/18/2023	289	6936
11/19/2023	285	6840
11/20/2023	306	7344
11/21/2023	314	7536
11/22/2023	317	7608
11/23/2023	312	7488
11/24/2023	315	7560
11/25/2023	279	6696
11/26/2023	330	7920
11/27/2023	264	6336
11/28/2023	309	7416
11/29/2023	306	7344
11/30/2023	303	7272
12/1/2023	297	7128
12/2/2023	296	7104
12/3/2023	251	6024
12/4/2023	303	7272
12/5/2023	301	7224
12/6/2023	304	7296
12/7/2023	301	7224
12/8/2023	301	7224
12/9/2023	305	7320
12/10/2023	307	7368
12/11/2023	297	7128
12/12/2023	298	7152
12/13/2023	306	7344
12/14/2023	307	7368
12/15/2023	311	7464
12/16/2023	306	7344
12/17/2023	302	7248
12/18/2023	299	7176
12/19/2023	287	6888
12/20/2023	296	7104
12/21/2023	330	7920
12/22/2023	444	10656
12/23/2023	273	6552
12/24/2023	157	3768
12/25/2023	42	1008
12/26/2023	4	96
12/27/2023	0	0

12/28/2023	145	3480
12/29/2023	324	7776
12/30/2023	350	8400
12/31/2023	354	8496
1/1/2024	355	8520
1/2/2024	355	8520
1/3/2024	352	8448
1/4/2024	357	8568
1/5/2024	370	8880
1/6/2024	374	8976
1/7/2024	374	8976
1/8/2024	345	8280
1/9/2024	350	8400
1/10/2024	347	8328
1/11/2024	332	7968
1/12/2024	358	8592
1/13/2024	366	8784
1/14/2024	358	8592
1/15/2024	375	9000
1/16/2024	257	6168
1/17/2024	248	5952
1/18/2024	370	8880
1/19/2024	384	9216
1/20/2024	364	8736
1/21/2024	345	8280
1/22/2024	368	8832

/

Biogas record data of Reactor & Biogas line to flare

Biogas per reactor grab sample

Jan,2021

Parameters	Units	1A	1B	1C	1D	1E	2A	2B	2C	2D	2E	Biogas line to flare grab sample
CH4	%	69.0	69.1	68.9	68.7	69.6	69.1	69.0	69.1	69.4	69.7	69.0
CO2	%	14.0	13.0	14.3	12.6	14.9	13.9	12.1	14.0	14.6	13.9	13.9
H2S	ppm	1088	1256	948	987	960	822	1001	924	1150	1141	1024

Biogas per reactor grab sample

Feb,2021

Parameters	Units	1A	1B	1C	1D	1E	2A	2B	2C	2D	2E	Biogas line to flare grab sample
CH4	%	71.5	69.0	69.5	68.3	68.4	70.2	69.9	69.8	69.1	66.4	69.4
CO2	%	15.3	12.7	12.9	11.2	13.8	13.0	13.1	11.4	11.9	11.7	12.7
H2S	ppm	2133	1448	1441	633	1187	1721	2059	1900	1482	553	1169

Matlab Code

```
% Define the input data

biogas_flow_rate = [30.0, 40.0, 50, 60, 70, 80, 91.9, 100, 110, 120, 130, 140, 150, 160, 170, 180, 190];

methane_flow_rate = [18.0, 24.0, 30.0, 36.0, 42.0, 48.0, 55.1, 60.0, 66.0, 72.0, 78.0, 84.0, 90.0, 96.0, 102.0, 108.0, 114.0];

heating_value_methane = 9.98; % kWh/m3
```

```
chp_input_power = [180, 240, 299, 359, 419, 479, 550, 599, 659, 719, 778, 838, 898, 958, 1018, 1078, 1138];

electric_efficiency = [35.5, 36.3, 36.8, 37.3, 37.7, 38.1, 38.4, 38.6, 38.9, 39.1, 39.3, 39.5, 39.7, 39.9, 40.0, 40.2, 40.3] / 100;

thermal_losses = [10.00, 10.10, 10.20, 10.30, 10.40, 10.50, 10.60, 10.70, 10.80, 10.90, 11.00, 11.10, 11.20, 11.30, 11.40, 11.50, 11.60] / 100;

thermal_efficiency = [54.5, 53.6, 53.0, 52.4, 51.9, 51.4, 51.0, 50.7, 50.3, 50.0, 49.7, 49.4, 49.1, 48.8, 48.6, 48.3, 48.1] / 100;

net_electric_power = [63.79, 86.84, 110.28, 134.04, 158.06, 182.30, 211.40, 231.34, 256.11, 281.01, 306.05, 331.20, 356.47, 381.84, 407.31, 432.87, 458.52];

net_thermal_power = [97.89, 128.49, 158.58, 188.24, 217.51, 246.44, 280.58, 303.39, 331.44, 359.22, 386.76, 414.06, 441.13, 467.98, 494.60, 521.02, 547.23];

overall_efficiency = [90.0, 89.9, 89.8, 89.7, 89.6, 89.5, 89.4, 89.3, 89.2, 89.1, 89.0, 88.9, 88.8, 88.7, 88.6, 88.5, 88.4] / 100;


% Additional calculations

CHP_net_electric_power = chp_input_power .* electric_efficiency;

CHP_net_thermal_power = chp_input_power .* thermal_efficiency;

CHP_overall_efficiency = (CHP_net_electric_power + CHP_net_thermal_power) ./ chp_input_power;


% Plot the data

figure;

subplot(3,1,1);
```

```
plot(biogas_flow_rate, CHP_net_electric_power, 'r-o');
title('Net Electric Power vs Biogas Flow Rate');
xlabel('Biogas Flow Rate (Nm^3/h)');
ylabel('Net Electric Power (kW)');

subplot(3,1,2);
plot(biogas_flow_rate, CHP_net_thermal_power, 'b-o');
title('Net Thermal Power vs Biogas Flow Rate');
xlabel('Biogas Flow Rate (Nm^3/h)');
ylabel('Net Thermal Power (kW)');

subplot(3,1,3);
plot(biogas_flow_rate, CHP_overall_efficiency * 100, 'g-o');
title('Overall Efficiency vs Biogas Flow Rate');
xlabel('Biogas Flow Rate (Nm^3/h)');
ylabel('Overall Efficiency (%)');

% Calculate and display additional performance metrics
fprintf('Biogas Flow Rate (Nm^3/h)\tNet Electric Power (kW)\tNet Thermal Power (kW)\tOverall Efficiency (%%)\n');
for i = 1:length(biogas_flow_rate)
```

```
    fprintf('%f\t\t\t\t\t%f\t\t\t\t\t%f\t\t\t\t\t%f\n', biogas_flow_rate(i), CHP_net_electric_power(i), CHP_net_thermal_power(i), CHP_overall_efficiency(i) * 100);

end
```